Improving Light Extraction Efficiency of AlGaN-Based Deep Ultraviolet Light-Emitting Diodes by Combining Thinning p-AlGaN/p-GaN Layer With Ni/Au/Al High-Reflectivity Electrodes

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***Abstract*—Improving light extraction efficiency (LEE) of AlGaN-based deep-ultraviolet (DUV) light emitting diodes (LEDs) has been attempted by thinning the p-AlGaN/p-GaN layer and adopting Ni/Au/Al composite electrodes. It is found that the thin p-AlGaN/p-GaN layer can reduce the light absorption and the Ni/Au/Al electrodes achieve high reflectivity and Ohmic contact to ensure the enhancement of the light extraction and maintain fine electrical properties. By this approach, the maximum external quantum efficiency of the DUV-LEDs with optimized Ni/Au/Al reflective electrodes is increased by 40%, compared to that with conventional Ni/Au electrodes over the whole current range.**

***Index Terms*—AlGaN, deep-ultraviolet light-emitting diode, light extraction efficiency, transparent p-type layer, reflective electrode.**

I. Introduction

IN RECENT years, AlGaN-based deep ultraviolet (DUV) light emitting diodes (LEDs) have attracted extensive attention due to their wide applications in sterilization, water/air purification, disinfection, and so forth [1], [2]. Especially since the end of 2019, the worldwide spread of coronavirus (COVID-19) has led to a serious economic and public safety crisis. AlGaN-based DUV-LEDs have shown potential in the elimination of coronavirus, with great application advantages such as high efficiency, fast, convenience, environmental protection and easy access [3], [4], [5]. Therefore, high-efficient DUV-LEDs have become more urgent to be well-developed. However, the performance of the AlGaN-based DUV-LEDs still stays at a relatively poor level because of some inherent obstacles. The most prominent problem among them is the low light extraction efficiency (LEE), which is typically below 10% and becomes the main difficulty restricting the further development of AlGaN-based DUV-LEDs [1], [2], [6].

The main factors that limit the LEE include the optical polarization of Al-rich AlGaN multiple quantum wells (MQWs), the total internal reflection at the interface between two layers with different refractive indexs, and the strong absorption of DUV light by p-GaN layer, which is essential for hole supply and the formation of Ohmic contact [7], [8], [9], [10], [11]. Many research groups have made efforts to overcome these difficulties and put forward various approaches: introducing a large-area AlN nanophotonic light extraction structure or moth-eye microstructure to enlarge the light escape cone thus weakening the limitation of the total reflection [12], [13], increasing the in-plane compressive strain of the quantum wells to obtain a higher polarization degree or taking micro-LED or arrays to help in-plane TM photons to escape [14], [15], [16], [17], [18], and adopting inclined sidewalls covered by a MgF_2/Al omni-directional mirror, distributed Bragg reflectors, Cr/Al n-type electrode or reflective photonic crystals to improve the reflection [19], [20], [21], [22]. In addition, many methods have been adopted to reduce the absorption of p-GaN and Ni/Au electrodes for improving the LEE, such as tunnel-injected LED, laterally over-etched p-GaN layer, micro-ring array DUV-LED and so on [23], [24], [25]. Recently, reflective electrodes with transparent p-AlGaN contact layer become a promising technical approach due to the simple process and outstanding effect. For example, RIKEN has remarkably improved the LEE by adopting a highly transparent p-AlGaN contact layer with Rh

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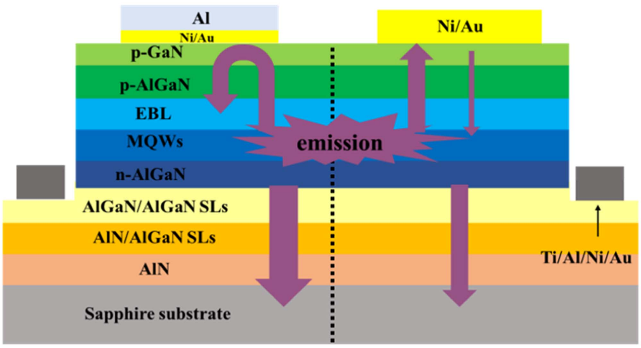

Fig. 1. Schematic structures of DUV-LEDs with Ni/Au/Al electrodes (structure A) and Ni/Au electrodes (structure B).

reflective electrode to replace the conventional thick p-GaN layer with Ni/Au electrodes. However, this method will lead to a significantly increased working voltage [26]. Therefore, finding an optimized AlGaN-based DUV-LED structure that can not only improve the light extraction but also maintain electrical properties is of great importance.

