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Recent Breakthrough in High-Efficiency ALGaN-Based UV LED

Haocheng Yu

Department of Materials, The University of Manchester, Manchester, UK
haocheng.yu@student.manchester.ac.uk

Abstract. Aluminum gallium nitride (AlGaN)–based deep-ultraviolet (DUV) light-emitting diodes (LEDs) is dominated by various applications including public health biocidal disinfection, industrial UV curing, clinical phototherapy, and solar-blind non-line-of-sight optical communication. These features and Becoming increasingly globally recognized compact, non-hazardous, high-efficiency deep-ultraviolet (DUV) light sources have driven up its development. Yet before these devices ever reached widespread use, a series of fundamental performance bottlenecks, such as low carrier injection efficiency and light extraction efficiency (LEE), have adversely impacted their performance. Here we provide an overview of the recent to transformative technologies addressing these limiting factors in three pillars of techniques: high-quality AlN templates growth by advanced epitaxial techniques, n/p-type layer engineering for high carrier injection efficiency (EIE), and nano-photonic design for LEE enhancement. In the following, the working principles of each approach are described in detail and the synergies between them to enhance the overall efficiency are shown. Therefore, it investigates the beneficial consequences for the widespread use of high-performance and high-power DUV LEDs.

Keywords: AlGaN LED, Deep UV LEDs, AlGaN doping, luminous efficiency

1. Introduction

Among outstanding non-thermal disinfection methods, ultraviolet radiation serves to sterilize air, water and surfaces of objects. In the public demand for continuous and non-contact disinfection technologies to pursue further environmental hygiene, compact and mercury-free ultraviolet light sources for space use are provided, which makes their widespread use in public and personal environments possible. In contrast to traditional chemical and thermal sterilization processes, DUV LEDs are less likely to cause degradation of the product, or leave carcinogenic residues. Beyond impact on public health, the adaptability of UV LEDs has been demonstrated through use in a variety of other industries. For example, UVA-LED can be utilized as the light source for photopolymerization based 3D printing technology, UVB-LED provides focused phototherapy for skin illnesses. Furthermore, DUV LEDs may be applied for high-precision microlithography as well as safe Non Line of Sight (NLOS) optical communications [1].

In response to these demands, the AlGaN-based LEDs has emerged the most promising candidate device in the next-generation optoelectronic field. The benefits of AlGaN-based UV LEDs include

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their environmental friendliness and long operational lifetimes, as well as their capability of being digitally modulated at high speeds, in contrast to the use of mercury lamps, which are poisonous. Nevertheless, the performance of AlGaN-based DUV LEDs especially in the far-UVC (220 - 240 nm) spectral region is still limited due to low EQE [2]. While the pandemic has sped up research, meeting the efficiency needed for mass adoption is still a tall order.

This article aims to summarize the latest research on the preparation of high-quality AlGaN to propose possible new strategies for improving the performance of deep-ultraviolet light-emitting diodes based on AlGaN. These methods are dedicated to addressing the fundamental bottlenecks of carrier transport and light extraction, providing an expandable path for efficient ultraviolet light-emitting devices.

2. Material properties and device structure of AlGaN-based DUV-LEDs

The light emission from AlGaN light-emitting diodes can be adapted to approximately cover the entire UV spectral range of wavelength, ranging from 210 nm to 400 nm, and this adjustability makes UV-LEDs fascinatingly suitable to a wide number of industrial, environmental, biological or medical applications. This adjustability is mainly due to the AlGaN that has the same crystal structure as GaN and AlN, namely, the wurtzite (WZ) structure. Because it is a ternary alloy of GaN and AlN, at room temperature and pressure (r.t.p.), the WZ structure is the thermodynamically stable phase for AlGaN, characterized by a hexagonal close-packed (HCP) arrangement in which metal atoms and nitrogen atoms are interleaved. The WZ structure is classified under the hexagonal crystal system with a space group of P63mc. Specifically, the atomic arrangement of AlGaN is a hexagonal close-packed arrangement with non-centrosymmetric properties.

