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Evaluation of Ti/Al/Ni/Au ohmic contact to n-AlGaN with different Ti/Al thickness for deep ultraviolet light emitting diode

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ABSTRACT

Ohmic contacts were formed by varying the Ti/Al thickness ratios in the Ti/Al/Ni/Au metal stack. Based on the Ti/Al/Ni/Au metal electrode in n-AlGaN, several deep ultraviolet light emitting diode (DUV LED) chips were fabricated. Annealed at different temperatures, the different structures and ohmic contacts in these Ti/Al/Ni/Au electrodes were correlated by X-ray diffraction (XRD) pattern, scanning electron microscope (SEM) and atomic force microscope (AFM). The XRD results show that the TiN and $AlTi_3$ phases were formed after two-step high-temperature annealing process. The influence of ohmic contact on the Ti/Al/Ni/Au metal stack on the n-AlGaN performance was explored by optimizing the Ti thickness of contact layer. It demonstrated that when the Ti/Al thickness ratio is 5.41 (Ti = 35 nm), the ohmic contact on Ti/Al/Ni/Au metal stack exhibited the lowest specific contact resistance which is about 3.21×10^{-5} ($\Omega \cdot cm^2$). The I-V curve and I-L curve results of the DUV LED devices fabricated by Ti/Al/Ni/Au metal stacks demonstrate the ohmic contact performance. These results indicated the ohmic contact formation by varying Ti/Al thickness ratios on the Ti/Al/Ni/Au metal electrode is favorable to the application in the n-AlGaN-based DUV LED.

1. Introduction

AlGaN-based deep ultraviolet light emitting diodes (DUV LEDs) are low power consumption and eco-friendly UV light sources, and have been wide applied in sterilization, water purification, polymer curing, UV communication and biomedical testing [1]. AlGaN is a wide bandgap semiconductor, and its bandgap (from 3.4 eV to 6.2 eV) is adjustable by changing the Al component. The emission wavelength of AlGaN covers all the UV wavelength range (100–400 nm). Therefore, AlGaN, as a representative of the third generation semiconductor, is an ideal candidate for the application in UV LEDs [2]. When increasing the Al components, the preparation of n-type ohmic contacts of AlGaN will become more and more difficult. Typically, it is difficult to maintain the two-dimension epitaxial growth of AlGaN, because high Al content will result in more defects in the AlGaN films and the uneven film surface. With increasing the Al content, the contact barrier between the metal and AlGaN will increase, resulting in an increase in specific contact resistance, which will hinder the ohmic contact behavior for the application in DUV LED.

There are several important factors to affect the external quantum efficiencies of UVC LED, such as the total reflection phenomenon between the interfaces of those layers, the shifting from transverse electric wave to transverse magnetic wave of AlGaN quantum wells, and the ohmic contact between the electrode and the surface of the n-AlGaN material [1]. Hirayama et al have reported that the external quantum efficiency of 275 nm DUV LEDs was about 20.3% at 40 mA [3]. However, for conventional ohmic contact in n-AlGaN-based DUV LEDs such as Ti/Al/X/Au (X = Ni, Ti, V, etc) [5], ITO/Al [6], the light extraction efficiency of UVC-LED is still less than 10% [4]. In this work, the ohmic contact performance of n-AlGaN-based DUV LEDs was investigated by varying the Ti/Al thickness ratios on the Ti/Al/Ni/Au metal electrode at different annealing temperatures. The Ti/Al/Ni/Au electrode is packaged into an n-AlGaN-based DUV LED to investigate the ohmic contact performance.

2. Materials and methods

Fig. 1(a) shows the schematic diagram of DUV LED. The epitaxial layers were grown by metal–organic chemical vapor deposition (MOCVD) technique on 2-inch c-plane sapphire substrate with a 0.2° off-cut angle to the m-plane. They are composed of a 3 μm-thick AlN buffer layer, 10 pairs of 10 nm-thick AlN/10 nm AlGaN supperlattice structure,

