

# Low resistivity Hf/Al/Ni/Au Ohmic Contact Scheme to n-Type GaN

Y. Liu, M. K. Bera, L. M. Kyaw, G. Q. Lo, E. F. Chor

**Abstract**—The electrical and structural properties of Hf/Al/Ni/Au (20/100/25/50 nm) ohmic contact to n-GaN are reported in this study. Specific contact resistivities of Hf/Al/Ni/Au based contacts have been investigated as a function of annealing temperature and achieve the lowest value of  $1.09 \times 10^{-6} \Omega \cdot \text{cm}^2$  after annealing at 650 °C in vacuum. A detailed mechanism of ohmic contact formation is discussed. By using different chemical analyses, it is anticipated that the formation of Hf-Al-N alloy might be responsible to form low temperature ohmic contacts for the Hf-based scheme to n-GaN.

**Keywords**—Gallium nitride, ohmic contact, Hafnium

## I. INTRODUCTION

GALLIUM nitride, with many characteristic properties compared to other semiconductor materials, has been attractive to researchers in the areas of electronics and optoelectronics since the last couple of decades. GaN has been successfully used in many applications of lasers [1], including blue and green light emitting diodes [2] by exploiting its direct wide bandgap (3.4 eV) [3]. Besides the wide bandgap, high breakdown field and high saturation velocity of GaN make it very promising for high-power, high-speed and high temperature electronic devices [4, 5]. However, in order to boost up the performance of GaN based devices, the formation of ohmic contact to n-GaN and its related alloys with AlN and AlInN is very essential to reduce power consumption and parasitic delays associated with the access resistances. Among the many potential metal candidates suitable for ohmic contact to n-GaN, Ti based multilayer structures are the most widely used metal scheme followed by a rapid thermal annealing (RTA) process which is usually performed at temperatures higher than 750 °C in order to obtain a low resistance ohmic contact [6-8]. Theoretically, any metal with a work function close to the electron affinity of GaN (~2.9–3.5 eV) could form an ohmic contact to n-GaN [9]. Among few potential candidates, hafnium, Hf is attractive since it has low work function ~3.9 eV close to electron affinity of n-GaN [10]. Therefore, it is expected that Hf could form an ohmic contact to n-GaN.

Y. Liu is a PhD candidate of the Department of Electrical and Computer Engineering, National University of Singapore, Singapore 119074, and is also attached to the Institute of Microelectronics, Agency for Science, Technology, and Research (A\*STAR), Singapore 117685. (e-mail: a0068100@nus.edu.sg).

M. K. Bera, and E. F. Chor are with the Department of Electrical and Computer Engineering, National University of Singapore, Singapore 119074. (e-mail: elecef@nus.edu.sg).

L. M. Kyaw is a PhD candidate of the Department of Electrical and Computer Engineering, National University of Singapore, Singapore 119074.

G. Q. Lo is with the Institute of Microelectronics, Agency for Science, Technology, and Research (A\*STAR), Singapore 117685. (e-mail: logq@ime.a-star.edu.sg).

Although, Hf based metallization scheme has been reported recently, however, the detail mechanism of ohmic contact formation has not yet been explored [11-13]. In this work, we report the electrical and structural properties of Hf/Al/Ni/Au based ohmic contacts to n-GaN. Specific contact resistivities of Hf/Al/Ni/Au based contacts are investigated as a function of annealing temperature in the range from 600 to 900 °C and are compared with those for conventional Ti/Al/Ni/Au based ohmic contacts to n-GaN. Besides, a detailed mechanism of ohmic contact formation has also been discussed.

## II. EXPERIMENTAL

In this experiment, we used n-type GaN epi-structure grown on 4 inch Si (111) substrate by means of metal organic chemical vapor deposition (MOCVD), purchased from NTT-AT Corporation, and the detail of our contact structure is schematically shown in Fig. 1.