The energy band structure of semiconductor material is directly determined by its crystal structure and electron configuration. As both GaN and AlN are direct bandgap materials, AIGaN is also a direct wide-bandgap semiconductor material, featured with same advantage of direct wide bandgap character. By altering the composition of AI, the bandgap width can be continuously adjusted from 3.39 eV to 6.1 eV, covering the UV wavelength range of 210 nm to 360 nm. To be more precisely, Equation (1) is always used to calculate the energy bandgap of AlGaN material with Al component of x,

$$E_g(Al_xGa_{(1-x)}N) = E_g(AlN) \times x + E_g(GaN) \times (1 - x) - b \times x \times (1 - x) \quad (1)$$

where $E_g(AlxGa_{(1-x)}N)$ is the energy bandgap of AlGaN, $E_g(AlN)$ and $E_g(GaN)$ represent the energy bandgap of AlN and GaN, and b is an experimentally determined bowing parameter. Based on the physical properties brought about by the crystal structure of AlGaN, AlGaN based UV LEDs have many advantages, compared with other semiconductors, such as higher operating temperature and better power handling capability. The electron channel mobility is up to 50 times as large and its charge carrier density is up to 10 times as large compared to what they are in a SiC metal oxide semiconductor. The reason for this is that the N-face (0001) plane carries a positive charge, while the opposite Ga-face (0001) plane carries a smaller negative charge. Thus, this spontaneous polarization phenomenon leads to the generation of a large number of electron carriers in the two-dimensional electron gas [1, 2]. These advantages make the design of AlGaN LED devices a priority for the world in the field of DUV LED development. Although AlGaN LED products are competitive and ready to enter the commercial field, as shown in Fig 1, there are still many difficulties to overcome in preparing high-quality and high-efficiency AlGaN UV LEDs.

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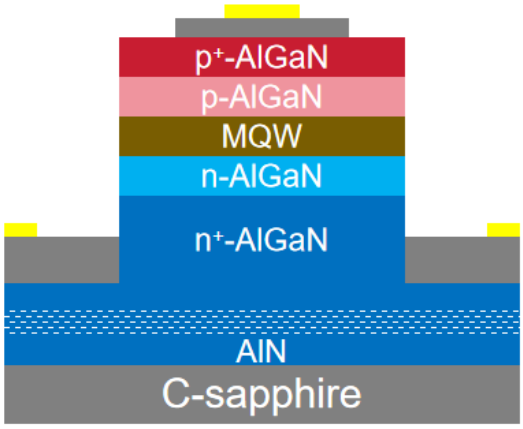

Figure 1. Schematic image of structure of AlGaN UV LED

In Fig 1, the LEDs were processed using conventional techniques, including photolithography, dry etching, and metal evaporation. A chlorine plasma reactive ion etching process was employed to etch the mesa structure (with an effective device area of 100 × 100 mm^2) [3].

In addition to the LED shown in Fig 1, a considerable portion of the current UV LEDs based on AlGaN utilize specially designed metal-organic chemical vapor deposition (MOCVD) systems on the sapphire substrate, where the LED structures are grown. In fact, the reason for adopting such special manufacturing techniques is that there are certain issues with the deep ultraviolet light-emitting diodes made of AlGaN.

• The Internal Quantum efficiency (IQE) of AlGaN LED will be significantly reduced due to the presence of threading dislocations. However, it is very difficult to obtain AlN with a low density of threading dislocations.

• The p-type concentration of AlGaN is relatively low, which leads to a severe leakage of electrons, thereby making it difficult to obtain sufficient quantum well EIE.

• The LEE may be below 10%

These material characteristics will ultimately be reflected in the decrease of EQE, a data that measures the ratio of photons output to the external by the LED to the number of injected electrons, as shown in the Equal (2).

$$EQE = EIE \times IQE \times LEE. \tag{2}$$

Therefore, the current approaches to improving the efficiency of AlGaN LEDs typically focus on reducing the density of threading dislocations and increasing the p-type concentration in high-Al compositions etc.