In this study, we have proposed a method by thinning the p-AlGaN/p-GaN layer combined with depositing Ni/Au/Al electrodes for high-performance DUV-LEDs. On the one hand, this design can remain electrical performance without removing the p-GaN and reduce the absorption of DUV light by cutting down the thickness of the p-type layer. On the other hand, by inserting a very thin layer of Ni/Au between p-GaN and Al, Ni/Au/Al electrodes can achieve Ohmic contact on p-GaN and also obtain high reflectivity. Therefore, this proposed structure is expected to bring a significant improvement to device performance with the superiority of LEE and maintain the electrical properties.

II. Experimental Details

Fig. 1 shows the schematic structures used in this study. Different p-type electrodes are deposited on the same epitaxial structure to compare the device performance. The p-type electrode of structure A adopts the proposed Ni/Au/Al electrodes, while structure B uses the conventional Ni/Au electrodes as the reference structure. The DUV-LED structure is grown on (0001) c-plane sapphire substrate by a 3×2″ close-coupled-showerhead (CCS) Aixtron metal-organic chemical vapor deposition (MOCVD) system. The structure consisted of a 1-μm-thick AlN buffer layer, 20 periods of AlN/$Al_{0.8}Ga_{0.2}N$ superlattice layers, 20 periods of $Al_{0.8}Ga_{0.2}N/Al_{0.65}Ga_{0.35}N$ strain modulation layers [27], a 1.5-μm-thick Si-doped n-$Al_{0.55}Ga_{0.45}N$ layer (n$\sim$2.0 $\times$ 10^{18} cm^{-3}), five pairs of 2.3-nm-thick $Al_{0.37}Ga_{0.63}N$ quantum well (QW) and 10-nm-thick Si-doped AlGaN quantum barrier layer (n$\sim$1.0 $\times$ 10^{18} cm^{-3}), and 20-nm-thick Mg-doped multiple quantum barrier (MQB) AlGaN electron blocking layer (EBL) (p$\sim$5 $\times$ 10^{17} cm^{-3}). The thickness and Al composition for the well layer of the EBL are constantly 2 nm and 60%, respectively. While the thickness of the barrier is 8 nm, and the Al composition in every barrier layer is graded from 80% to 60% along [0001] direction. At last, a very thin p-type layer (designed thickness less than 20 nm) is grown, involving a Mg-doped p-$Al_{0.6\rightarrow0}Ga_{0.4\rightarrow1}N$ graded layer with thickness of 10 nm and a Mg-doped p-GaN (p$\sim$4 $\times$ 10^{17} cm^{-3}) with thickness less than 10 nm as the contact layer, which is expected to reduce the absorption of DUV light.

After the growth, a standard microfabrication process is adopted to fabricate the AlGaN-based DUV-LEDs with a chip size of 510 $\times$ 510 μm^2. The electrodes with interdigital shapes are adopted to guarantee the current spreading. Ti/Al/Ni/Au metals are deposited on the mesa surface as the n-type electrodes to form Ohmic contact after rapid thermal annealing under N_2 ambient at 850°C. Different p-type electrodes are severally deposited on structures A and B. For structure A, Ni(2 nm)/Au(2 nm) metal is firstly deposited and then annealed in oxygen at 550 °C. After that, the composite Ni/Au/Al electrodes are completed by covering with a 150 nm thick Al film and the Al metal is deposited in the same area as the Ni/Au metal. For structure B, Ni(10 nm)/Au(50 nm) is adopted as the p-type electrode followed by an annealing treatment in the O_2 ambient at 550 °C to form p-type Ohmic contact. Finally, the chips are obtained by a normal flip-chip encapsulation process. The emitted DUV light is collected from the sapphire side to measure the light output power and EQE. Besides, the transmission line method (TLM) patterns with the contact electrode area of 200 $\times$ 200 μm^2 and gap spacing of 10-40 μm are formed on the p-GaN sample surface by standard lithography to evaluate the electrical properties of the p-type electrodes. The p-type electrodes are deposited on the double-side polished sapphire substrate and perform the reflectivity measurements to confirm the reflectivity of each p-type electrode. The current-voltage (I-V) characteristics of the DUV-LEDs and the contact samples are measured using a semiconductor parameter analyzer (Agilent 4155C).

