RESEARCH ARTICLE | MAY 22 2024

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Yaqin Wang ; Muhammad Shafa ; Peng Wu ; Yitao Liao



*AIP Advances* 14, 055026 (2024)
https://doi.org/10.1063/5.0210229

# Investigation of MBE grown high Al concentration AlGaN ohmic contact

Cite as: AIP Advances 14, 055026 (2024); doi: 10.1063/5.0210229
Submitted: 25 March 2024 • Accepted: 7 May 2024 •
Published Online: 22 May 2024

View Online Export Citation CrossMark

Yaqin Wang, Muhammad Shafa,[a)] Peng Wu,[a)] and Yitao Liao

## AFFILIATIONS

Xuzhou LIYU Advanced Technology, Xuzhou, Jiangsu, China

[a)]Authors to whom correspondence should be addressed: shafauaf@yahoo.co.uk and pengwubuaa@gmail.com

## ABSTRACT

Achieving low resistance ohmic connections is one of the significant factors in improving the performance of optoelectric and semiconductor devices. In this work, we examined the decrease in specific contact resistance ($\rho_c$) after high-temperature annealing and vanadium thickness variation on an n-type AlGaN epitaxial layer with a high aluminum concentration (75%). To measure it, we prepared rectangular transmission line model electrodes and measured the specific contact resistance at annealing temperatures ranging between 800 and 950 °C. The results showed that the minimum specific contact resistance achieved was $4.12 \times 10^{-2}\ \Omega\ \text{cm}^2$ at an annealing temperature of 850 °C, which was two times lower compared to that of surface contact mode. It is also demonstrated how the contact resistance of the epitaxial n-type AlGaN layer varies as the vanadium thickness changes from 2 to 15 nm.





## I. INTRODUCTION

AlGaN/GaN as high electron mobility devices hold great promise for high-voltage, high-power, and high-temperature applications.[1] However, the ohmic-contact[2–5] properties of these devices must be improved in order to be used in high-power applications[6] and to achieve higher efficiency.[6,8] Due to the need for a transparent current spreading layer, sub-240-nm ultraviolet light emitting diodes (UVC-LEDs) require a n-$Al_xGa_{1-x}N$ layer with an aluminum (Al) molar fraction x higher than x = 0.8.[8] For deep UV LEDs to have higher wall-plug efficiency (WPE), ohmic n-contacts with low contact resistivities on the high Al mole fraction n-AlGaN are consequently necessary.

Formation of ohmic contact is challenging because of the high concentration[2] of Al (75%) in n-AlGaN. Furthermore, as a result of the high Al concentration at the metal–semiconductor interface, it is harder to lower the potential barriers; hence, the electron affinity of AlGaN decreases, going from 3.18 eV for GaN to 1.01 eV for AlN.[7] In addition to the problem of high Al concentration, the thickening of vanadium at the Schottky barrier also has a major impact. When the metal work function is low, the Schottky barrier increases because AlGaN is energetically stable, which prevents N removal and the formation of an n-doped layer during annealing.[4] Ohmic contacts with n-AlGaN are only formed by Ti/Al-based metallization schemes up to an Al molar proportion of x 0.5. Due to the low formation enthalpy of TiN (−336 kJ/mol), Ti strongly interacts with the n-AlGaN layer.[5] Ti will then substitutionally replace Ga in the alloy when the concentration of Al is increased, resulting in (i) highly defected Al–Ti–N phases, (ii) voids, and (iii) TiN protrusion islands (forming along dislocations, preferably) at the M/S interface. These events impede the development of a uniform contact area. Using V/Al/Ni/Au-based electrodes, Nagata *et al.* recently established ohmic connections on n-AlGaN up to an Al molar percentage of x = 0.70.[9] For Al mole fractions greater than 0.4, V/Al-based metallizations have been shown to yield poorer contact resistivities at lower annealing temperatures than Ti/Al-based ones, in part because of a relatively limited reactivity with the semiconductor.[10,11] In this instance, the aluminum in the metallization scheme drives the development of the highly n-doped thin layer at the M/S interface, while the vanadium serves as an in-diffusion barrier.

