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Transparent AlGaN Tunnel Junctions for Deep Ultraviolet LEDs: A Systematic Review of Light Extraction Enhancement and Optical-Electrical Trade-offs

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Abstract. Deep ultraviolet (DUV) LEDs are critical for applications like water purification, surface disinfection, and biomedical sensing. However, conventional p-GaN contact layers exhibit strong optical absorption, causing extremely low external quantum efficiency and light extraction efficiency. Transparent AlGaN tunnel junctions have been proposed as an effective solution to eliminate this parasitic absorption while maintaining efficient hole injection. This paper provides a systematic review of transparent AlGaN tunnel junctions as a solution to the p-GaN absorption bottleneck in DUV LEDs. By synthesizing recent studies on Al composition engineering, doping strategies, thickness optimization, and interface control, the design principles of optimized AlGaN tunnel junction structures are summarized. Remaining challenges and future research directions are also discussed, including material growth limitations, balance between transparency and conductivity, long-term reliability, novel materials, new nanostructures, photonic structure integration, and machine learning-assisted design optimization. This review offers a comprehensive understanding of transparent AlGaN tunnel junctions, promoting the development of next-generation high-efficiency DUV LEDs.

Keywords: Deep ultraviolet LEDs, AlGaN, Tunnel junction, Light extraction efficiency, Optical-electrical trade-off

1. Introduction

Driven by the global phase-out of mercury lamps under the Minamata Convention, deep ultraviolet (DUV) LEDs are emerging as critical light sources for water purification, disinfection, and biomedical sensing [1-3]. However, the EQE of AlGaN-based DUV LEDs remains below 10% for sub-280 nm devices, primarily due to extremely low LEE [4,5]. One major factor limiting LEE is the strong optical absorption of the conventional p-GaN contact layer in the DUV spectral region [6,7]. To overcome this restriction, transparent tunnel junction (TJ) structures have been proposed as an alternative to p-GaN contact layers [8]. By replacing the p-GaN layer with a transparent p^+-AlGaN/n^+-AlGaN tunnel junction, parasitic absorption can be significantly reduced while maintaining efficient hole injection through band-to-band tunneling [9]. Consequently, increasing research efforts have explored various TJ design strategies, including thickness optimization, Al composition grading, and polarization engineering [4,10-12].

Despite these advances, a comprehensive review on transparent AlGaN TJs for DUV LEDs is lacking, as existing studies focus on individual devices and have not systematically addressed the critical balance between optical transparency and electrical conductivity [13,14]. Therefore, this paper provides a systematic review of transparent AlGaN tunnel junctions for high-efficiency DUV LEDs. Specifically, this paper aims to: (1) analyze the requirements of the materials and structure to realize both high transparency and efficient hole injection; (2) synthesize experimental results to identify key design trends and performance standards; (3) evaluate the optical-electrical balance in existing TJ designs; and (4) identify research gaps and future directions. Through evaluating the growing research in this field, this review seeks to provide researchers with a clear understanding of this field, contributing to the development of next-generation high-efficiency DUV LEDs.

2. Light extraction bottlenecks in DUV LEDs and tunnel junction technology

2.1. Fundamental operating principles and key performance metrics of DUV LEDs

DUV LEDs are semiconductor light-emitting devices based on AlGaN materials that operate through carrier injection into a p-n junction followed by radiative recombination in the quantum wells of the active region. In typical AlGan-based DUV LEDs, the active region consists of high-Al-content AlGaN multiple quantum wells (MQWs). By adjusting the Al composition in the quantum wells and barrier layers, emission wavelengths in the range of 200-280 nm can be achieved [6]. The key metric used to evaluate DUV LED performance is the EQE, defined as:

$$EQE=IQE * \eta_{inj} * LEE \tag{1}$$

where IQE is the internal quantum efficiency; η_{inj} is the injection efficiency; and LEE is light extraction efficiency [6]. For current DUV LEDs, the EQE typically remains below 10%, mainly resulting from low LEE [4,5].