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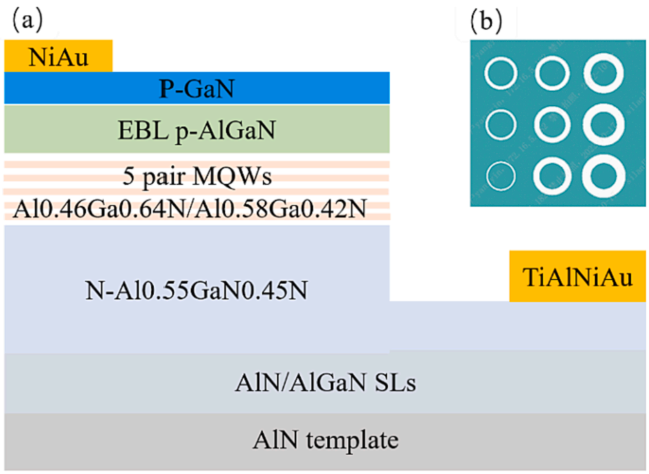

Fig. 1. Schematic diagram of UVC LED (a), and c-TLM structure delineated on the sample (b).

2 µm-thick n-type $Al_{0.55}Ga_{0.45}N$ as electron injection layer (2×10^{19} cm^{-3} Si doping concentration), 5 pairs of 2.5 nm-thick $Al_{0.46}Ga_{0.55}N$/12 nm $Al_{0.58}Ga_{0.42}N$ quantum well (1×10^{19} cm^{-3} Si doping concentration), 25 nm-thick p-AlGaN electron barrier layer (1×10^{19} cm^{-3} Mg doping concentration) and 50 nm-thick p-type GaN (1×10^{20} cm^{-3} Mg doping concentration).

Table 1 shows five ohmic contact Ti/Al/Ni/Au electrodes #A - #E with different Ti thickness. To investigate ohmic contact formation on Ti/Al/Ni/Au electrodes, the procedure is as following: Firstly, the surface of epitaxial wafers was cleaned by H_2O_2/H_2SO_4 to remove surface oxides and impurities, and some HCl was also used to acid cleaning. Secondly, the n-$Al_{0.55}Ga_{0.45}N$ steps were engraved by inductively coupled plasma (ICP) etching method. Finally, n-type contact electrodes Ti/Al/Ni/Au and p-type electrodes Ni/Au were deposited by electron beam evaporation. The epitaxial wafer was annealed in ambient N_2 at 350 °C (200 s) + 850 °C (30 s) for n electrodes, while for p electrodes the annealing process is 600 °C (240 s). Lithography graphic was employed to delineate circular transmission line mode (c-TLM) pattern on the wafer. Fig. 1(b) depicts the c-TLM structure delineated on the samples for the electrical measurement of the ohmic contacts with 40um diameter and 10–50 um contact spacing. The X-ray diffraction (XRD) of these samples were measured by an X-ray diffractometer (X'pert pro X-ray diffractometer, Panalytical Co.) [7,8]. The morphology of the ohmic contact on Ti/Al/Ni/Au metal electrode was evaluated using SEM (Zeiss, Supra 55) and AFM (Veeco, nanoscope, IIIA).

3. Results and discussion

In order to investigate the structure of Ti/Al/Ni/Au metal electrode, Fig. 2 shows the XRD patterns of samples #A-#E annealed in ambient N_2 at 850 ℃. From the main diffraction peaks of samples #A-#E shown in this figure, it is obvious that the phase purity of Ti/Al/Ni/Au metal electrodes is high after annealing process. These figures show that the Ti-Al compound tends to form AlTi, Al_2Ti, and Al_3Ti phases. When the Ti/Al thickness ratio is about 2.82, the main compound is Al_3Ti which is favorable to low-resistance ohmic contact on Ti/Al/Ni/Au electrode [9–11]. In our work, the ohmic contacts of the Ti/Al/Ni/Au metal electrodes are mainly attributed to the TiN, Al_3Ti, and Al_2Ti [12]. The formation of Ti-Al or Ti-N phase might be beneficial to obtain a low-resistance ohmic contact on the Ti/Al/Ni/Au electrode. It can be seen from the figure that compared with the sample #B the intensity of diffraction peaks from TiN phase of the sample #A is higher, which can attribute to more thickness Ti in the contact layer. The diffraction peak of TiN of the sample #B is the highest ones among those samples. As the thickness of Ti continues to increase, excessive interfacial voids and hole within the contact interface between Ti and AlGaN will come into being and results in incomplete ohmic contact between TiN and AlGaN. The diffraction peak of Al_3Ti in samples #D-#E is strong and accompany with the strong diffraction peaks of Al_2Au. It attributes to that because the Ni-Au is a solid solution [13], the Al-Au tends to form a high-configuration Al_2Au phase. The existing of Al_2Au in the Ti/Al/Ni/Au metal electrode reduces the ohmic contact performance of the sample #D-#E.