This work has investigated the structural and electrical characteristics of V/Al/Ti-based n-contacts on n-AlGaN with elevated Al content. After that, these electrodes were annealed for 60 s at temperatures ranging between 800 and 950 °C. The transmission line model (TLM) was utilized to assess the specific contact resistance.

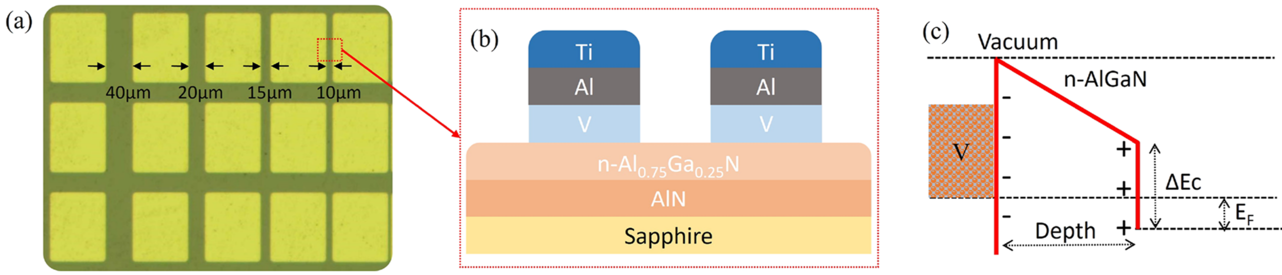


FIG. 1. (a) The schematic diagram of the rectangular electrode TLM structure along with the cross-section. A pad gap is illustrated with several pad distances (10, 15, 20, and 40 $\mu$m) shown in the device diagram. (b) The schematic of the device with electrical pads. (c) Change in the energy level due to the vanadium thickness shown in the bandgap diagram.

Additionally, we look into how the thickness of the vanadium affects the ohmic contact.

## II. EXPERIMENT

The n-AlGaN/AlN films were grown at elevated temperatures using plasma assisted molecular beam epitaxy; a detailed description of this method is given elsewhere.[2] 3-in. sapphire (0001)-oriented substrates were prepared for growth by degassing at 800 °C for 30 min. n-AlGaN films were grown at nominal temperatures of 1000 °C with AlN buffer layers under a slightly N-rich flux. The schematics of the growth is shown in Fig. 1(b). Growth temperature was measured with a c-type thermocouple on the back side of the sapphire substrate. *In situ* RHEED is used to monitor and control the stoichiometry of the films. Al, Ga, and Si were supplied from a Knudsen thermal evaporator, keeping the aluminum mole fraction (75%). The energetic neutral N atoms were supplied using plasma source technology. Al and N fluxes and growth duration were kept constant during the whole growth process. Film thicknesses ranged from 800 to 900 nm. Finally, the Au free top contact was deposited by an electron beam evaporated with V/Al/Ti (2,5,10,15/50/10 nm) while keeping the thickness of Ti and Al the same for all four samples. After the deposition of the metal stack, an annealing step of 1 min was carried out in a rapid thermal processor ranging from 800 to 950 °C.

## III. RESULTS AND DISCUSSIONS

The specific contact resistance is commonly measured using the Transmission Line Model (TLM) method, which can be implemented using either circular electrode or rectangular electrode configurations. In the circular electrode TLM method, the metal electrode is directly deposited onto the bulk material without the need for mesa formation. However, the calculation of specific contact resistance in this method can be complex. On the other hand, the rectangular electrode TLM method offers a simpler and more accurate way to calculate specific contact resistance, although it requires the preparation of an isolated mesa. Figure 1(a) illustrates the schematic diagram of the rectangular electrode TLM structure.

The TLM pattern used for characterization consists of a square with a side length of 100 μm and a width of 80 μm. The contact resistance was determined by analyzing TLM patterns with gap widths ranging from 10 to 40 μm, as shown in Fig. 1(a). The specific contact resistance was determined by examining the current–voltage relationship obtained from TLM measurements. Electrical characterization revealed that the voltage–current (I–V) characteristics of the contacts (V/Al/Ti on AlGaN) exhibited a relatively linear behavior up to a specific applied voltage threshold. The measured total resistance consists of several components: $R_T = 2R_m + 2R_C + R_{semi}$, where