Hall measurements conducted at room temperature exhibit the carrier concentration of  $\sim 3.5 \times 10^{18} \text{ cm}^{-3}$ , the carrier mobility of  $\sim 220 \text{ cm}^2/\text{V.s}$ , and a sheet resistance of  $84.38 \Omega/\square$ . The 4 inch n-GaN-on-Si wafer was cut into several small pieces. Thereafter, a proper surface cleaning procedures were carried out first by degreased in acetone solution followed by 2-propanol in an ultrasonic bath for about 10 mins each before thoroughly rinsed in de-ionized (DI) water. Subsequently, a dilute HCl acid solution (HCl: H<sub>2</sub>O=1:3) was used to remove the remaining native oxides on n-GaN surface followed by rinsed in DI water and blown dry with N<sub>2</sub>. Before patterning, the samples were pre-baked at 110 °C for 10 mins in an oven for dehydration. The circular transmission line model (CTLM) structure was defined using UV photolithography. The detailed configuration of CTLM structure is shown in Fig. 2. It consists of an outer circle of radius 90  $\mu\text{m}$  with different inner circles having gap spacing in the range between 5 to 45  $\mu\text{m}$ . Pre-metallization cleaning was performed by dipping the patterned samples into dilute HCl solution (HCl: H<sub>2</sub>O=1:10) for about 15 sec. The samples were then immediately loaded into an e-beam evaporator chamber. Metal layers of Hf/Al/Ni/Au (20/100/25/50 nm) and Ti/Al/Ni/Au (20/100/25/50 nm) were deposited sequentially by e-beam evaporation. A rapid thermal annealing (RTA) process was carried out to do thermal annealing at various temperatures in the range between 600-900 °C for 1 min in vacuum.

Current-voltage (*I-V*) characteristics were obtained at room temperature using an Agilent B1500A semiconductor parameter analyzer. X-ray diffraction (XRD), time-of-flight secondary ion mass spectroscopy (ToF-SIMS) and cross-sectional transmission electron microscope (TEM) were used in order to investigate the metallurgical reactions and the mechanism behind the ohmic contact formation for Hf/Al/Ni/Au based scheme.

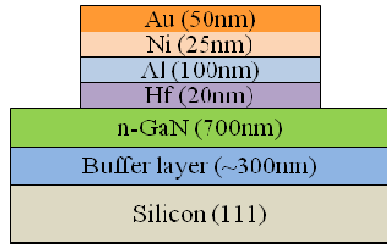


Fig. 1 Schematic cross section of Hf/Al/Ni/Au based ohmic contact on n-GaN-on-Si

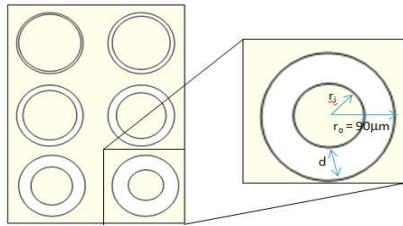


Fig. 2 Schematic of Circular Transmission Line Model (CTLM) structure used in this experiment

### III. RESULT AND DISCUSSION

Fig. 3 shows the results of  $I$ - $V$  characteristics as a function of annealing temperature for Hf/Al/Ni/Au (20/100/25/50 nm) contacts on n-GaN with the CTLM structure having a gap spacing of 10  $\mu\text{m}$ . A rectifying behavior is observed for the 600  $^{\circ}\text{C}$  annealed sample, however, the contacts become ohmic for  $\geq 630$   $^{\circ}\text{C}$  annealed conditions in which the steepest  $I$ - $V$  slope is noted for the 650  $^{\circ}\text{C}$  annealed sample. The specific contact resistivity was calculated from the linear curve fitting of the relationship between measured resistances versus gap spacing.