Fig. 3(a) shows the cross section scanning electron microscope (SEM) images of sample #B. It can be found that the intermixing of the metal layers occurred on the Ti/Al/Ni/Au electrode layer annealed at 850 °C. It can attribute to that the recrystallization temperature of Ni is about 450 °C, and globular aggregation will occur at 850 °C, therefore it will result in the Al-Au layers on the Ti/Al/Ni/Au electrode [14,15]. then it will prevent from forming the NiAl phases on the Ti/Al/Ni/Au electrode [16]. However, further increasing the Al thickness will result in the high-resistance Al_2Au phases in the Ti/Al/Ni/Au electrode after higher-temperature annealing [17]. Close inspection of the SEM micrographs show that the surface of the Ti/Al/Ni/Au metal electrode is flat and smooth. Fig. 3(b) is the atomic force microscope (AFM) scan of surface morphology of sample #B. The image further demonstrate that the surface of the Ti/Al/Ni/Au electrode is flat after annealing, and its average roughness of the electrode is about several microns. The formation hillocks and valleys in this sample can be found in the AFM images and is unavoidable phenomenon due to high temperature annealing.

In order to further investigate ohmic contact performance of the Ti/Al/Ni/Au electrode, the specific contact resistivity of samples #A-#E was measured by c-TLM. Fig. 4(a) shows the ohmic contact current–voltage (I-V) curve of sample #B. It can be found that when c-TLM gap is in the range of 10–50 nm, this sample shows linear I-V characteristics. The total resistance of two electrodes between inside and outside the ring can be obtained based on following equation [18,19].

$$R_c = \frac{R_{sh}}{2\pi} \ln\frac{r+n}{r} + L_t\frac{1}{r} + \frac{1}{r+n} \tag{1}$$

where R_{sh} represents the bulk resistance of semiconductor, R_c is the total resistance, r is the radius of the inner circle, n is the distance between the inner and outer circles of the ring, and L_t is the conversion length. Based on the I-V characteristics, the relationship between the total resistance R_c and $\ln[(r+n)/r]$ can be obtained and the results are shown in Fig. 4 (b). Then the specific contact resistivity ρ_c can be calculated by following equation:

$$\rho_c = L_t^2 \bullet R_{sh} \tag{2}$$

The specific contact resistivity ρ_c of the Ti/Al/Ni/Au electrode of sample #A-#E is calculated and the results are shown in Fig. 5(a). As shown in this figure, increasing the Ti thickness, the specific contact resistivity ρ_c of sample #A-#B gradually decreases. When the Ti thickness is about 35 nm, the specific contact resistance of the Ti/Al/Ni/Au electrode is minimal, which is about 3.21×10^{-5} ($\Omega \cdot cm^2$), and it is show a good agreement with the XRD results shown Fig. 2. Further increasing the Ti thickness, the specific contact resistivity ρ_c of sample #C-#E will increase. This observation can attribute to the existing Ti-N and Al-Au

Table 1
Ohmic contact in Ti/Al/Ni/Au electrodes with different Ti thickness.

Sample	Metal thickness (Å)			
	Ti	Al	Ni	Au
#A	250	1800	400	500
#B	350	1800	400	500
#C	450	1800	400	500
#D	550	1800	400	500
#E	650	1800	400	500