3. Growth of high-quality AlN film

Prepare Sapphire has a band gap of about 8.8 eV and a corresponding intrinsic absorption cutoff wavelength of ~140 nm. In contrast, the corresponding intrinsic absorption is much smaller than the emission wavelength range of DUV-LEDs, where the photon energy corresponding to 210~365 nm is 3.4~5.9 eV. This characteristic makes the sapphire substrate completely transparent to the light of this wavelength range, and the light emitted by the LED will not be absorbed by the substrate. Moreover, it is one of the very few low-cost substrate materials that can meet this requirement. C-plane sapphire is the mainstream epitaxial substrate for AlGaN-based DUV-LEDs, yet it suffers

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from severe lattice and thermal mismatch with high-Al-content AlGaN, necessitating an AlN buffer layer for transition. The crystalline quality of AlN films directly defines the device performance ceiling. Thus, developing controllable fabrication technologies for high-quality AlN is critical to breaking the efficiency bottleneck of DUV-LEDs. MOCVD, one of the most initial technique used in producing LED (e.g., the LED shown in Fig. 1) aims to improve the quality of the AlGaN films. This is achieved by allowing high temperature growth on sapphire that promotes Al adatom migration and thus high-quality AlN with an atomically flat surface. This method of using high-temperature MOCVD can grow high-quality AlN layers with a thickness of 5-10 micrometers, and its TDD can be as low as 2×10^{9} cm^{-2}. As a result, this low-density dislocation AlN template serves as the foundation for the subsequent growth of high-quality, low-defect AlGaN active layers.

Later, another improved growth method was introduced, known as the ammonia pulsed-flow multi-layer (ML) growth method, shown in Fig 2. This method further enhanced the quality of the AlN substrate and reduced the edge dislocation density by a factor of 100.

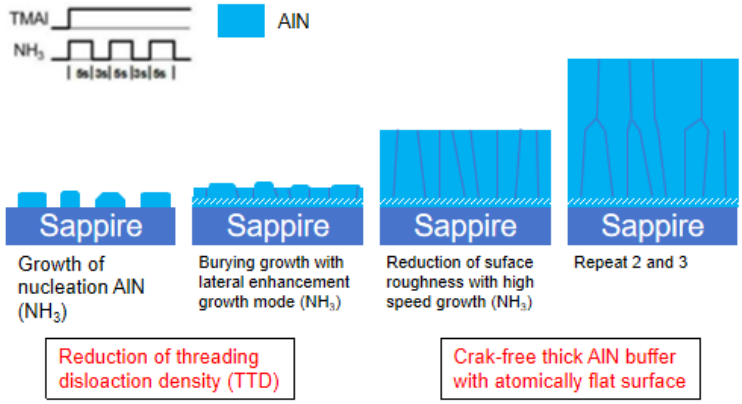

Figure 2. Schematic image and gas-flow sequence used in NH3 pulsed-flow multi-layer (ML) AlN growth

Figure 2 illustrates the conceptual framework for AlN epitaxial growth on a sapphire substrate, along with the corresponding gas-flow sequence employed in the ammonia pulsed-flow multi-layer growth technique. The process forms high-quality AlN nucleation layer on the sapphire in pulsed ammonia flow. The nucleation layer is then lateral overgrown to reduce the propagation of threading dislocations. The pulsed-flow nucleation stage and the lateral overgrowth stage astutely combine to progressively reduce the TDD in the AlN epilayer. Although lateral overgrowth significantly reduces TDD, a thick film (>1 μm) results in tensile strain induced by the lattice mismatch of AlN and sapphire, and crack generating. To compensate, a high-speed continuous-flow growth mode is activated after lateral overgrowth; this process allows for enhanced surface planarity as well as relaxation of accumulated strain, thereby minimizing crack initiation. Therefore, alternative continuous-flow and pulsed-flow AlN growth cycles are performed to simultaneously reach atomic-layer-scale surface flatness, further TDD reduction, and maintain structural integrity. Remarkably, the high-speed continuous-flow growth enabled longitudinal grain extension that contributed to strain accommodation and crack prevention [1, 4]. Furthermore, the ammonia pulsed-flow regime enhances the surface adatom mobility, thus leading to migration-enhanced growth, and at the same time promotes the emulsification of an Al-rich interfacial layer. This dual role guarantees a stable group-III polarity throughout the epitaxy and avoids parasitic nucleation due to nitrogen-polarity inversion. The merit of this approach consists in its crystal growth process is simple. In addition, the

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AlN buffer layer that results is free of an AlGaN layer, so it doesn't absorb deep ultraviolet light. This makes it possible to produce useful platforms for high-efficiency DUV LEDs.