III. Results and Discussions

The properties of the DUV-LED wafer is first evaluated. Fig. 2(a) is a typical atomic force microscopy (AFM) image of the DUV-LED surface after growth. It can be seen that the sample surface is very flat and featured with clear and straight atomic steps, and the surface roughness value is 0.335 nm (5 $\times$ 5 μm^2), presenting a smooth morphology. Fig. 2(b) shows the cross-sectional transmission electron microscopy (TEM) image of the p-type region in the DUV-LED structure. It can be seen that the thickness of the p-GaN layer is 9.2 nm, and the thickness of the p-$Al_{0.6\rightarrow0}Ga_{0.4\rightarrow1}N$ graded layer is 10.2 nm. The total thickness of these two layers is less than 20 nm, which follows the design. To confirm the absorption of DUV light by the p-type layers, transmission spectra of the DUV-LEDs with different thicknesses of p-GaN are measured and shown in Fig. 2(c). Although the transmittance of DUV-LED with 9.2 nm thick p-GaN decreases with wavelength shortening, it still has a high transmittance of 75% at 280 nm due to the thinning of the p-type composite layer, while in comparison, when the p-GaN is 50 nm, it lowers down to 40% at 280 nm. On the basis of the inversely proportional relationship between transmittance and the product of the absorption coefficient and absorption layer thickness, the transmittance of a 9.2 nm thick p-GaN layer at 280 nm is about 85%, while the transmittance of the 10.2 nm thick p-AlGaN

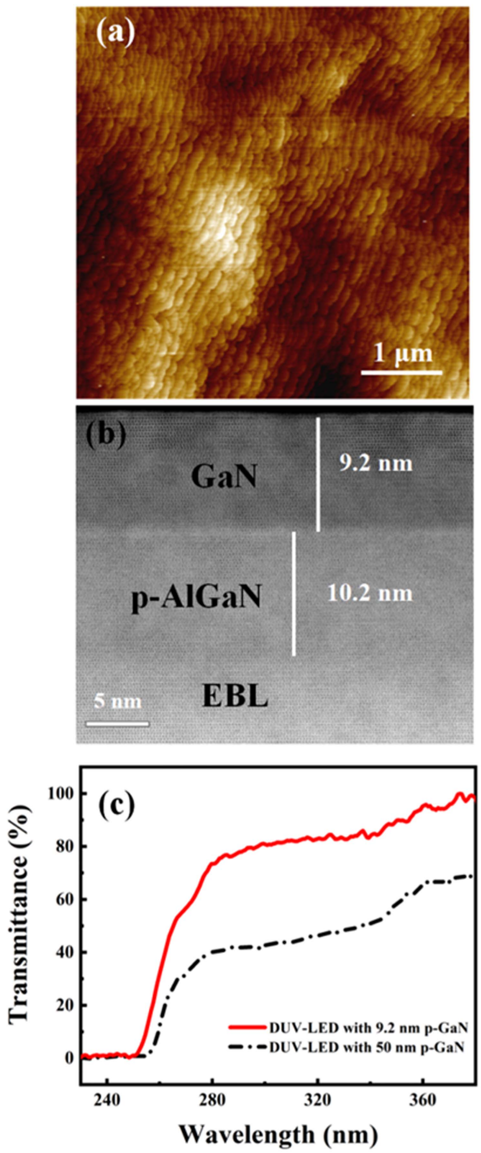

Fig. 2. (a) AFM image of the DUV-LED wafer. (b) Cross-sectional TEM image of the p-type layer in the DUV-LED. (c) Transmittance spectra of the DUV-LED severally with 9.2 nm and 50 nm thick p-GaN.