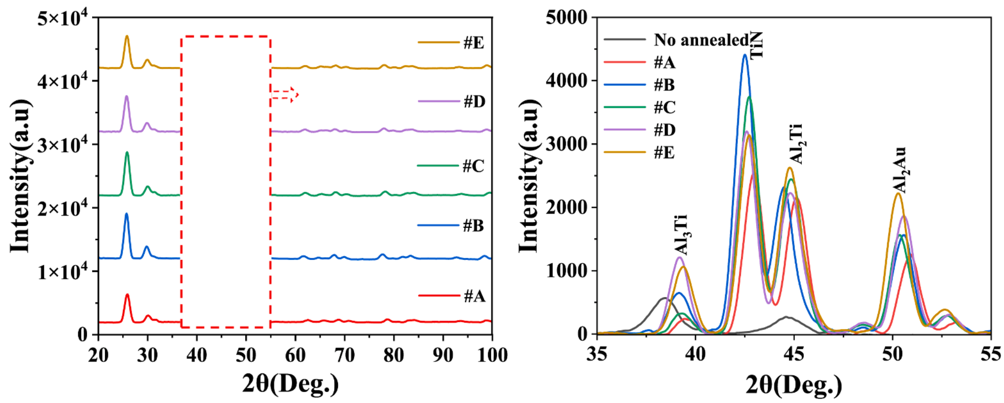

Fig. 2. The XRD patterns of samples #A- #E (left) and the enlarged X-ray diffraction (XRD) patterns (35–55 deg.) of samples #A- #E.

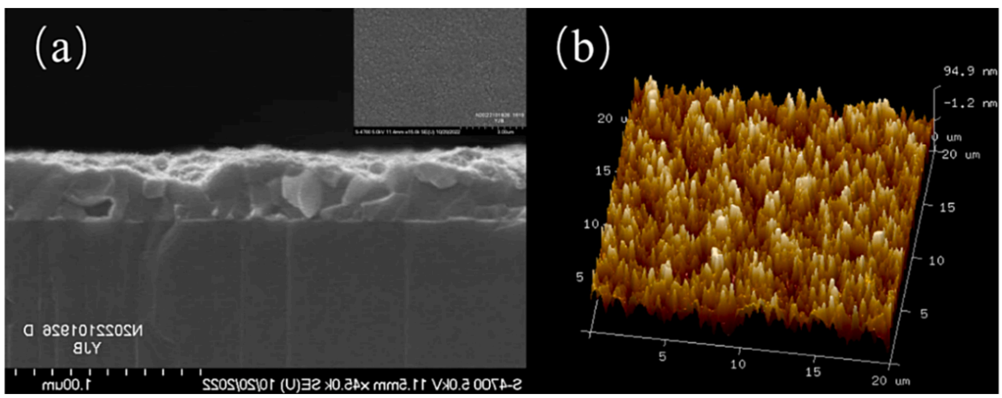

Fig. 3. Cross section SEM images of sample #B (a); AFM scan of surface morphology of sample #B (b).

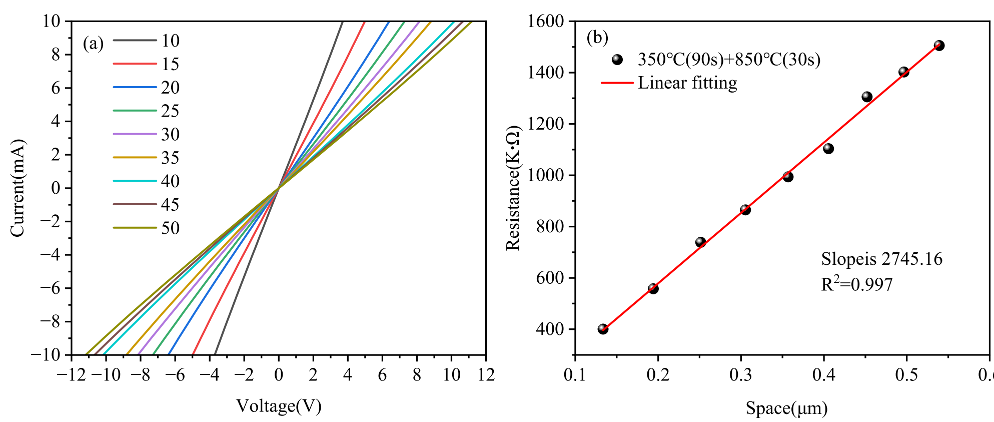

Fig. 4. I-V curves of sample #B measured by c-TLM with different ring widths (a); The specific contact resistivity ρ_c of sample #B (b).

