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Comparative study of Ti/Al and Ti/Al/Ti/Au ohmic contacts to AlGaN/GaN heterostructures

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ABSTRACT

We investigated the electrical properties and the ohmic contact formation considering Ti/Al and Ti/Al/Ti/Au ohmic contact metallization schemes on AlGaN/GaN heterostructures. The specific contact resistance of contacts was determined by characterizing the current–voltage relation from TLM measurement. The lowest value for the specific contact resistivity was obtained using Ti/Al/Ti/Au metallization. An interfacial TiN layer was monitored at the contact-AlGaN interface. TiN phases were found at both contacts, but the thickness in the Ti/Al/Ti/Au contact reached 8 nm, while the thickness in Ti/Al was thinner and discontinuous. The surface roughness of the Ti/Al/Ti/Au contact was determined as 8.17 nm and that of the Ti/Al contact as 36.23 nm. It was found that the spesific contact resistance depends on the atomic structure of the metal–semiconductor interface and composition and structure of the ohmic contact layers. These results showed that it is possible to achieve higher reliability and uniformity as well as lower contact resistance in AlGaN/GaN HEMTs with Ti/Al/Ti/Au contact compared to Ti/Al contact.

1. Introduction

In the last two decades, AlGaN/GaN heterostructures have attracted increasing attention for high power, high temperature and frequency semiconductor device applications due to its outstanding material properties [1–2]. Research on ohmic contacts to AlGaN/GaN heterostructures is of great importance to enhance the usability of these materials in electronic and optoelectronic devices. Dependable ohmic contacts with low contact resistance, thermal and mechanical stability, smooth surface morphology, and good edge sharpness are of great importance to ensure a high transconductance and a high saturation current of AlGaN/GaN heterostructure field-effect transistors (HEMTs). Because of the resistive internal of the wide-bandgap materials and the presence of natural oxides between contact metals and materials, it is difficult to form a high quality ohmic contact [3]. It has been observed in the previous studies that Al mole fraction, thickness and structure of the substrate, metal stacking order and thickness, as well as annealing conditions of ohmic contact are highly effective in contact formation. A wide variety of ohmic contact schemes on Ti/Al basis have been successfully applied to n-GaN or AlGaN/GaN heterostructures [3]. The common use of Ti as a contact layer in ohmic contacts to AlGaN/GaN heterostructures due not only to its low work function (4.32 eV), but also to the fact that it forms a TiN layer with an even lower work function (3.74 eV) [4]. Pang et al., observed TiN phase at metal–semiconductor interface after RTA at 830 °C, 30 s [5]. Understanding low-resistance ohmic contact formation and the underlying mechanisms is essential for the preparation of high-efficiency electronic devices. In this study, the characteristics of Ti/Al/Ti/Au and Ti/Al ohmic contacts on AlGaN/GaN heterostructures have been investigated. Electrical measurements were correlated with morphological and structural analyses of the metal contact layers and metal–semiconductor interfaces.

2. Experimental

In this study, AlGaN/GaN heterostructure grown by MOCVD method on 4H-SiC substrate was used. Epitaxial layers consist of 1.8 μm Fe-doped GaN buffer layer, 3 nm AlN layer, 21 nm unintentionally doped n-type $Al_{0.20}Ga_{0.80}N$ layer and 2 nm GaN cap layer. To remove the organic impurities, samples were washed with trichloroethylene, acetone, methanol, ethanol and deionized (DI) water in an ultrasonic

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cleaner for 5 min each and dried with nitrogen gas. The samples were then immersed in boiling KOH (1 M) to reduce the surface roughness and in aqua regia (3:1 HCl:HNO_3) to remove the natural oxide on the surface of the substrate. After each step, the substrates were rinsed with DI water and dried with nitrogen gas. Ti/Al (225/1000 Å) and Ti/Al/Ti/Au (225/1000/225/300 Å) ohmic contact layers were deposited using different deposition techniques for different metals. Ti films were deposited at a rate of 0.4 Å/sec under argon atmosphere using DC magnetron sputtering. Al and Au films were thermally evaporated at rates of 1.2 Å/sec and 0.5 Å/sec, respectively. Photolithography was used to define the transmission line method (TLM) patterns. The TLM pads were sized 35x7 μm^2 and spaced 3–16 μm apart. After the lift-off process, in order to restore ohmic characteristics, rapid thermal annealing (RTA) was carried out at 850 °C for 30, 60 and 120 sec in an N_2 environment. To investigate the electrical properties of the ohmic contacts, current–voltage (I-V) measurements were carried out using a computer-controlled HP4140B instrument. The surface roughness of the contacts was analyzed by Veeco Multimode 8 atomic force microscope (AFM) and the microstructure of the contacts was analyzed by FEI Tecnai G2 F30 transmission electron microscope (TEM).