According to Mohan's group (2025),the flow rate of ammonia (NH_3) has a significant and decisive effect on the growth mode, crystal quality and dislocation density of ALN film grown on c-plane sapphire substrate by pulsed atomic-layer epitaxy metal-organic vapor phase epitaxy (PALE-MOVPE) [5]. Both the experimental data and the theoretical calculations indicate that the optimal NH_3 flow rate for high-quality AlN epitaxy is near 900 sccm. When the NH_3 flow rate is too low, nitrogen source supply on the surface of growth cannot satisfy the demand, and the surface migration of Al adatoms is limited, which induces a 3D island growth mode with a rough surface and a rapid increase in screw dislocation density. On the other hand an NH_3 flow rate too high tends to facilitate parasitic gas-phase reactions of the precursors and produces a high concentration of nano-islands which prevent the removal of dislocations and deteriorate the crystal quality of the AlN film. The moderate flow rate of 900 sccm can well suppress the formation of parasitic reactions, provide for adequate surface diffusion of Al adatoms, and realize a two-dimensional step-flow growth mode that promotes grain coalescence and dislocation annihilation. Under this optimized growth condition, a screw dislocation density (Ds) of 7.86×10^{7} cm^{-2} and an edge dislocation density (De) of 1.68×10^{10} cm^{-2} are achieved for the AlN film. The total threading dislocation density (TTD) is calculated as follows, resulting in a final value of $\sim 1.69\times10^{10}$ cm^{-2}.

$$TTD = Ds + De \tag{3}$$

This result confirms that high-quality AlN buffer layers, suitable for high-performance deep ultraviolet optoelectronic devices, can be achieved at the optimized NH_3 flow rate.

4. Improvements of EIE by both enhancing the performance of n-AlGaN and p-AlGaN

For AlGaN-based deep ultraviolet LEDs, performance optimization of the core functional layers, n-type and p-type AlGaN, is critical to improve the optoelectronic efficiency of the devices. The optimized interface engineering for n-type AlGaN can reduce the additional n-type ohmic contact resistance and total series resistance in the device caused by the reactive ion etching (RIE) process, suppress the Joule heat loss, and ensure efficient electron injection. In high-Al-content systems, the core bottleneck of p-type doping is that the Mg acceptor level deepens sharply with increasing Al composition, resulting in an extremely low room-temperature acceptor ionization rate. Therefore, the key research direction in this field is to increase the effective hole concentration and reduce the hole injection barrier via band engineering. The synergistic optimization of the two can significantly enhance the EIE, reduce carrier loss, and ultimately improve the EQE of the device.

The core contradiction lies in the distinct response of high-Al n-AlGaN (Al composition >50%) to reactive ion etching (RIE), an indispensable process for mesa etching and n-layer exposure in LED manufacturing. For low-Al AlGaN, RIE-induced nitrogen vacancies serve as shallow donors, increasing surface electron concentration and facilitating ohmic contact formation. In sharp contrast, for high-Al n-AlGaN, RIE plasma damage introduces nitrogen vacancies as deep-level defects, causing severe Fermi level pinning, while RIE-generated aluminum vacancies act as acceptor-like defects that compensate free surface electrons, drastically elevating contact resistivity.

Multiple strategies have been proposed to mitigate this issue, including two-step plasma etching, nitrogen-atmosphere thermal annealing, and NH_3/SiH_4 plasma pretreatment. However, these methods have inherent limitations: two-step etching only reduces but cannot fully eliminate surface damage; high-temperature annealing risks interface interdiffusion and crystal quality degradation;

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plasma pretreatment frequently introduces extra impurities and secondary lattice damage. None can fundamentally repair RIE-induced surface damage or restore the intrinsic electrical properties of high-Al n-AlGaN.