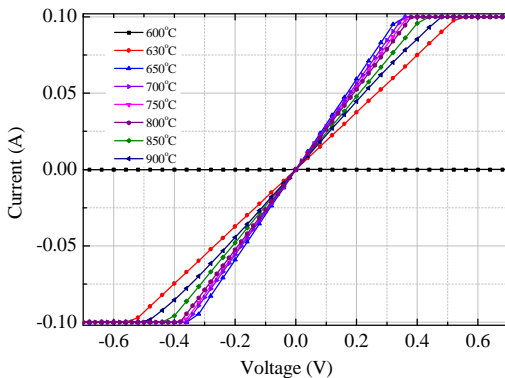


Fig. 3 Typical  $I$ - $V$  characteristics dependences of Hf/Al/Ni/Au (20/100/25/50 nm) based contacts on n-GaN as a function of annealing temperature performed in vacuum for 1 min

Fig. 4 shows the variation of specific contact resistivity as a function of annealing temperature for the Hf and Ti based contacts on n-GaN. For Hf based contacts, it is observed that the specific contact resistivity initially decreases to  $1.09 \times 10^{-6} \Omega \cdot \text{cm}^2$  upon annealing from 630 to 650  $^{\circ}\text{C}$ , and increases again to a value of  $5.79 \times 10^{-6} \Omega \cdot \text{cm}^2$  after annealing at 900  $^{\circ}\text{C}$ .

On the contrary, Ti based contact exhibits a significant drop in specific contact resistivity beyond 750  $^{\circ}\text{C}$  annealing temperature, in fact, demonstrates the lowest value of  $8.65 \times 10^{-7} \Omega \cdot \text{cm}^2$  at 850  $^{\circ}\text{C}$ , and again shows an increasing trend at 900  $^{\circ}\text{C}$ , which is consistent with previous studies [14]. Therefore, from this figure it is clear that Hf-based metal scheme can achieve a low specific contact resistivity at a comparatively low temperature of 650  $^{\circ}\text{C}$ .

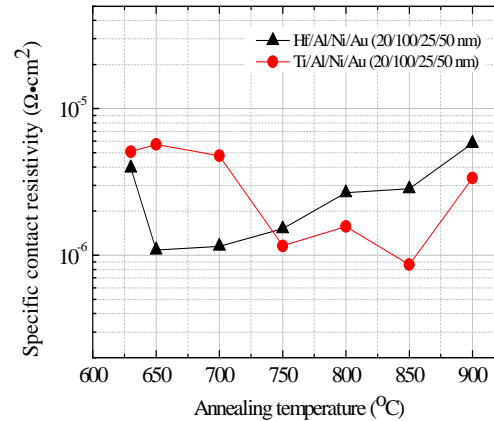


Fig. 4 Variation of specific contact resistivity as a function of annealing temperature for Hf/Al/Ni/Au (20/100/25/50 nm) and Ti/Al/Ni/Au (20/100/25/50 nm) contacts on n-GaN

In order to investigate the mechanism behind the low temperature formation of ohmic contact for the Hf-based metal scheme, several physic-chemical characteristics have been performed.

Fig. 5 shows the SIMS depth profiles of several constituent metals for the Hf/Al/Ni/Au based contacts for the as-deposited and 650  $^{\circ}\text{C}$  annealed samples. It can be observed that after 650  $^{\circ}\text{C}$  annealing, most of the four constituent metals are mixed together, especially the Hf and Al layers, which are completely mixed and have partly diffused into GaN while the out diffusion of nitrogen at the metal-semiconductor interface is also observed, as shown in Fig. 5 (b).

This signifies that there will be a heavily doped layer appearing at the interface between the metal stack and GaN layer, which is similar to the main reason for the formation of Ti based ohmic contacts to n-GaN. Eventually, the out diffused nitrogen could react with Hf-Al alloys and form metal nitride which is very helpful to reduce the contact resistivity by introducing a heavily doped interlayer at the metal-GaN interface.

In order to identify the metal alloy phases formed, XRD analysis was performed. Fig. 6 shows the XRD profiles of the Hf/Al/Ni/Au based contacts for the as-deposited and annealed samples whose annealing is done at 650  $^{\circ}\text{C}$  in vacuum for 1 min.

