Vanadium-based Ohmic Contact for Aluminum-rich *n*-AlGaN

T.-T. Kao*, Y.-S. Liu, T. Detchprohm, R. D. Dupuis, and S.-C. Shen

School of Electrical and Computer Engineering, Georgia Institute of Technology,
777 Atlantic Drive NW, Atlanta, GA, 30332-0250
*e-mail: tkao6@gatech.edu Phone: 404-385-8327

Keywords: AlGaN, III-nitride, ohmic contact

Abstract

We report a study of Vanadium (V)-based ohmic contact on Al-rich *n*-AlGaN films using the transfer length measurement (TLM) and x-ray photoemission spectroscopy. The V-based ohmic contact shows lower contact resistance, smoother surface morphology, and lower annealing temperature when compared to the Ti-based ohmic contact. With the formation of the nitrogen-vanadium bond after the thermal annealing, the N:1*s* core-level peak at the V-$Al_{0.55}Ga_{0.45}N$ interface was shifted by 0.7 eV toward the higher binding energy. The interface states help the surface pinning of the Fermi level that further facilitates the current conduction for the *n*-type AlGaN ohmic contact. The data demonstrated that the use of V as the first layer of the *n*-type ohmic contact for Al-rich *n*-AlGaN could be a better choice of ohmic contact metal than the conventional Ti/Al-based ohmic contact.

INTRODUCTION

Since the first demonstration of high efficiency blue light emitting diodes (LEDs), the development of ultraviolet (UV and deep-ultraviolet (DUV) LEDs had led to rapid commercializations of these devices in various lighting applications. With the growing interest in nitride semiconductor emitters and detectors operating at DUV wavelengths, suitable ohmic contact for Al-rich *n*-AlGaN materials would be highly desired. In general, AlGaN has a work function of less than 4.0 eV. There would be a need to find appropriate methods to form an ohmic contact with intermediate transition layers. The issue of forming low-resistivity ohmic contact Al-rich AlGaN layers was also challenging with the increase of the dopant's activation energy as the aluminium composition increases.

The commonly reported ohmic contact systems for *n*-AlGaN are Titanium (Ti)-based metallization schemes since TiN has a work function of 3.74 eV and it could be formed at the interface after the annealing process. Miller *et al.* reported the ohmic contact on *n*-$Al_xGa_{1-x}N$ (x = 0.58) can be achieved after the sample was annealed at 900-1000 ^{o}C under the nitrogen ambient, yielding a specific contact resistance (ρ_c) of 4.0×10^{-4}-1.7×10^{-3} Ω-cm^2 [1]. However, the high-temperature annealing process is typically undesired as the ohmic contact morphology would become rough after high-temperature annealing process. There are also concerns of the device process integration compatibility as well as potential device reliability in lieu of the high-temperature process. Vanadium (V)-based ohmic contact could be a suitable choice for Al-rich *n*-AlGaN because thermally stable nitride complex can be created at the metal-III-N interface using low temperature annealing processes [2-5].

In this paper, we report a study of the V-based ohmic contact properties on AlGaN films for various Al compositions. We studied the evolution of the contact resistance as a function of the annealing temperature and the material bonding characteristics at the V-AlGaN interface using an x-ray photoemission spectroscopy (XPS) measurement. When compared to the Ti-based contact, V-based ohmic contact consistently shows lower ρ_c and smoother surface morphology at lower annealing temperature for *n*-type $Al_xGa_{1-x}N$ films (x up to 0.55.) A study of the N:1*s* core-level peak at V-$Al_{0.55}Ga_{0.45}N$ interface shows that the formation of nitrogen-vanadium (N-V) bond helps shift the peak binding energy by 0.7 eV at the V-AlGaN interface when compared to annealed Ti-AlGaN interface. The increase in the binding energy facilitates the current conduction by providing more effective electron states for carrier transport at the metal-semiconductor interface. The results indicated that the use of V-based ohmic contact is a suitable choice of achieving low contact resistance for *n*-AlGaN layers.

DEVICE STRUCTURES AND FABRICATION PROCESSING

The *n*-type $Al_xGa_{1-x}N$ films (x = 0.06, 0.49, 0.55, 0.6, and 0.73) were grown on *c*-plane sapphire substrates by a Thomas Swan metal-organic chemical vapor deposition (MOCVD) system. In this study, the $Al_{0.06}Ga_{0.94}N$ film was grown on a 2.5 µm-thick GaN buffer layer and its thickness is 250 nm. Other Al-rich $Al_xGa_{1-x}N$ films (x = 0.49, 0.55, 0.6, and 0.73) were 200 nm thick and they were grown on a 1 µm-thick AlN buffer layer. V/Al/Ti/Au and Ti/Al/Ti/Au stacks were deposited on each of the AlGaN samples for contact study.