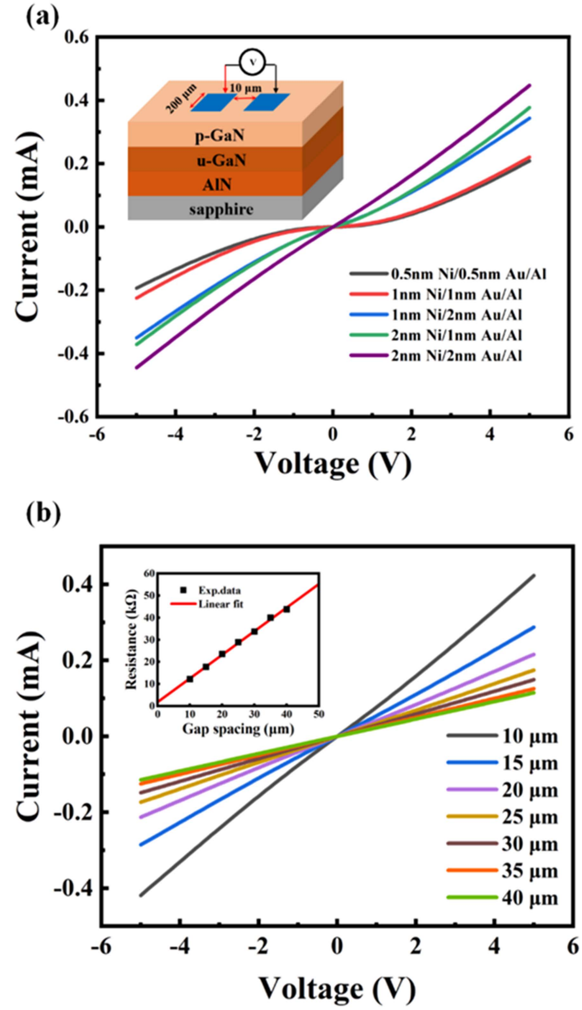

Fig. 3. (a) Room temperature I–V characteristics of Ni/Au/Al contacts using TLM pads with a gap spacing of 10 μm. (b) Contact characteristics and TLM fitting curve of Ni(2 nm)/ Au(2 nm)/Al electrodes with a gap spacing from 10 to 40 μm.

graded layer is about 87% corresponding to its equivalent Al component [9], [28]. Therefore, the measured absorption at 280 nm is close to the calculated value of GaN and p-AlGaN layers. That means that using a thin p-type layer in the DUV-LED to achieve high DUV light transparency will actually set up the foundation for the subsequent reflective electrodes.

In order to find an optimized electrode above the transparent p-type layer to balance the light extraction and electrical properties, the contact characteristics between the Ni/Au/Al electrodes and p-GaN contact layer are further investigated. The contact sample structure and transmission line method (TLM) pads are shown in the inset of Fig. 3(a). At room temperature, the hole concentration of the contact sample measured by Hall effect is 4.2×10^{17} cm^{-3}. To make full use of the high reflectivity of Al, 0.5 nm/0.5 nm, 1 nm/1 nm, 1 nm/2 nm, 2 nm/1 nm and 2 nm/2 nm Ni/Au metals are deposited at a rate of 1 A/s by e-beam to reduce light absorption, respectively. After that, 150 nm thick Al metal is deposited to complete the preparation of the Ni/Au/Al electrodes. Fig. 3(b) shows the room temperature I-V characteristics of Ni/Au/Al electrodes with different Ni/Au thicknesses between two TLM electrodes with a gap spacing of 10 μm. As illustrated in the figure, when the thicknesses of the Ni and Au layers are less than 2 nm, the contact behavior presents nonlinear characteristics. While as the thickness of the Ni and Au layers reaches 2 nm, the contact characteristics present a true Ohmic behavior. This phenomenon suggests that the sufficiently thick Ni/Au layer annealing under O_2 ambient are essential in forming Ohmic contact with p-GaN [29], [30]. The contact characteristic of the Ni(2 nm)/Au(2 nm)/Al electrodes electrodes is further tested. Fig. 3(b) shows the I-V characteristics of each TLM electrode gap spacing between Ni(2 nm)/Au(2 nm)/Al and p-GaN. It can be seen that the I-V characteristics with different gap spacing are linear. By fitting the linear relationship between resistance at different electrode

