Boosting Light Extraction in AlGaN-Based Deep Ultraviolet Micro-LEDs Through *p*-GaN Layer Removal

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Abstract

In this study, we propose an AlGaN-based deep ultraviolet micro-light-emitting diode (DUV Micro-LED) with the removal of the contact layer p-GaN, and based on this, we investigate the effects of different concentrations of the hole injection layer. The research shows that the proposed p-GaN-free LED structure can significantly enhance the device's light extraction efficiency (LEE), thereby greatly improving the external quantum efficiency (EQE). Meanwhile, the angular emission intensity of the p-GaN-free LED structure can be improved by increasing the doping concentration of the hole injection layer.

Keywords

DUV Micro-LED, EQE, LEE.

Introduction

In recent years, AlGaN-based deep ultraviolet light-emitting diodes (DUV LEDs) have attracted widespread attention due to their significant potential in applications such as water sterilization, air purification, and antiviral measures [1-4]. Compared to traditional ultraviolet light sources, DUV LEDs offer advantages such as compact size, non-toxicity, and long lifespan [1,5], making them an ideal choice for future ultraviolet light technology. Despite significant progress in areas such as energy band engineering [5], etching processes [6], and light extraction [2,7], AlGaN-based DUV LEDs still face the challenge of low external quantum efficiency (EQE), typically below 10%. This bottleneck primarily arises from two major factors: low light extraction efficiency (LEE) and current crowding effects.

The issue of LEE is particularly prominent; although recent research has improved the LEE of DUV LEDs through structural design optimization and the use of new materials, the high absorption characteristics of DUV light continue to significantly restrict light extraction [8-10]. The current crowding effect also limits device performance, especially at high power densities, where uneven current distribution leads to current accumulation at the edges of the chip [7], further reducing the light efficiency of the LEDs. To address these issues, researchers have explored various methods, including the use of moderately thick p-GaN layers to enhance current injection efficiency [2,7]. However, while thin p-GaN layers can effectively improve LEE, their inherent strong absorption characteristics can lead to losses of DUV light, thereby affecting overall optoelectronic performance. Therefore, finding ways to enhance LEE and optimize current distribution while avoiding the light absorption effects of the p-GaN layer has become a key focus and challenge in current research.

In this study, we propose a novel AlGaN-based DUV LED design by removing the p-GaN contact layer. This modification aims to alleviate the negative impact of p-GaN absorption on DUV light extraction, a well-known issue in conventional DUV LEDs. To investigate the effects of this change, we explore the role of different hole injection layer concentrations on the overall device performance.

Device Structures and Parameters

The reference DUV LED, named as LED 0, represents a typical DUV LED structure that includes the standard p-GaN contact layer (Fig. 1). The device structure includes a sapphire substrate, an AlN buffer layer on the substrate, an n-type doped $Al_{0.65}Ga_{0.35}N$ layer, the multi-quantum wells (MQWs) layers, a p-type doped $Al_{0.65}Ga_{0.35}N$ electron blocking layer (EBL), a p-type doped $Al_{0.40}Ga_{0.60}N$ hole injection layer, and a p-type doped GaN layer. The Si doping concentration of the n-$Al_{0.65}Ga_{0.35}N$ layer is 5×10^{18} cm^{-3}. The MQWs layers consist of five pairs of $Al_{0.45}Ga_{0.55}N$ (3 nm)/$Al_{0.6}Ga_{0.4}N$ (10 nm) quantum well/barrier structures. The p-region is composed of a 10 nm thick $Al_{0.65}Ga_{0.35}N$, a 40 nm thick $Al_{0.4}Ga_{0.6}N$ layer,

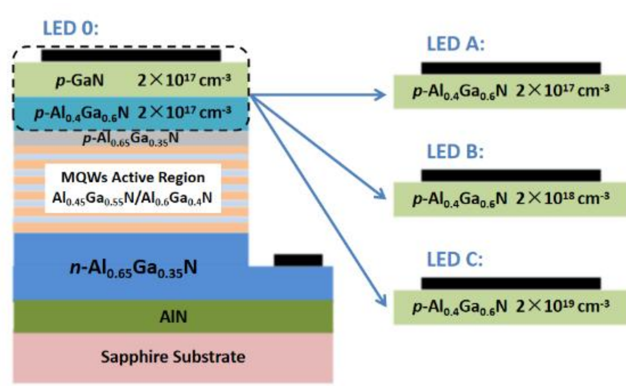

Fig. 1. Schematic diagram of Micro-LEDs in the study.

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and a 40 nm thick p-GaN layer, with magnesium doping concentrations of 2×10^{17} cm^{-3}, 2×10^{17} cm^{-3}, and 1×10^{17} cm^{-3}, respectively. The dimensions of the device are 10×10 μm². This structure serves as a baseline for comparison, allowing us to evaluate the impact of the p-GaN removal. The modified design, referred to as the p-GaN-free LED, maintains the same overall structure as LED 0, but with the exclusion of the p-GaN layer. To further investigate the effect of hole injection efficiency on device performance, three variations of the p-GaN-free LED are considered. These are denoted as LEDs A, B, and C, where each corresponds to a p-GaN-free LED structure with different hole injection layer doping concentrations of 2×10^{17} cm^{-3}, 2×10^{18} cm^{-3}, and 2×10^{19} cm^{-3}, respectively (Fig. 1).

Results and discussion

Use the Reverse Ray-Tracing technique in Silvaco Atlas software to trace the propagation, reflection, and refraction paths of light. In this approach, light is modeled as originating from dipole sources within the LED, and the LEE is defined as the ratio between the power extracted from the LED and the total power emitted by the dipole sources.