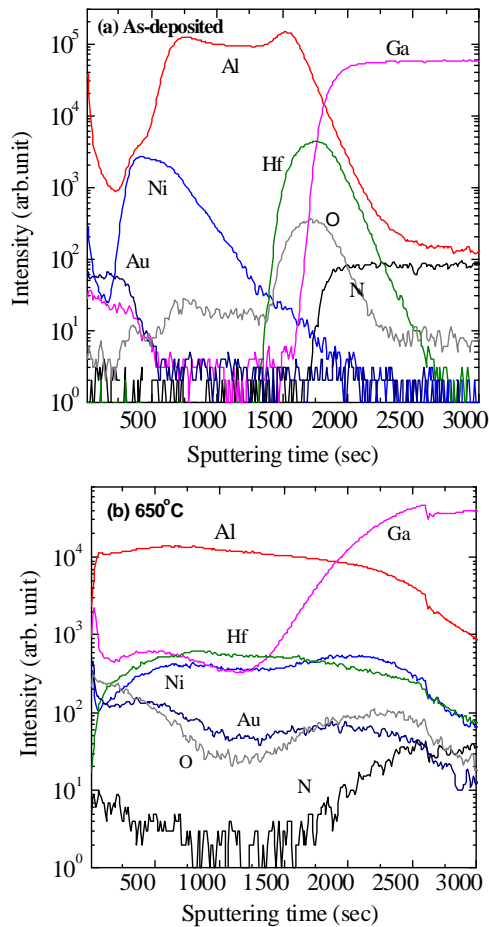


Fig. 5 ToF-SIMS depth profiles of Hf/Al/Ni/Au on n-GaN (a) as-deposited, and (b) after annealing at 650 °C for 1min in vacuum

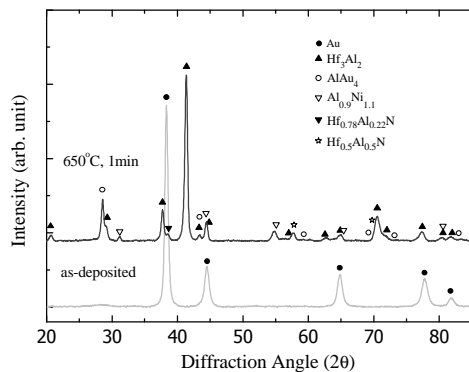


Fig. 6 XRD scans of Hf/Al/Ni/Au (20/100/25/50 nm) contacts: (a) as-deposited, and (b) after annealing at 650 °C for 1 min in vacuum.

It can be observed from the XRD scans in Fig. 6 that the peaks corresponding to Au have disappeared after annealing at 650 °C, while new alloy phases corresponding to Au-Ni, Al-Au, Hf-Al and especially  $\text{Hf}_{0.78}\text{Al}_{0.22}\text{N}$  and  $\text{Hf}_{0.5}\text{Al}_{0.5}\text{N}$  alloy phases begin to appear.