2.2. Optical absorption mechanisms of the p-GaN contact layer and its impact on LEE

Conventional DUV LEDs generally employ p-type GaN as the hole injection layer due to its excellent electrical conductivity and mature doping processes. However, the bandgap of GaN is approximately 3.4 eV, corresponding to a wavelength of 365 nm. This means that for deep ultraviolet light with wavelengths shorter than 365 nm, the p-GaN layer reveals strong intrinsic absorption [7].

The absorption coefficient of p-GaN in the 280 nm band can reach 10^5 cm^{-1}, and the absorption rate of upward-emitted photons from the active region can exceed 60% [7]. Research by Hsu et al. further confirms that despite enhancing light extraction with micro-nano structures such as nanorod arrays, the absorptive p-GaN layer fundamentally limits the maximum LEE of the device [7].

2.3. Transparent tunnel junctions as an alternative hole injection structure

To overcome the absorption problem associated with p-GaN layers, transparent TJ structures have been proposed as an alternative hole injection scheme [8]. A tunnel junction is essentially a heavily doped p^+-n^+ junction that enables interband tunneling. When the junction is reverse biased, electrons from the valence band of the p^+ side can directly tunnel to the conduction band of the n^+ side, showing as hole injection from the n-type layer into the p-type layer on the macro level [9].

In DUV LEDs, the tunnel junction is generally designed as a p^+-AlGaN/n^+-AlGaN structure positioned above the active region. When the device is forward biased, electrons are injected into the active region from the n-type layer while holes are injected into the p^+-AlGaN from the n^+-AlGaN through band-to-band tunneling, entering the active region. The advantage of this design is that the p-GaN layer is completely replaced by AlGaN layers that are transparent to deep ultraviolet light, thereby fundamentally eliminating the p-GaN absorption problem [9].

2.4. Development history of tunnel junctions in DUV LEDs

Tunnel junctions were first widely studied in III-nitride optoelectronic devices such as visible LEDs and laser diodes. Since Zhang et al. first demonstrated sub-260 nm DUV LEDs with AlGaN/InGaN tunnel junctions in 2017 [14], significant progress has been made in material growth, doping optimization, and polarization engineering [4,12,13]. Key advances include cascaded multi-active region designs [12], AlGaN homojunction TJs with reduced operating voltage [13], and optimized TJ contact layers combined with asymmetric electron blocking layers [4]. Simulation studies further predict that optimally designed TJ-based DUV LEDs can achieve IQE approaching 88% with zero efficiency droop [10].

3. Material requirements and design parameters of transparent algan tunnel junctions

3.1. Optical properties of algan materials and transparency requirements

The core advantage of tunnel junctions to replace p-GaN is their transparency. Thus, it is essential to understand the optical properties of AlGaN materials in the deep ultraviolet band. The optical properties of AlGaN are primarily dependent on its Al composition. As the Al composition increases, the bandgap widens from 3.4 eV (365 nm) to 6.2 eV (200 nm) for AlN [6].

For DUV LEDs emitting at 280 nm (photon energy $\approx$ 4.43 eV), the tunnel junction material must possess a bandgap larger than the photon energy to avoid optical absorption. This requirement corresponds to Al composition above 40%. Experimental studies have discovered that when the Al content exceeds this level, the absorption coefficient in the 280 nm band can decrease to below 10^2 cm^{-1}, representing a significant reduction compared to the 10^5 cm^{-1} of p-GaN [6].

However, transparency is determined not only by material composition but also by free carrier absorption introduced by heavy doping. High concentrations of Mg or Si dopants introduce impurity-related absorption and free-carrier absorption effects, which can partially reduce optical transparency [13]. Therefore, the design of transparent tunnel junctions requires balancing Al composition, doping concentration, and layer thickness.