The results of the simulations show a significant enhancement in the light extraction efficiency for the p-GaN-free LED structures (LEDs A, B, and C) when compared to the reference LED (LED 0). As shown in Table 1, the LEE of LED 0, LEDs A, B, and C are 16.534%, 24.053%, 24.052%, and 24.047%, respectively. Specifically, the LEE of LEDs A, B, and C increased by 45.48%, 45.47%, and 45.44%, respectively, relative to the LEE of the standard LED 0. These improvements in LEE can be attributed to the reduction in p-GaN absorption losses, which typically hinder the extraction of DUV light in traditional DUV LED designs. By removing the p-GaN layer, more light is able to escape from the device, leading to a higher LEE and, consequently, improved overall device efficiency.

In addition to the significant improvements in LEE, the EQE of the LEDs also shows substantial enhancement when the p-GaN layer is removed (Fig. 2). The removal of the p-GaN layer effectively reduces internal losses, enabling a more efficient conversion of electrical energy into light. This is a crucial factor for DUV LEDs, where achieving high EQE is essential for practical applications such as water purification, air sterilization, and UV curing. The combined improvements in LEE and EQE highlight the potential of the p-GaN-free LED design to outperform conventional DUV LED structures, making it a promising candidate for future high-performance DUV light sources.

Table. 1. LEE for LEDs 0, A, B and C

LED numbers	LEE	Improvement
LED 0	16.534%	--
LED A	24.053%	45.476%
LED B	24.052%	45.470%
LED C	24.047%	45.440%

The angular emission patterns of all the studied DUV LEDs are presented in Fig. 3. The results reveal notable differences in the light extraction intensity between the various configurations. For LED A, the light extraction intensity is lower than that of the reference LED 0. This reduction can be attributed to the removal of the p-GaN layer, while mitigating the absorption losses associated with p-GaN, which leads to a more uneven distribution of injected holes within the active region. The uneven hole injection results in a decrease in the radiative recombination efficiency, as the carriers are not uniformly distributed across the quantum wells. This non-ideal hole injection not only reduces the internal quantum efficiency but also impacts the angular emission pattern, causing a lower overall light extraction intensity.

In contrast, the light extraction intensity of LEDs B and C shows a gradual increase with higher doping concentrations in the hole injection layer. The light extraction intensity of LED C significantly exceeds that of LED 0, indicating the effectiveness of the higher doping concentration in improving the light extraction. This improvement can be primarily attributed to the combined effects of hole injection optimization and the removal of the p-GaN layer. The absence of the p-GaN layer reduces the absorption of DUV-emitted light within the device, allowing a higher proportion of the generated light to escape the structure. As a result, more light is extracted from the device, leading to a significant enhancement in light extraction efficiency, particularly at larger emission angles.

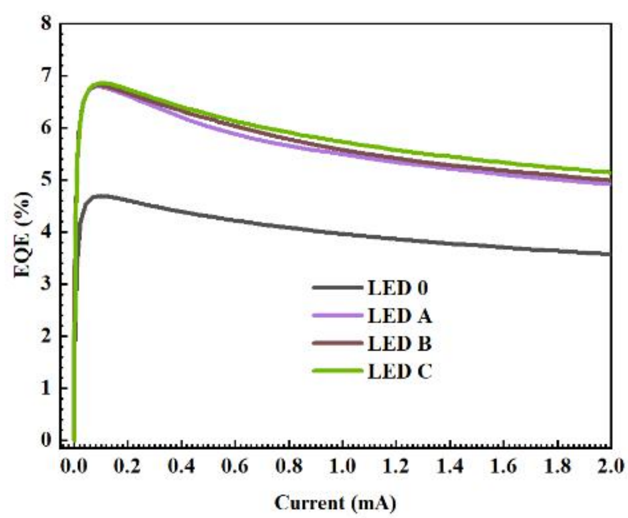

Fig. 2. EQE for LEDs 0, A, B and C.

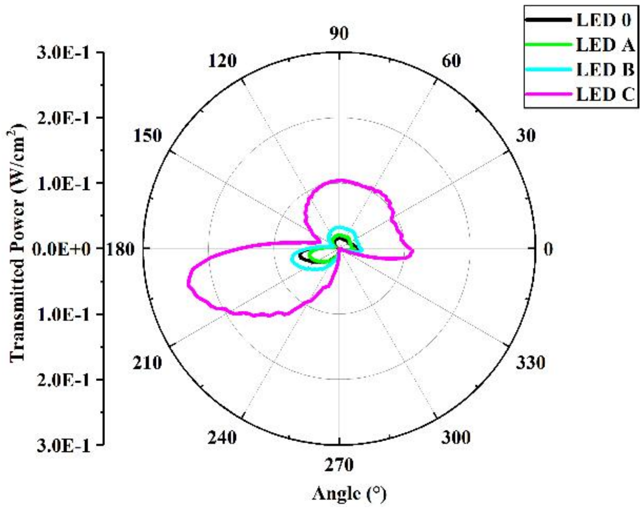

Fig. 3. Angular emission patterns for LEDs 0, A, B and C.

As the doping concentration in the hole injection layer increases, the enhancement in light extraction intensity can be attributed to a more uniform carrier distribution and higher radiative recombination efficiency, which reduces current crowding effects and enhances overall current injection.

Conclusion

Overall, the proposed p-GaN-free LED structure can significantly enhance the device's LEE, which in turn leads to a notable improvement in EQE. By removing the p-GaN layer, the device effectively reduces light absorption losses that typically occur in the p-GaN layer, thereby allowing more light to escape from the device. Meanwhile, the angular emission intensity of LED C has also shown a noticeable improvement compared to that of LED 0. The improvement in angular emission intensity demonstrates the effectiveness of optimizing both the hole injection layer and the removal of the p-GaN layer, which reduces internal absorption and enhances the overall performance of the LED, especially in DUV applications.

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