Atomic layer etching (ALE) has emerged as a highly promising strategy to solve this bottleneck, with core innovations in atomic-precision damage removal and non-destructive surface modification. Unlike conventional RIE with continuous physical bombardment, ALE adopts a cyclic two-step half-reaction process, enabling angstrom-level etching precision with minimal secondary damage to bulk materials [6]. The underlying physical mechanism of performance improvement is twofold: first, ALE completely removes the RIE-induced nitrogen-deficient damage layer, eliminating deep-level defects and acceptor-like vacancies, thus lifting Fermi level pinning and restoring the surface stoichiometry of n-AlGaN; second, the recovery of surface chemical composition increases surface electron concentration, narrows the Schottky barrier width at the metal-semiconductor interface, and enhances electron tunneling efficiency, eventually realizing high-quality ohmic contact. This optimization directly reduces device series resistance and operating voltage, suppresses Joule heat loss, mitigates thermal-induced efficiency droop, and achieves a nearly 2-fold enhancement in peak WPE of high-Al DUV-LEDs. Beyond DUV-LEDs, Liu's team (2024) also showed that ALE has great potential in surface damage repair for other wide-bandgap semiconductor devices, providing a universal solution for high-precision, low-damage semiconductor processing.

For a long time, p-type doping of Al-rich AlGaN has long been confronted with two intrinsic bottlenecks that cannot be broken through conventional processes, which act as the primary barriers limiting the EIE and overall optoelectronic performance of the devices. The first bottleneck is the deep acceptor level of Mg and extremely low room-temperature ionization efficiency. In wurtzite III-nitrides, substitutional Mg occupying group-III lattice sites is the only practical p-type acceptor for AlGaN, while its ionization energy increases nonlinearly and drastically with Al composition: rising from approximately 170 meV in GaN to 510 meV in AlN. For Al-rich AlGaN with Al composition over 60%, the ionization energy of Mg acceptors exceeds 300 meV, far higher than the thermal excitation energy at room temperature (26 meV), resulting in less than 1% ionization efficiency of Mg acceptors at room temperature [7, 8]. In other words, the vast majority of doped Mg atoms cannot be ionized to provide free holes. The second bottleneck is the intrinsically low solubility of Mg in Al-rich AlGaN. From the perspective of statistical thermodynamics, the equilibrium solid solubility of substitutional impurities follows the formula

$$C = N_{sites} \times e^{-\Delta H_f / k_B T} \tag{4}$$

Where N_{sites} is the density of group-III lattice sites available for Mg occupation in AlGaN, ΔH_f is the formation enthalpy of substitutional Mg doping, k_B is the Boltzmann constant, and T is the epitaxial growth temperature. In Al-rich AlGaN, the formation enthalpy ΔH_f of substitutional Mg doping increases significantly with rising Al composition, leading to a sharp drop in the equilibrium solid solubility of Mg. Meanwhile, excessively incorporated Mg tends to form interstitial defects and donor-like complexes, which compensate free holes and further deteriorate p-type conductivity. These two bottlenecks directly cause low hole concentration and high resistivity in Al-rich AlGaN p-type layers, triggering a cascade of issues: insufficient hole injection, severe electron-hole injection imbalance in the active region, aggravated electron leakage, elevated operating voltage, and significant Joule heat loss. These effects ultimately drive a sharp decline in

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EIE, severe efficiency droop, and degraded device reliability. Thus, realizing efficient and stable p-type doping is the most critical strategy to boost the EIE of AlGaN-based DUV-LEDs.

To address these bottlenecks, two classic optimization schemes have been established in the field, the first being short-period superlattice (SPSL) doping. For periodically stacked AlGaN/AlGaN heterostructure superlattices, this design lowers the effective activation energy of Mg acceptors, promotes hole ionization and lateral transport, and achieves higher effective hole concentration than bulk AlGaN. However, this scheme still relies on thermal ionization of Mg impurities and cannot fundamentally break through the deep acceptor level limitation. Meanwhile, superlattice interface defects and UVC-band parasitic light absorption restrict further device performance improvement. Growth-interruption surface modification technology: During AlGaN epitaxy, group-III metal sources such as trimethylaluminum (TMAl) and trimethylgallium (TMGa) are periodically turned off, while NH_3 and Mg doping sources are continuously supplied, realizing surface adsorption and substitutional incorporation of Mg in a group-V-rich atmosphere. This process eliminates the surface lattice site competition between group-III sources and Mg sources, and effectively improves the substitutional occupancy rate and solid solubility of Mg [9]. Nevertheless, this scheme only optimizes the incorporation efficiency of Mg, cannot reduce the ionization energy of Mg acceptors, and has a limited effect on improving room-temperature hole concentration. In addition, growth interruption tends to introduce interface defects and crystal quality degradation, which aggravates non-radiative recombination loss.