3.2. Doping engineering: achieving heavy doping and associated challenges

Efficient tunnel junction operation relies on heavy doping in both the p^+ and n^+ layers to create sufficient band bending for band-to-band tunneling. However, there remain difficulties for the doping of AlGaN materials, especially for p-type doping.

For n-type AlGaN, Si is the most commonly used donor dopant. Although the donor activation energy increases with higher Al composition, relatively high electron concentrations can still be achieved for Al content below 80% [6]. Electron concentrations in n^+-AlGaN can reach the order of 10^{19} cm^{-3} by controlling growth conditions.

P-type doping faces greater challenges. Mg is the most commonly used acceptor dopant in AlGan, but its acceptor activation energy is relatively high, resulting in low hole activation efficiency at room temperature, typically below 1% [13]. This issue becomes more severe for high-Al-composition AlGaN materials. To improve p-type conductivity, several strategies have been proposed: (1) Polarization-induced doping [12]. (2) δ-doping [13]. (3) Short-period superlattices [6].

The review by Nagata et al. indicated that through applications of these strategies, hole concentrations in p^+-AlGaN have reached the order of 10^{18} cm^{-3}, meeting the requirements for tunnel junction operation [13].

3.3. Thickness optimization and electrical-optical trade-offs

The thickness of tunnel junctions significantly influences both electrical and optical performance. A thinner tunnel junction layer enhances tunneling probability because the tunneling current density decreases exponentially with increasing barrier thickness. According to quantum tunneling theory, the current density J can be approximately expressed as:

$$J \propto \exp(-2d\sqrt{2m^{*}\Delta E/\hbar^{2}}) \tag{2}$$

where d is the tunneling layer thickness, m* is the carrier effective mass, and ΔE is the tunneling barrier height [10]. This indicates that tunneling current decreases exponentially with increasing tunnel junction layer thickness. Simulation studies by Karmakar et al. suggested that the optimal p^+ layer thickness range is between 10-30 nm for AlGaN tunnel junctions [10]. Within this range, tunneling resistance remains acceptable while optical absorption losses are relatively low. When thickness exceeds 50nm, losses caused by the optical absorption begin to outweigh the electrical gains, resulting in decreased overall EQE.

The study by A. Zhang et al. chose to use a tunnel junction contact layer thickness of 45 nm and achieved good overall performance in 254 nm DUV LEDs [4]. In the AlGaN homojunction tunnel junction devices reported by Nagata et al., the p^+ layer thickness was designed at 20 nm, effectively reducing optical absorption losses while maintaining low operating voltage [13].

3.4. Al composition design: balancing band alignment and transparency

The Al composition of the p^+ and n^+ layers in the tunnel junction strongly influences both optical transparency and band alignment. In homojunction tunnel junctions, the p^+ and n^+ layers share identical Al composition. This results in symmetric band structures and avoids lattice mismatch at the interface, which helps reduce interface defects and non-radiative recombination. Such design was employed by Nagata et al., achieving excellent device performance [13].

In contrast, heterojunction tunnel junctions use different material compositions to engineer band offsets and reduce tunneling barriers. In the cascaded DUV LED reported by Yu et al., AlGaN/InGaN heterojunction tunnel junctions were employed, effectively reducing the tunneling barrier through the narrow bandgap characteristics of the InGaN layer. Thus, the injection efficiency was also improved [12]. Composition grading is also an effective strategy. By introducing an Al-graded transition layer between the p^+ and n^+ layers, band variations can be smoothed. This results in less carrier accumulation and recombination losses at the interface [6]. In the review by Chen et al., composition-graded tunnel junctions improved carrier transport efficiency and reduced operating voltage [6].