$$R_{semi} = R_S * (L/W).$$

In the context of contact resistance, we can consider the total resistance as the sum of three components: $R_m$, which represents the resistance due to the contact metal; $R_C$, associated with the metal/semiconductor interface; and $R_{semi}$, which represents the usual semiconductor resistance. The resistance of a single contact can be expressed as $R_m + R_C$. However, in many cases, the resistivity of the metal in the contact is significantly lower than $R_C$, making $R_C$ much larger than $R_m$. As a result, the contribution of $R_m$ becomes negligible and can be ignored,

$$R_T = R_S * (L/W) + 2R_C = R_S * (L/W) + 2(R_S * L_T)/W.$$

Current crowding analysis reveals that the drop-off of current occurs exponentially with a characteristic length referred to as $L_T$, which is commonly known as the transfer length. This transfer length can be considered the effective length of the contact. Consequently, the effective area of the contact can be approximated as the product of $L_T$ and W, where W represents the width of the contact,

$$\rho_c = R_C * A_C = R_C * (L_T * W).$$

The contact resistance between metal (AlGaN) plays a crucial role in determining the performance and stability of semiconductor devices. Therefore, conducting comprehensive research on contact resistance is important. The formation mechanism of contact resistance involves several factors, including the band structure at the metal–semiconductor interface, electron transfer characteristics, and interface chemical reactions. In the case of Schottky contacts, a potential barrier is formed between the metal and the semiconductor. The height of this electron potential barrier determines the efficiency of electron injection and extraction, which is a key factor in determining the magnitude of the contact resistance. On the other hand, ohmic contacts form a good electrical connection between the metal and the semiconductor, and the transport process of electrons through the metal–semiconductor interface determines the level of contact resistance. Ohmic contacts exhibit linear or quasi-linear current–voltage (IV) characteristics, whereas Schottky contacts display non-linear IV characteristics. The energy level can be controlled by varying the thickness of the n-AlGaN and also depends on the vanadium thickness shown in the bandgap diagram in Fig. 1(c).

However, optimizing the contact resistance of metal AlGaN contacts is influenced by various factors. These factors include the choice of contact metal, surface treatment methods, and annealing conditions, all of which have significant effects on the resulting contact resistance. Figures 2(a)–2(d) focus primarily on investigating the impact of annealing temperature on contact resistance, while the inset of Figs. 2(a)–2(d) shows the effect of annealing temperature on the surface morphology of the top contact.

The influence of annealing temperature on the contact resistance of the metal AlGaN is a complex phenomenon. Optimal annealing treatment can have several beneficial effects such as enhancing the crystal quality and lattice matching at the metal AlGaN interface, promoting metal diffusion and interface bonding, reducing the barrier height, and transforming Schottky contacts into ohmic contacts. These effects ultimately lead to a decrease in contact resistance. However, it is important to note that excessively high annealing temperatures can induce structural changes in the material, which may have adverse effects on the contact resistance. Therefore, finding the right balance in the annealing temperature is crucial to achieve desirable contact properties and minimize contact resistance.

Figures 2(a)–2(d) show different annealing temperatures within the commonly used range of 800–950 °C to validate their effects on contact resistance. Insets in Figs. 2(a)–2(d) also show optical images that describe the surface morphological changes due to high temperature annealing. Figures 2(e) and 2(f) illustrate the test results obtained for each annealing temperature, along with the corresponding values of $R_c$ (contact resistance) and ρ (resistivity). From the analysis of Figs. 2(e) and 2(f), it can be observed that the contact resistance exhibits a noticeable variation with changing annealing temperature. The lowest contact resistance is achieved when the annealing temperature is set at 850 °C, resulting in a specific contact resistivity value of $4.12 \times 10^{-2}$ Ω-cm$^2$. Contact resistance tends to increase when the annealing temperature falls below 850 °C. This increase is primarily attributed to insufficient interface bonding caused by inadequate annealing temperature, leading to a limited reduction in the height of the interface potential barrier. Conversely, when the temperature exceeds 850 °C, the contact resistance experiences a significant twofold to threefold increase. This considerable increase is attributed to structural changes in the metal material induced by excessively high temperatures, which adversely affect contact resistance.