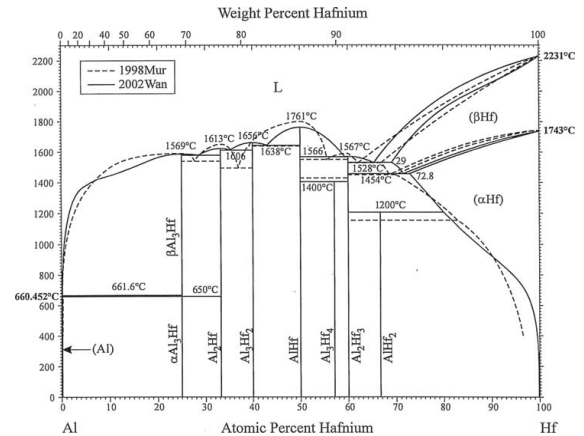


Fig. 7 Phase diagram and thermochemistry data of the binary Hf-Al system

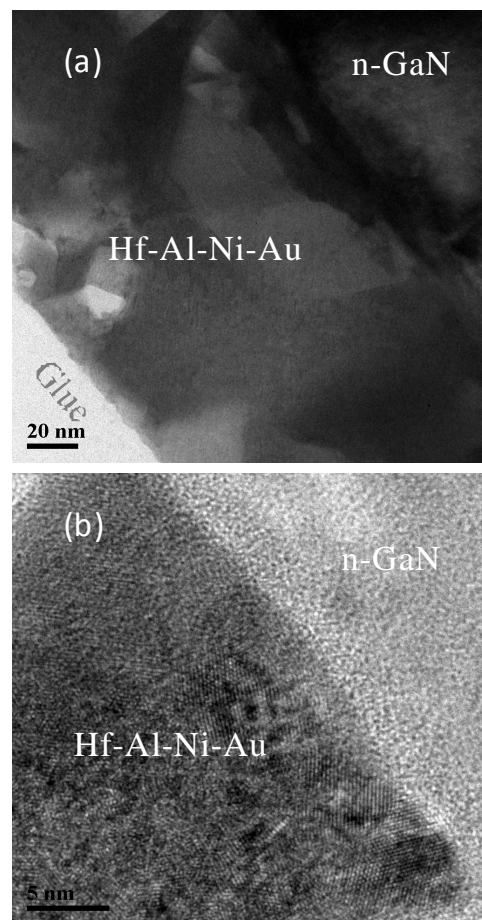


Fig. 8 Cross-sectional TEM images of the Hf/Al/Ni/Au (20/100/25/50 nm) contact after annealing at 650 °C

The observation of Hf-Al-N alloy phase has recently been reported [15]. Indeed, the formation of several Hf-Al intermetallic alloy phases at low temperature less than 400 °C has been reported earlier, as can be seen from the phase diagram and thermochemistry data of the binary Hf-Al system shown in Fig. 7 [16].

It is anticipated that the existence of Hf-Al-N alloy similar to Ti-Al-N alloy for Ti based contacts [17] plays a crucial role to the formation of low temperature ohmic contact to n-GaN. Fig. 8 presents the cross-sectional TEM images of the Hf/Al/Ni/Au (20/100/25/50 nm) based contact annealed at 650 °C. The interface between the metal and semiconductor can be seen clearly, which might be good to enhance the stability of Hf based contacts.

#### IV. CONCLUSION

In conclusion, it has been demonstrated that Hf/Al/Ni/Au based metal scheme can form ohmic contact with low specific contact resistivity to n-GaN-on-Si substrate at a comparatively low temperature of 650 °C. The SIMS and XRD results confirm the formation of Hf-Al and Hf-Al-N alloy phases which are likely to be responsible for the ohmic contact formation at low annealing temperature. The development of Hf-based metallization scheme to form low resistance ohmic contacts at an annealing temperature lower than the aluminum melting point could significantly reduce the risk of lateral overflow that often causes short-circuit between the gate and source/drain of the devices. However, a detailed investigation is needed to further understand the mechanism behind the Hf-based ohmic contacts to n-GaN.

#### ACKNOWLEDGMENTS

This work is supported by SERC (grant No. 106 169 0129) under A\*star funded project: GaN-on-Si Thematic Strategic Research Programme: GaN-on-Si RF-Power Devices. Y. Liu and L.M. Kyaw would also like to acknowledge the research scholarship provided by the National University of Singapore for the pursuance of their PhD studies.