phase or the porosity at the contact interface when the Ti thickness increases further. It has been demonstrated that with different Ti/Al thickness ratios, The formation of Ti-Al-Au phase will affects the ohmic contact performance of the Ti/Al/Ni/Au electrode [20]. In order to further explore the effect of thermal annealing process on ohmic contact in n-AlGaN, n-$Al_{0.55}Ga_{0.45}N$ epitaxial wafers (2×10^{19} cm^{-3} Si doping concentration) was obtained for the following measurement. The specific contact resistivity ρ_c of n-$Al_{0.55}Ga_{0.45}N$ epitaxial wafer with 5.41 Ti/Al thickness ratio (Ti = 35 nm) is collected at 800–950 °C annealing temperatures, and the results are shown in Fig. 5(b). It can be seen that when annealed at 350 °C (200 s) + 850 °C (30 s), the ohmic contact performance of n-$Al_{0.55}Ga_{0.45}N$ epitaxial wafers is the best, and the specific contact resistivity is about 5.912×10^{-5} ($\Omega\cdot cm^2$). Further increasing the annealing temperature, the specific contact resistivity of n-$Al_{0.55}Ga_{0.45}N$ will increase, and the ohmic contact performance becomes poor. It is proved again that the Ti-N phase may exist in the Ti/Al/Ni/Au metal electrode when annealed at 800–900 °C temperature. It can be concluded that at higher annealing temperature, the internal diffusion between the Ti/Al/Ni/Au metal electrode and n-AlGaN will become intensive, which results in more holes between the contact interface, and the high-resistance Al_2Au phase may exist when more Au diffuse within the layer.

To investigate the ohmic contact performance of Ti/Al/Ni/Au metal electrode in n-AlGaN-based DUV LED, several n-AlGaN-based DUV LEDs fabricated by sample #A-#E are obtained and the voltages of DUV LEDs are shown in Fig. 6 at 40 mA injection current. The voltage of n-AlGaN-

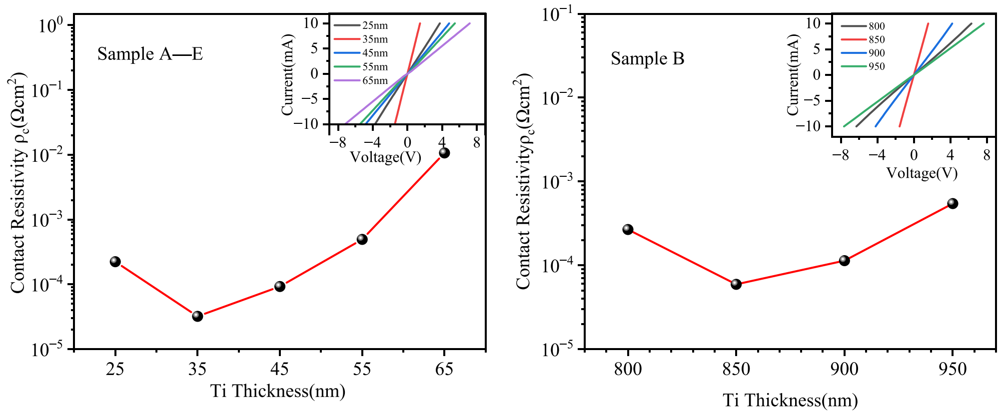

Fig. 5. Specific contact resistivity ρ_c of the Ti/Al/Ni/Au electrode of sample #A-#E (a), the inset show I-V curves of those samples; and Specific contact resistance ρ_c of sample #B as a function of annealing temperatures (b), the inset show I-V curves of samples #B.

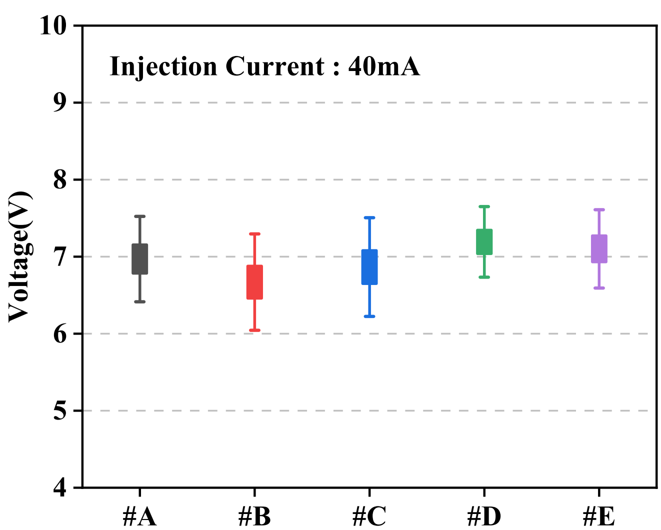

Fig. 6. The LED voltage of n-AlGaN-based DUV LEDs #A-#E.