Recently, Grigoletto and his team (2026) introduced a tunable distributed polarization doping (DPD) technology [10]. It realizes a paradigm shift in p-type doping of Al-rich AlGaN and fundamentally breaks through the intrinsic limitations of traditional impurity doping. The core principle of DPD technology is as follows: in AlGaN films pseudomorphically grown along the metal-polar c-plane (as shown in Fig 3), the Al composition is linearly graded from Al-rich to Ga-rich. Since the spontaneous and piezoelectric polarization intensity of wurtzite AlGaN varies linearly with Al composition, the continuous gradient of polarization intensity generates uniformly distributed fixed negative polarization charges in the bulk material. These negative charges spontaneously attract free holes as compensation carriers, achieving stable and efficient p-type conductivity without relying on thermal ionization of Mg acceptors [11].

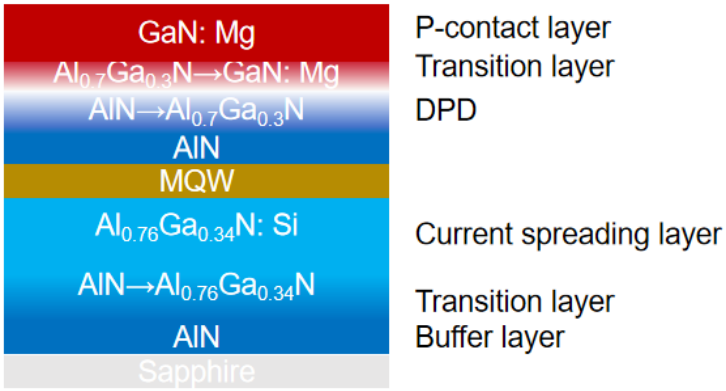

Figure 3. Schematic of the UV-LED heterostructures emitting near 265 nm with DPD layer varies from 50nm to 320nm

The core advantages of DPD technology are reflected in four aspects: ① It completely gets rid of the dual limitations of the deep Mg acceptor level and low solid solubility, achieving a high hole concentration of 6×10^{17}–4×10^{18} cm^{-3} in Al-rich AlGaN with an average Al composition over

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85%, far exceeding the theoretical limit of traditional Mg doping. ② The hole concentration can be precisely tuned by the Al composition grading slope, layer thickness, and strain state, with excellent process controllability. ③ The p-type layer has extremely low resistivity, and the device operating voltage remains almost unchanged as the DPD layer thickness increases from 50 nm to 320 nm, with negligible contribution to the total series resistance of the device, perfectly solving the industry pain point of voltage surge in traditional thick p-layers. ④ It avoids parasitic UVC absorption caused by heavy doping, and can withstand an ultra-high current density of up to 90 kA/cm² under pulsed operation without breakdown, providing core support for the development of high-power DUV-LEDs and ultraviolet laser diodes. ⑤ Due to the absence of high-concentration Mg impurities, where Mg and its related defect centers act as deep ultraviolet absorption sources. The DPD layer absorbs less ultraviolet light emitted by the device, which is beneficial for light extraction.

In summary, p-type doping of Al-rich AlGaN is limited by the intrinsic bottlenecks of deep Mg acceptor levels and low Mg solubility, which is the core factor restricting the EIE of DUV-LEDs. While superlattice doping and surface modification can only achieve partial performance optimization, tunable DPD technology replaces traditional impurity doping with polarization-induced carriers, fundamentally breaking through the intrinsic limitations. It is currently the most promising technical solution to achieve efficient p-type doping of Al-rich AlGaN and greatly improve the EIE and comprehensive performance of DUV-LEDs.