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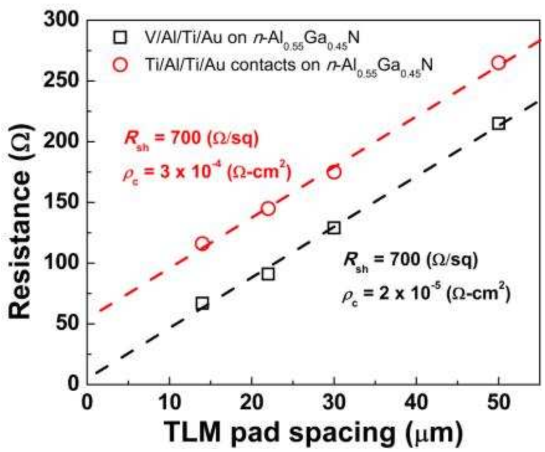
RESULTS AND DISCUSSIONS

Shown in Figure 1 (a) is the comparison of transmission line method (TLM) results for V-based and Ti-based ohmic contact on $Al_{0.55}Ga_{0.45}N$ films. The V-based ohmic contact was annealed at 775 ºC for 1 minute in N_2 and Ti-based ohmic contact was annealed at 825 ºC for 1 minute in N_2. By linear extrapolation, V-based ohmic contact shows ρ_c and sheet resistance (R_{sh}) of 2×10^{-5} Ω-cm² and 700 Ω/□, respectively. The Ti-based ohmic contact shows one order of magnitude higher ρ_c (3×10^{-4} Ω-cm²) with the same R_{sh}. Figure 1 (b) shows ρ_c as a function of the annealing temperature on $Al_{0.55}Ga_{0.45}N$ film. V/Al/Ti/Au metal stacks have lower ρ_c at a lower annealing temperature when compared to the Ti/Al/Ti/Au-based contact.



(a)

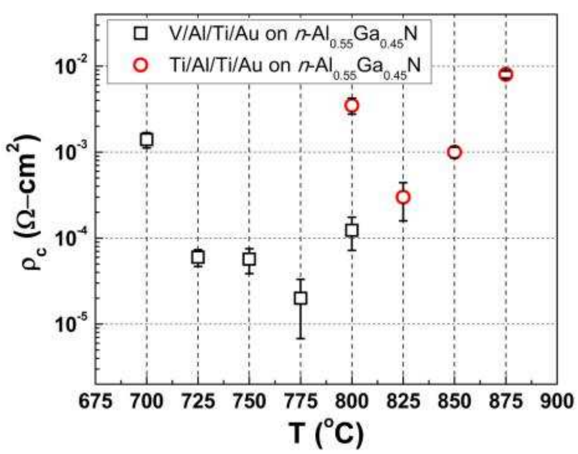


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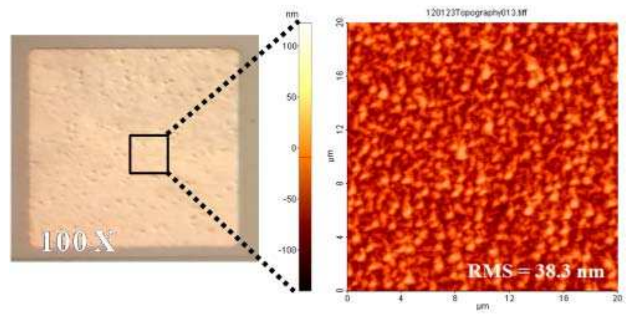
Figure 1. (a) TLM results of V/Al/Ti/A and Ti/Al/Ti/A ohmic contact on $Al_{0.55}Ga_{0.45}N$ film. The V-based ohmic contact was annealed at 775 ºC for 1 minute in N_2. The Ti-based ohmic contact was annealed at 8255 ºC for 1 minute in N_2. (b) ρ_c as a function of annealing temperature for V/Al/Ti/Au and Ti/Al/Ti/Au ohmic contact on $Al_{0.55}Ga_{0.45}N$ film.