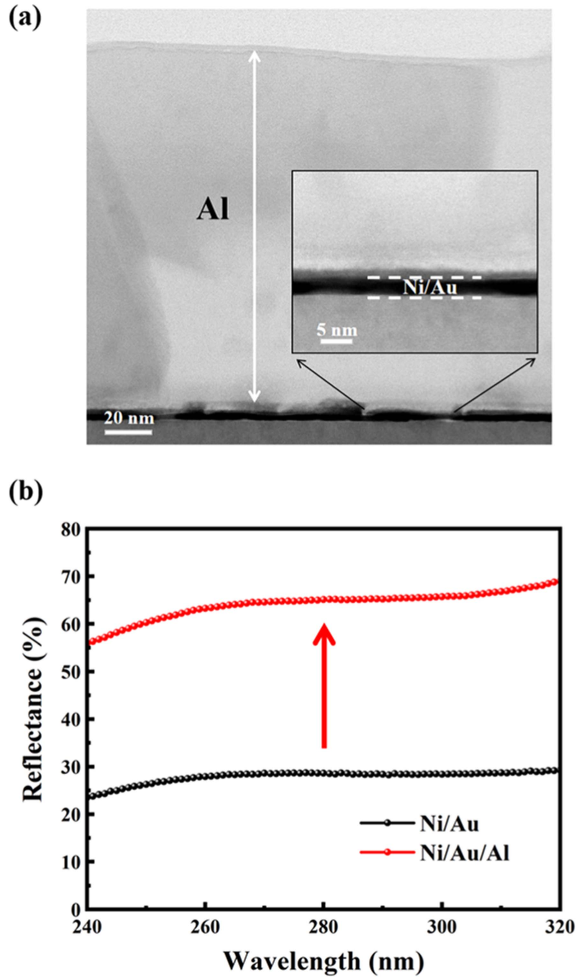

Fig. 4. (a) TEM image of the Ni(2 nm)/Au(2 nm)/Al electrodes. (b) Measured reflectance of Ni /Au /Al and reference Ni /Au electrodes.

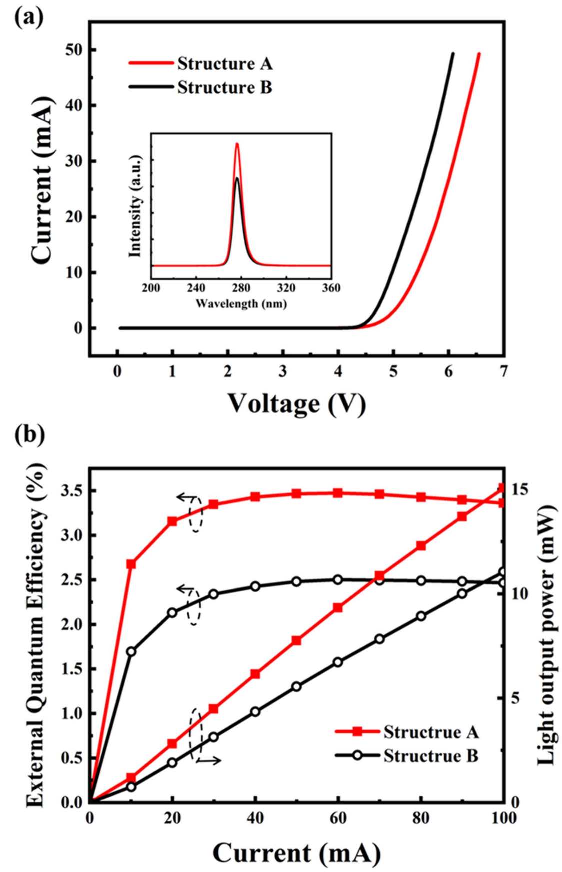

Fig. 5. (a) I–V characteristics of DUV-LED structures A and B. The inset shows the EL spectra under 100 mA. (b) The EQE and LOP versus injection current of structures A and B.