The previous section focused on investigating the impact of annealing temperature on contact resistance and identified the optimal annealing conditions for the metal electrodes currently employed. However, it was observed that even under these optimal annealing conditions, the current–voltage (IV) curve did not exhibit linearity. This indicates that the contact between the metal and AlGaN is still not an ohmic contact, leaving room for further optimization. As previously mentioned, the choice of contact metal also plays a crucial role in determining contact resistance. Therefore, in this section, we explore the influence of contact metal thickness on contact resistance.

In this section, we conducted experiments using a uniform AlGaN epitaxial wafer. The substrate was divided into four sections, and TLM metal electrodes with varying vanadium thicknesses of 2, 5, 10, and 15 nm were fabricated. Subsequently, we employed the optimal annealing temperature (850 °C) and performed annealing followed by TLM testing. The test results corresponding to different metal thicknesses are illustrated in Figs. 3(a)–3(d), and the corresponding contact resistance ($R_c$) and resistivity (ρ) were calculated based on these results.



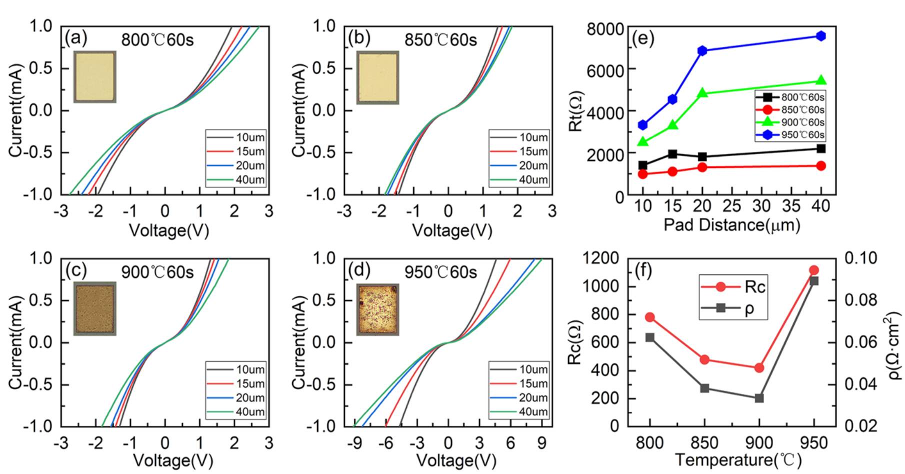


**FIG. 2.** Current–voltage (I–V) curves after annealing at elevated temperatures from (a) 800 °C, (b) 850 °C, (c) 900 °C, and (d) 950 °C acquired on various pad distances (10, 15, 20, and 40 μm) of the Transmission Line Model (TLM) structure. The insets show the optical images of the top contact. (e) Shows a variation of $R_t$ as the gap changes, while (f) shows a variation in contact resistance ($R_c$) and resistivity (ρ) with the change in annealing temperatures.

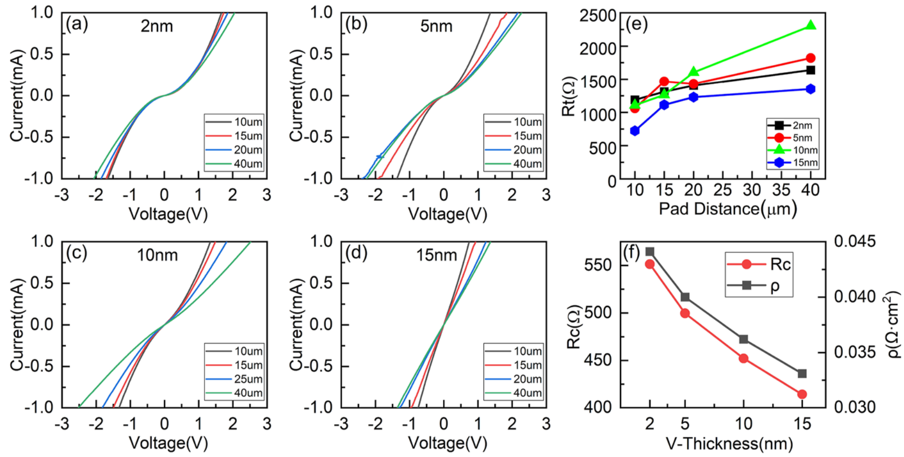


**FIG. 3.** Current–voltage (I–V) curves after variation in vanadium thickness: (a) 2 nm, (b) 5 nm, (c) 10 nm, and (d) 15 nm. Where (e) shows the variation of total resistance $R_T$ vs pad distance in corresponding V-metal thickness. (f) Show contact resistance ($R_c$) and resistivity (ρ) with a change in vanadium thickness.