5. Improvements on the LEE

The LEE (device transmittance) of AlGaN-based DUV-LEDs are fundamentally constrained by their intrinsic material properties and device architecture. The strong built-in spontaneous and piezoelectric polarization fields in c-plane (0001) grown AlGaN quantum wells—an inherent property of the wurtzite crystal structure—induce a pronounced quantum-confined Stark effect (QCSE) that. This effect spatially separates electron and hole wavefunctions, impairs radiative recombination efficiency, and causes severe photon trapping and self-absorption within the semiconductor, which constitutes the fundamental physical bottleneck for LEE enhancement. Moreover, contact structures and the functional layers essential for efficient electrical injection introduce further significant optical losses. The p-side region presents a particularly critical challenge: the commonly used p-GaN contact layer or heavily Mg-doped p-AlGaN layers (adopted to balance electrical performance) exhibit strong optical attenuation or even complete blocking of deep-UV light emitted from the active region to the p-side, mainly originating from bandgap absorption or deep-level defect absorption. Meanwhile, the top p-type metal electrode not only physically blocks a portion of the effective light-emitting area, but also causes substantial parasitic photon absorption due to its limited reflectivity in the deep-UV spectrum. These intertwined optical loss mechanisms, stemming from both intrinsic material properties and essential device construction, represent the core impediment to high light output efficiency in DUV-LEDs [2, 9]. Therefore, the development of novel material systems and device architectures capable of co-optimizing electrical injection and optical transmission characteristics is the essential pathway to break through the current performance ceiling and realize high-efficiency deep-ultraviolet light sources.

To address the critical bottleneck of low deep-ultraviolet light transmittance in the p-type AlGaN contact layer, which severely limits the LEE of flip-chip DUV LEDs, this experiment proposes and implements an artificial intelligence-assisted inverse-designed mesa-sidewall nanoscale reflective structure, shown in Fig 4.

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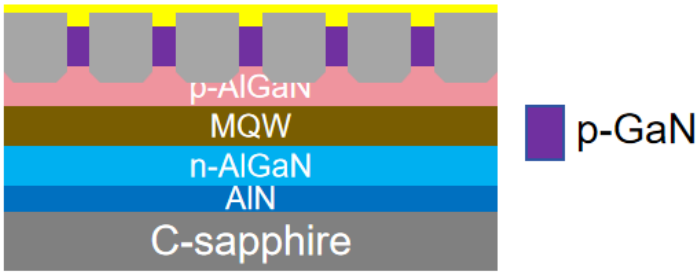

Figure 4. Schematic of the mesa sidewall nanoscale reflective structure

The overarching strategy of this solution is to circumvent the protracted development of intrinsically high-transparency p-type materials by employing a device-level photonic engineering approach. The experiment lead by Zhu (2025) constructs a periodic array of nanoscale mesas with inclined sidewalls on the surface of the conventional, strongly absorbing p-GaN layer, with the gaps between mesas filled with a high-reflectivity metal (aluminum) [10]. This design overcomes the limitations of LEE by physically thinning the absorption layer and creating a novel photon propagation pathway. In this case, the thinner nanostructure significantly reduces the total coverage area of p-GaN material, directly diminishing parasitic absorption loss. The inclined sidewalls and metal reflectors form a complex optical microstructure that effectively scatters and redirects photons, particularly coupling out the traditionally hard-to-extract TM-polarized light from its waveguide mode parallel to the quantum wells and reflecting it towards the transparent sapphire substrate output surface. This principle is free from restricted by only offering simple reflections of normal planar mirrors, which are excessively modulated by the optical resonant cavity effect. To execute, the experiment uses a closely integrated top-down and bottom-up process based on the Chaos-Jaya intelligent optimization algorithm and 3D FDTD optical simulations. This method allows us to perform an automatic and effective global search in a huge parameter space. With treating these four important nanscale parameters, period, height, top diameter and bottom diameter, as design variables or optimization variables, the objective function is defined to maximize the simulated LEE value. Therefore, the AI-based iterative optimization leads to the best-possible structure with the parameters: period ~650 nm, height ~85 nm, top diameter ~450 nm and bottom diameter ~300 nm. The simulation results show that the structure optimized by AI can increase the LEE of the device to 16.54%, which is up to 185% and 442% comparing to the baseline structure with only planar Al reflector (5.8%) and the traditional structure without reflector (3.1%), individually. This approach elegantly marries nanophotonic structure design with AI optimization, and is likely to facilitate overcoming the light extraction efficiency challenge in deep-UV LEDs.