Shown in Figure 2 (a) and (b) are microscope and AFM images of the annealed V/Al/Ti/Au and Ti/Al/Ti/Au metal stacks on $Al_{0.55}Ga_{0.45}N$ film, respectively. The metallization using V/Al/Ti/Au ohmic contact is relatively shiny and smooth while several bumps are visible on the surface of Ti/Al/Ti/Au contact. The root-mean-square (RMS) roughness of the annealed V/Al/Ti/Au and Ti/Al/Ti/Au metal stacks are 38.3 nm and 91.7 nm across a 20×20 μm² area, respectively. The smoother surface of the V-based metal stacks could be attributed to the lower annealing temperature for achieving an optimum ρ_c. Figure 3 shows ρ_c as a function of the annealing temperature on $Al_{0.06}Ga_{0.88}N$ film. V/Al/Ti/Au ohmic contact provides a lower ρ_c at each annealing temperature compared to Ti/Al/Ti/Au ohmic contact. The optimum value of ρ_c= 6.6×10^{-6} Ω-cm² is found at 725 ºC.



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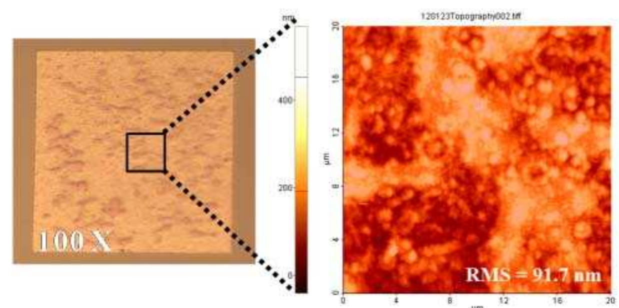

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Figure 2. The microscopic and AFM images for the annealed (a) V/Al/Ti/Au and (b) Ti/Al/Ti/Au metal stacks.

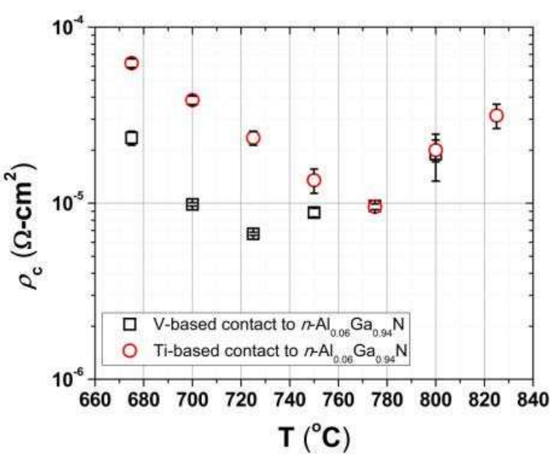

Figure 3. ρ_c of V/Al/Ti/Au and Ti/Al/Ti/Au ohmic contact as a function of annealing temperature on $Al_{0.06}Ga_{0.88}N$ film.

The optimum annealing temperature for V-based ohmic contact was investigated on AlGaN films with different Al compositions. As shown in Figure 4, ρ_c is 6.6×10^{-6} Ω-cm^2 for $Al_{0.06}Ga_{0.94}N$ film. As Al composition increases from 6 % to 73 %, ρ_c increases from 6.6×10^{-6} Ω-cm^2 to 4.4×10^{-3} Ω-cm^2 and the bulk resistivity (ρ_s) increases from 5×10^{-3} Ω-cm to 5.6 Ω-cm. The increase in ρ_c and ρ_s can be attributed to the low free carrier concentration of n-$Al_xGa_{1-x}N$ films as Al composition increases. It is also noted that Ti-based metal stacks cannot form ohmic contact as the Al composition is greater than 60 %.

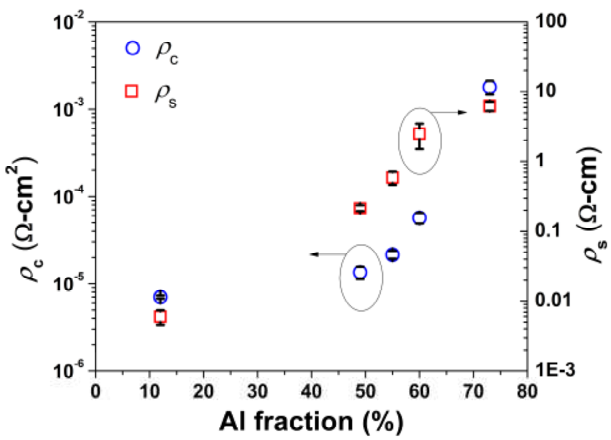

Figure 4. ρ_c and ρ_s of V/Al/Ti/Au ohmic contact on n-$Al_xGa_{1-x}N$ films with various Al compositions (x= 0.06, 0.49, 0.55, 0.6, and 0.73).