From Figs. 3(e) and 3(f), it can be observed that as the thickness of the metal (V) increases, the contact resistance gradually decreases. Additionally, we compared the current–voltage (IV) curves of different metal thicknesses at the same gap spacing, as shown in Fig. 4(a). It is evident that as the metal thickness increases, the IV curve becomes more linear, indicating a transition from Schottky contact to ohmic contact between the metal and AlGaN. This can be attributed to insufficient metal diffusion and poor interface bonding when the contact metal (V) is too thin. Comparing the results of Figs. 3(f) and 4(a), it can be concluded that the reduction in contact resistance is primarily due to the gradual transformation of Schottky contact into ohmic contact.

Furthermore, to ascertain the effect of contact resistance on the performance of LED devices, we fabricated a simple LED chip using metal electrodes with different V thicknesses. The N electrodes of the LED chip were annealed at the same temperature using various V thicknesses (2, 5, 10, and 15 nm), while a standard P-type electrode (Ti/Au/Ti) was employed for the P electrodes. By utilizing this structure, we can investigate the relationship between LED device performance and contact resistance, which has been previously explored in other literature as well.

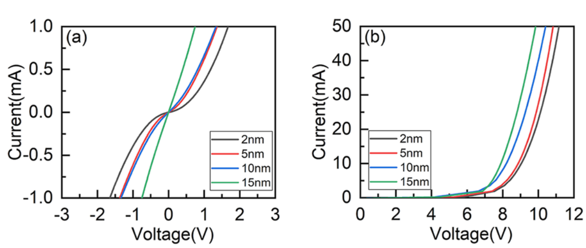


**FIG. 4.** (a) Current–voltage (I–V) curves with different V thicknesses in the same gap of 10-$\mu$m. (b) Current–voltage (I–V) characteristics after device fabrication. The smaller the intercept, the better the ohmic contact.

It is evident from the figure that as the thickness of the metal (V) increases, the voltage required for the device decreases. This implies that lower contact resistance leads to improved performance in LED devices. Figure 4(b) presents the IV curve results of the corresponding LED device, which show that the thicker the V thickness, the better the performance of the LED devices due to a reduction in contact resistance.

## IV. CONCLUSION

Here, we investigated the characteristics of V/Al/Ti on n-type $Al_{0.75}GaN$ ohmic contacts grown on a sapphire substrate using radiofrequency nitrogen plasma-assisted molecular beam epitaxy (PA-MBE). Rectangular TLM electrodes were prepared in a side ohmic contact mode, which was then annealed at temperatures between 800 and 950 °C. Our results showed that, particularly at lower annealing temperatures, the side ohmic contact mode for the double-channel GaN/AlGaN epitaxial layer achieved a lower specific contact resistance compared to the conventional surface contact mode. Variations in the annealing temperature and annealing duration were discovered to have an impact on the specific contact resistivities of this bi-layer system. Based on the calculations, the minimum specific contact resistance of $4.12 \times 10^{-2}$ $\Omega$ cm$^2$ was achieved at an annealing temperature of 850 °C. It is also concluded that as the thickness of the metal (V) increases, the voltage required for the device decreases. This implies that lower contact resistance leads to improved performance in LED devices.


## ACKNOWLEDGMENTS

The authors acknowledge the financial support from the 2023 Jiangsu Provincial Science and Technology Plan Special Fund (Key R&D Plan Industry Outlook and Key Core Technologies) Project through Grant No. BE2023048.

## AUTHOR DECLARATIONS

### Conflict of Interest

The authors have no conflicts to disclose.

### Author Contributions

**Yaqin Wang**: Formal analysis (equal); Funding acquisition (equal); Project administration (equal). **Muhammad Shafa**: Writing – original draft (equal). **Peng Wu**: Conceptualization (equal); Funding acquisition (equal). **Yitao Liao**: Project administration (equal).

## DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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