gap spacings, as shown in inset of Fig. 3(b), the specific contact resistivity of Ni(2 nm)/Au(2 nm)/Al electrodes can be calculated to be $1.55 \times 10^{-3}\ \Omega\cdot cm^{-2}$. That is only slightly higher than that of the conventional Ni/Au electrodes ($1.5 \times 10^{-3}\ \Omega\cdot cm^{-2}$). The Ohmic contact results indicate that the contact characteristics of the proposed reflective Ni/Au/Al electrodes do not degrade obviously when they are used to achieve p-GaN contact [31].

Fig. 4(a) shows the cross-sectional TEM image of the proposed Ni(2 nm)/Au(2 nm)/Al electrodes. As can be seen from Fig. 4(a), the thin layer of Ni and Au metals has no obvious interface after annealing and uniformly covers the structure surface, which effectively avoids the Ohmic contact degradation and voltage increasing caused by Al metal contacting the p-GaN layer. Furthermore, the reflectance spectra of the Ni(2 nm)/Au(2 nm)/Al electrodes and conventional Ni(10 nm)/Au(50 nm) electrodes are tested respectively. As shown in Fig. 4(b), the Ni/Au/Al electrodes have much higher reflectivity in the DUV region. For example, at 280 nm, the reflectivity of the Ni(2 nm)/Au(2 nm)/Al electrodes is more than 65%, twice that of conventional Ni/Au electrodes. Consequently, applying this electrode on DUV-LEDs with highly transparent p-type layer is expected to achieve higher device performance.

The device performance comparison based on the Ni(2 nm)/Au(2 nm)/Al(150 nm) highly reflective electrodes (structure A) and a conventional Ni(10 nm)/Au(50 nm) electrodes (structure B) has been conducted. Fig. 5(a) shows the I-V characteristics of structures A and B. The measured forward voltages at an injection current of 50 mA are 6.5 V and 6.1 V for the LEDs with Ni/Au/Al and Ni/Au electrodes, respectively. The voltage increase is significantly reduced relative to directly depositing Rh on p-AlGaN [26], which shows great potential in holding fine electrical properties. The inset shows the typical EL spectra of structures A and B at 50 mA. Both of them exhibit a single peak emission with a wavelength of 277 nm and with a full-width half-maximum (FWHM) of 9.2 nm, but the luminescence intensity of structure A is significantly higher than that of structure B. The external quantum efficiency (EQE) and light output power (LOP) of these two LED structures at different injection currents have been further compared, as shown in Fig. 5(b). It can be found that within the current test range of 0-100 mA, the maximum EQE and LOP of structure A reach 3.5% and 15.1 mW, which are 40% and 35% higher than that of structure B, respectively. Those results indicate that the combination of thinning p-type layer and Ni/Au/Al reflective electrodes can indeed greatly improve the LEE, thereby significantly enhancing the device performance.

IV. Conclusion

In conclusion, improving the LEE for AlGaN-based DUV-LEDs has been attempted by thinning p-AlGaN/p-GaN layer combined with the high-reflectivity Ni/Au/Al electrodes. The proposed structure with thin p-AlGaN/p-GaN layer exhibits high transparency and the optimized Ni/Au/Al reflective electrodes well coordinate the electrical properties and enhancement of LEE. By this approach,the maximum external quantum efficiency of the DUV-LEDs with Ni/Au/Al reflective electrodes is increased by 40%, compared to that with conventional Ni/Au electrodes within the current test range of 0–100 mA.

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