#### REFERENCES

- [1] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, Y. Sugimoto, T. Kozaki, H. Umemoto, M. Sano, and K. Chocho, "Continuous-wave operation of InGaN/GaN/AlGaIn-based laser diodes grown on GaN substrates," *Applied Physics Letters*, vol. 72, pp. 2014-2016, Apr 20 1998.
- [2] S. Nakamura, T. Mukai, and M. Senoh, "Candela-Class High-Brightness Ingan/Algan Double-Heterostructure Blue-Light-Emitting Diodes," *Applied Physics Letters*, vol. 64, pp. 1687-1689, Mar 28 1994.
- [3] I. Vurgaftman and J. R. Meyer, "Band parameters for nitrogen-containing semiconductors," *Journal of Applied Physics*, vol. 94, pp. 3675-3696, Sep 2003.
- [4] K. T. Lee, C. F. Huang, J. Gong, and C. T. Lee, "High-Performance 1- $\mu$ m GaN n-MOSFET With MgO/MgO-TiO<sub>2</sub> Stacked Gate Dielectrics," *Ieee Electron Device Letters*, vol. 32, pp. 306-308, Mar 2011.
- [5] C. Y. Tsai, T. L. Wu, and A. Chin, "High-Performance GaN MOSFET With High-k LaAlO<sub>3</sub>/SiO<sub>2</sub> Gate Dielectric," *Ieee Electron Device Letters*, vol. 33, pp. 35-37, Jan 2012.
- [6] S. Ruvimov, Z. Liliental-Weber, J. Washburn, K. J. Duxstad, E. E. Haller, Z. F. Fan, S. N. Mohammad, W. Kim, A. E. Botchkarev, and H. Morkoc, "Microstructure of Ti/Al and Ti/Al/Ni/Au Ohmic contacts for n-GaN," *Applied Physics Letters*, vol. 69, p. 1556, 1996.
- [7] D. F. Wang, S. W. Feng, C. Lu, A. Motayed, M. Jah, S. N. Mohammad, K. A. Jones, and L. Salamanca-Riba, "Low-resistance Ti/Al/Ti/Au multilayer ohmic contact to n-GaN," *Journal of Applied Physics*, vol. 89, pp. 6214-6217, Jun 1 2001.
- [8] D. Selvanathan, L. Zhou, V. Kumar, and I. Adesida, "Low resistance Ti/Al/Mo/Au ohmic contacts for AlGaIn/GaN heterostructure field effect transistors," *Physica Status Solidi a-Applied Research*, vol. 194, pp. 583-586, Dec 16 2002.
- [9] S. Kurtin, T. C. McGill, and C. A. Mead, "Fundamental transition in the electronic nature of solids," *Physical Review Letters*, vol. 22, pp. 1433-1436, 1969.
- [10] D. R. Lide, *CRC handbook of chemistry and physics: CRC Pr I Llc*, pp.12-124, 2012.
- [11] A. C. Schmitz, A. T. Ping, M. A. Khan, Q. Chen, J. W. Yang, and I. Adesida, "Metal contacts to n-type GaN," *Journal of Electronic Materials*, vol. 27, pp. 255-260, Apr 1998.
- [12] M.-S. Chung, W.-T. Lin, and J. R. Gong, "Formation of Hf ohmic contacts by surface treatment of n-GaN in KOH solutions," *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures*, vol. 19, p. 1976, 2001.
- [13] N. Yafune, M. Nagamori, H. Chikaoka, F. Watanabe, K. Sakuno, and M. Kuzuhara, "Low-Resistivity V/Al/Mo/Au Ohmic Contacts on AlGaIn/GaN Annealed at Low Temperatures," *Japanese Journal of Applied Physics*, vol. 49, p. 04DF10, 2010.
- [14] A. N. Bright, P. J. Thomas, M. Weyland, D. M. Tricker, C. J. Humphreys, and R. Davies, "Correlation of contact resistance with microstructure for Au/Ni/Al/Ti/AlGaIn/GaN ohmic contacts using transmission electron microscopy," *Journal of Applied Physics*, vol. 89, p. 3143, 2001.
- [15] D. Holec, R. Rachbauer, L. Chen, L. Wang, D. Luef, and P. H. Mayrhofer, "Phase stability and alloy-related trends in Ti-Al-N, Zr-Al-N and Hf-Al-N systems from first principles," *Surface & Coatings Technology*, vol. 206, pp. 1698-1704, Dec 25 2011.
- [16] H. Okamoto, "Al-Hf (Aluminum-Hafnium)," *Journal of Phase Equilibria & Diffusion*, vol. 27, pp. 538-539, 2006.
- [17] J. S. Kwak, S. E. Mohny, J. Y. Lin, and R. S. Kern, "Low resistance Al/Ti/n-GaN ohmic contacts with improved surface morphology and thermal stability," *Semiconductor Science and Technology*, vol. 15, pp. 756-760, Jul 2000.