The binding energy at the metal/$Al_{0.55}Ga_{0.45}N$ interface was characterized by a XPS system to understand the formation of interfacial energy states created by either Ti-based or V-based ohmic contact. Figure 5 shows the N:1*s* core level spectra at the annealed V-$Al_{0.55}Ga_{0.45}N$ and Ti-$Al_{0.55}Ga_{0.45}N$ interfaces. Weaker intensity was observed on the sample with Ti-based contact, which implies severe nitrogen desorption due to the higher temperature annealing process. In addition, the N:1*s* core-level peak at the V-$Al_{0.55}Ga_{0.45}N$ interface shifts toward higher binding energy by 0.7 eV. Shown in Figure 5 is a fitting of the N:1*s* core level spectra at the Ti-$Al_{0.55}Ga_{0.45}N$ and V-$Al_{0.55}Ga_{0.45}N$ interfaces. Four common component peaks, i.e., N-Al (397.8 eV), N-Ga (397.4 eV), N-C (395.7 eV) and Ga LMM Auger electrons (393 eV), were found at both metal/AlGaN interfaces [6-8]. The shift of the N:1*s* core level spectrum at the V-$Al_{0.55}Ga_{0.45}N$ interface consists of to the N-V bond at a higher binding energy of 397.3 eV [9]. This binding energy is higher than that of the N-Ti bond at 396.8 eV [10]. Since the interface states help the surface pinning of the Fermi level, the increase in the binding energy facilitates the current conduction by providing N-V energy states for carrier transport at the metal-semiconductor interface. The results indicated that the use of V-based ohmic contact is a suitable choice of achieving low contact resistance for n-AlGaN layers.

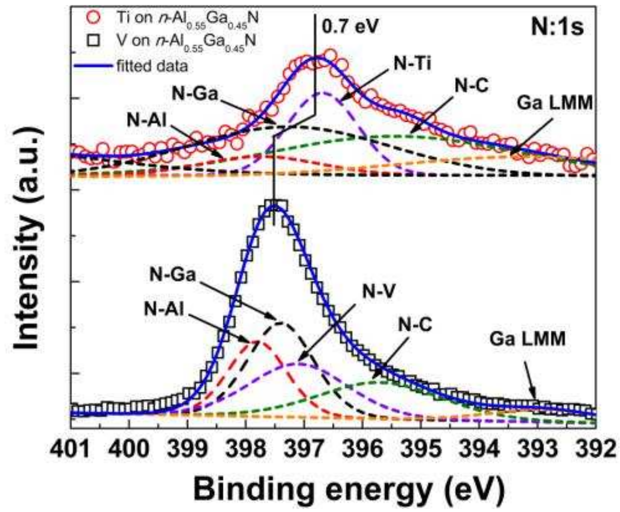

Figure 5. XPS spectra of N:1*s* core level at the annealed V-$Al_{0.55}Ga_{0.45}N$ and Ti-$Al_{0.55}Ga_{0.45}N$ interfaces. The N:1*s* core level was fitted using Shirley background and mixed Lorentzian-Gaussian line shapes.

CONCLUSIONS

In conclusion, we report a study of the V-based ohmic contact on AlGaN films using TLM and XPS analysis. When compared to the Ti-based ohmic contact, V-based ohmic contact consistently shows lower ρ_c and smoother surface morphology at lower annealing temperature for n-type $Al_xGa_{1-x}N$ films (x up to 0.55). A study of the N:1*s* core-level peak at V-$Al_{0.55}Ga_{0.45}N$ interface shows that the formation of N-V bond helps shift the peak binding energy by 0.7 eV at the V-AlGaN interface when compared to the annealed Ti-AlGaN interface. The increase in the binding energy facilitates the current conduction by providing more effective energy states for carrier transport at the metal-semiconductor interface. As a result, using V-based contact helps achieve low annealing temperature requirement (< 800 ^oC) that leads to better surface morphology than conventional Ti-based ohmic contact.

ACKNOWLEDGEMENTS

The authors are thankful for the cleanroom facility support of the staff in the Microelectronic Research Center at the Georgia Institute of Technology in Atlanta, GA. This work is supported by the Defense Advanced Research Projects Agency under Contract #W911NF-15-1-0026.

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ACRONYMS

UV: ultraviolet
DUV: deep-ultraviolet
TLM: Transfer length measurement
XPS: X-ray photoemission spectroscopy
LED: Light emitting diode
Ti: Titanium
V: Vanadium
MOCVD: metal-organic chemical vapor deposition
ρ_c: specific contact resistance
ρ_s: bulk resistivity
ICP: inductively coupled plasma
R_{sh}: sheet resistance
RMS: root-mean-square