The silica array patterned sapphire substrate (PSS) with array technology introduced in experiment of Hu et al (2020) provides a viable way to enhance the transparency of the p-type contact layer for overcoming the LEE limitation. Its basic concept is that the optical characteristics of the substrate-buffer layer interface are totally modified by influencing the photon propagation at the photons level with the introduction of a material having the refractive index of air [12]. In the standard epitaxial layers the small refractive index difference between the AlN buffer layer and the sapphire substrate (Δn ~0.3-0.5) limits the interface to manipulating photons. The experiment establishes a high-index-contrast interface (Δn ~ 0.64) between AlN (n~2.1) and the substrate by filling the patterned structures in the sapphire substrate with SiO2 (n~1.46). This brings about a decisive optical effect says the Snell law

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$$n1 \times \sin(\theta_1) = n_2 \times \sin(\theta_2) \quad (5)$$

the critical angle in total internal reflection at the AlN/SiO2 interface is dramatically diminished. Three-dimensional finite-difference time-domain simulations demonstrate that this high-contrast interface can effectively reflect a greater proportion of photons propagating at medium and large angles back into the epilayer, rather than allowing them to leak or be absorbed. These reflected photons gain a second or even third opportunity to have their propagation direction altered through multiple scattering events, ultimately meeting the escape condition at the top or bottom AlN/air interface. Simulation data confirm that, owing to this enhanced reflection and recirculation mechanism, the LEE from the top and bottom escape cones of the PSSA device is increased by 17.0% and 10.7%, respectively, compared to the conventional PSS device, resulting in a net gain of 6.8% in overall LEE. Concurrently, characterization by X-ray diffraction and scanning transmission electron microscopy reveals that this structure also reduces the threading dislocation density in the epilayer from 5.63×10^8cm-2 on conventional PSS to 2.80×10^8cm-2, synergistically improving the IQE. Therefore, the PSSA technology does not passively "reduce" the mismatch; instead, it transforms the inherent "refractive index mismatch" at the interface into an efficient "photon recycler and redistributor." By starting at the origin of the light source, it complements surface nano-engineering solutions, collectively establishing a comprehensive, multi-dimensional light extraction enhancement system.

6. Conclusion

In this review, this article has summarized the recent dramatic advancements in technology overcoming the long-standing efficiency and reliability bottlenecks that limited the performance of AlGaN-based DUV LEDs. (1) Advanced epitaxial growth techniques for high-crystalline-quality AlN templates on c-plane sapphire substrates take care of the root cause of non-radiative recombination by reducing lattice and thermal mismatch induced threading dislocations, providing the necessary crystallographic prerequisite for high IQE. (2) Selective interface engineering for n-type ohmic contacts and the revolutionary distributed polarization doping concept for p-type AlGaN surmount the fundamental physical barriers of plasma-induced n-contact degradation, as well as the extremely deep Mg acceptor level and poor dopant solubility that hinder regular impurity doping in high-Al-content AlGaN, allowing for balanced,effective carrier injection and transport for substantial improvements in EIE. (3) Engineered nanostructured photonic architectures and substrate interface optical engineering overcome fundamental optical constraints of total internal reflection, poor extraction of TM-polarized emission and parasitic absorption in p-type layers, through deterministic control of photon propagation pathways to maximize LEE. These three are not separate, independent technology enhancements, but instead, they work together to constitute a full-chain integrated efficiency improvement system. Due to their synergistic synergy interaction, the core performance parameters of AlGaN-based DUV light-emitting diodes (photoelectric current efficiency (EQE), and power efficiency (WPE)) have been averaged enhanced. Together, these innovations overcome the major technical barriers that had previously impeded the mass use of deep ultraviolet light-emitting diodes. This has enabled AlGaN ultraviolet light-emitting diodes to achieve high brightness, low power consumption, high efficiency, and long lifespan. This undoubtedly enhances their competitiveness in the commercial market and prompts the industry to invest more resources in the research and development of such devices, further strengthening their potential. From this perspective, AlGaN light-emitting diodes have a promising sustainable development prospect.

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