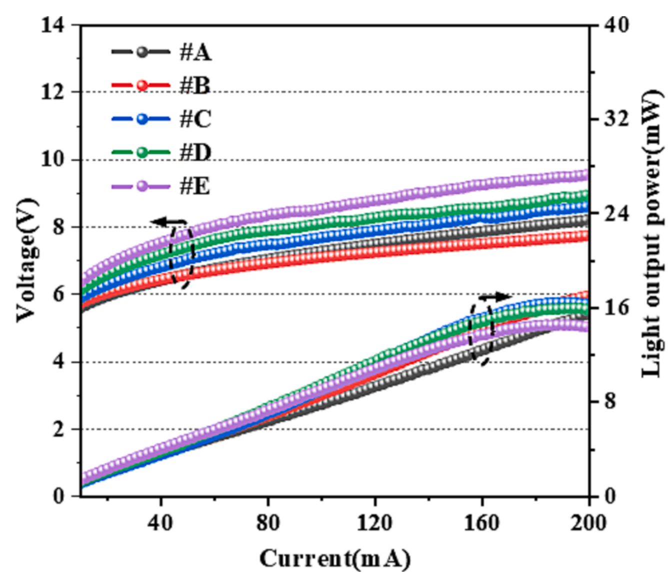

Fig. 7. I-V curve and I-L curve of DUV LED devices #A-#E.

based DUV LEDs #A-#E is in the range of 6.0–8.0 V. It attribute to that Si doping concentration of the electron injection layer is 2×10^{19} cm^{-3}, results in the tunneling effect in the contact interface between metal layer and semiconductor. The voltage of DUV LED #B is lower compared with other LEDs. This results originate from that annealed at 350 °C (200 s) + 850 °C (30 s), and the 5.14 (Ti = 35 nm) Ti/Al ratio, the best ohmic contact is formed on the Ti/Al/Ni/Au metal electrode and n-$Al_{0.55}Ga_{0.45}N$, which favor to reduces the voltage of n-AlGaN-based DUV LED.

To further verify the effect of TiAlNiAu metal system on DUV LED devices, five sets of DUV LEDs with different Ti/Al thickness ratios were fabricated and the I-V curves and I-L curves of these DUV LEDs are shown in Fig. 7. It is obvious that the slope of I-V curve gradually decreases as the injection current increases and the forward operating voltage of DUV LED device #B is lower compared to the other samples. For the DUV LED device #B, the operating voltage is about 7.75 V when the injection current is 200 mA, which is obviously lower than the values of other LEDs. This observation is attributed to the M−S ohmic contact of Ti/Al/Ni/Au metal electrode in DUV LED device #B.

As can be found from the I-L curves in the figure, the light output power (LOP) of those LED devices show a little differences when the injection current range is less than 40 mA. As the injection current further increase, the LOP of devices #C-#E decrease at around 180 mA, while the LOP of DUV LED #A and #B continues to increase. These results imply that for high injection current, the large series resistance will be introduced when the Ti/Al thickness ratio is low. Therefore, the decrease of LOP should be attributed to large series resistance in the LED devices.

4. Conclusions

In this work, the ohmic contact performance in the TiAlNiAu metal electrode of n-AlGaN-based DUV LED by vary the Ti/Al thickness ratios and annealed at different annealing temperatures was studied. The results demonstrated that the best ohmic contact performance on the Ti/Al/Ni/Au metal stack can be obtained by optimizing the Ti thickness of contact layer. When the Ti/Al thickness ratio is 5.41 (Ti = 35 nm), the ohmic contact on Ti/Al/Ni/Au metal stack exhibited the lowest specific contact resistance, which will reduces the voltage of n-AlGaN-based DUV LED. The results of I-V curve and I-L curve manifest the ohmic contact effect. The XRD pattern proved that the formation of Ti-Al or Ti-N phase might be beneficial to obtain a low-resistance ohmic contact. The AFM/SEM results confirm the ohmic contact formation in Ti/Al/Ni/Au metal stack. These results indicate that the ohmic contact in Ti/Al/Ni/Au metal electrode would be an important factor for high-efficiency n-AlGaN-based DUV LEDs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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