4. Device performance evaluation

4.1. Key performance indicators

The performance of tunnel junction DUV LEDs is commonly evaluated using several key metrics: (1) EQE, which is defined by equation (1). (2) Forward voltage (V_f), a key parameter that directly affects power consumption and heat generation. For tunnel junction devices, V_f consists of three components: the voltage drop across the active region, the voltage drop across the tunnel junction, and the contact resistance [4]. For example, the 254 nm tunnel junction DUV LED reported by A. Zhang et al. achieved a forward voltage of approximately 6.5 V at a current density of 20 A/cm² [4]. (3) Wall-plug efficiency (WPE), which is defined as the ratio of output optical power to input electrical power. It can be expressed as:

$$WPE=EQE^{*}\ (e^{*}V_f/h\nu)^{-1} \tag{3}$$

WPE is a key indicator of energy conversion efficiency in practical applications [14]. For instance, the reflective metal/semiconductor tunnel junction structure reported by Y. Zhang et al. achieved a power density of 83.7 W/cm² and a WPE of 1.55% at 1200 A/cm² [14].

4.2. Comparison of reported tunnel junction designs

Table 1 summarizes the structure parameters and performance of typical tunnel junction DUV LEDs reported in recent years. Several development trends can be observed: (1) Continuous reduction in forward voltage: From 19.2 V in early studies to 5.4 V currently, a decrease of over 70%. (2) Expanding design dimensions: From single electrical optimization (doping, thickness) to optical-electrical collaborative design. (3) Diversification of tunnel junction types: Homojunctions, heterojunctions, and metal/semiconductor junctions, each offering unique advantages. (4) Theoretical predictions guiding directions: Simulation studies predicting 88% IQE and zero efficiency droop represent potential performance limits.

Table 1. Representative tunnel junction DUV LEDs reported in recent studies

Wavelength	TJ Type	Key Design	Operating Condition	Performance
<260 nm	AlGaN/InGaN heterojunction	Mg doping optimization	19.2V	First validation of TJ feasibility [14]
326 nm	Metal/AlGaN	Reflective metal junction	-	WPE=1.55% & 1200 A/cm² [14]
-	AlGaN/InGaN heterojunction	Polarization-induced TJ	-	Multiple-fold output power increase [12]
-	AlGaN homojunction	20 nm p^+ layer	10.8V & 63 A/cm²	One of early lowest V_f[13]
254 nm	TJ contact layer	45 nm + asymmetric EBL	6.5V & 20 A/cm²	Comprehensive performance optimization [4]
254 nm	Simulation	Thickness 20-30 nm, Al 40-60%	5.4V & 200 A/cm²	IQE≈88%, zero droop prediction [10]

5. Conclusion

This review confirms that transparent AlGaN tunnel junctions effectively overcome the p-GaN absorption bottleneck in DUV LEDs. Transparent tunnel junctions are capable of eliminating parasitic absorption and maintaining efficient hole injection through band-to-band tunneling, which significantly improves LEE and reduces forward voltage. By analyzing literature from recent years, optimal designs (Al: 40-60%, thickness: 15-30 nm, p^+ doping: $\sim 10^{18}$ cm^{-3}) achieved forward voltages of 5.4-6.5 V and nearly zero droop with IQE up to 88%. Therefore, transparent AlGaN tunnel junctions have emerged as a crucial technology for next-generation DUV LEDs. Despite these achievements, there are several challenges to be overcome before transparent AlGaN tunnel junction technology becomes widespread commercialization. Difficulties persist in p-doping in high-Al-content AlGaN due to high Mg activation energy and the incomplete optimization of the tunneling-transparency trade-off due to a lack of systematic experimental platforms. Furthermore, urgent investigation is required to address long-term reliability issues, such as degradation mechanisms under continuous high-current operation.

Future research should explore novel materials like BAlN and ScAlN for superior polarization and transparency. Nanostructured designs (e.g., nanowires, quantum dots) leveraging quantum confinement and the integration of photonic structures (photonic crystals, DBRs), offer pathways to further enhance performance. Finally, machine learning-assisted materials design and structural optimization holds promise for accelerating the exploration of multi-parameter design spaces and identifying optimal trade-off points.

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