3. Results and discussion

The current–voltage characteristics of ohmic contacts as a function of RTA times are given in Fig. 1. Ti/Al contact exhibits semi-linear current–voltage characteristics at all RTA times. In the Ti/Al/Ti/Au contact, a minor deviation from linearity is observed after 30 s annealing at 850 °C, while a linear current–voltage characteristic is observed over the entire measurement range when the annealing time is increased above 60 s. Lowest specific contact resistance, ρ_c value (2.9x10^{-5} Ωcm^2) obtained in Ti/Al/Ti/Au contact at 30 s RTA time and ρ_c slightly increased with increasing RTA time in both contacts. The literature reports a wide range of ρ_c values (10^{-2}-10^{-7} Ωcm^2) [3]. This variation may be related to a number of parameters including the metal work function, doping level of the semiconductor, the thickness and order of the metal layers, the structure of the substrate and the annealing process. Regardless of the annealing time, Ti/Al/Ti/Au contact exhibited better results than Ti/Al contact.

In order to comprehend ohmic behaviours of Ti/Al and Ti/Al/Ti/Au contacts, the samples annealed at 850 °C for 60 s were subjected to cross-sectional TEM analysis and combined EDX elemental mapping. As shown in Fig. 2, the formation of Ti-Al phases after annealing has been observed in both samples. The most plausible Ti-Al phase is $TiAl_3$, which is generally considered to result in good ohmic contact on n-type GaN, and it has been observed to form even at 500 °C annealing temperature [6,7].

The elemental mapping in Fig. 2 shows that there are transitions of N atoms from the semiconductor to the metal contact layers. Here, it can be said that the additional N vacancies formed in the AlGaN underlying the contact make the semiconductor heavily doped. When the AlGaN is heavily doped near the metal-AlGaN interface, a pronounced band bending occurs in the conduction band. Such a case narrows the space charge region of the semiconductor so that the electrons easily pass through via tunneling. The unintentionally doped AlGaN layer used in this study has a doping level of $8x10^{16}$ cm^{-3}. At this low doping level, the dominant transport mechanism is in most cases the thermionic emission. However, for semiconductors with a wide bandgap such as AlGaN, ohmic contact formation is difficult because there is no metal with a sufficiently low work function. This rules out the thermionic emission as the dominant current transport mechanism across the contact. [8]. The thickness of the TiN layer observed at the metal–semiconductor interface after RTA can provide information about the doping level of the underlying AlGaN layer. Comparing Fig. 2 (a) and (b), a continuous TiN layer with a thickness of 4–8 nm is observed at the metal–semiconductor interface of the Ti/Al/Ti/Au contact. At the Ti/Al contact, TiN formation is also observed locally, but not continuously along the metal–semiconductor interface. As shown in Fig. 2, the contiguous TiN layer at the metal–semiconductor interface in the Ti/Al/Ti/Au contact implies a tunnelling contact, whereas in the Ti/Al contact, the TiN layer is formed in lower amounts and is sectional, indicating that sufficient tunnelling current may not be established. This may be the reason for the semi-linear behaviour and higher specific contact resistance seen in the I-V curve of the Ti/Al contact. Such a case was also reported for the Au/Ni/Al/Ti/n-GaN ohmic contact by Greco et al [3].

In addition to contact resistance, the surface roughness of the contact is another important aspect in evaluating the quality of the ohmic contact. A surface with high roughness adversely affects the life and stability of the contact and reduces the edge sharpness. This can cause safety problems in high power devices and is an important problem in reducing the size of the device. The surfaces of as-deposited and annealed (850 °C 60 s) samples of Ti/Al and Ti/Al/Ti/Au contacts were analysed by AFM. While the rms roughness of the Ti/Al contact was 5.10 nm for the as-deposited sample, it increased to 36.23 nm as a result of the reactions during the annealing process. In the Ti/Al/Ti/Au contact, it increased from 3.66 nm to 8.17 nm. As can be seen in Fig. 3, semi-spherical bulges were observed in Ti/Al contact after RTA. A similar result was reported in the literature for Ti/Al/Ni/Au contacts after annealing at 900 °C. These bulges were also observed in TEM images and were found to consist of Al by EDX measurements. Since the RTA temperature (850 °C) is above the melting point of aluminium (600 °C), in the absence of second Ti layer and Au layer to bond Al, it melts during the annealing process and forms agglomerates on the contact surface.

4. Conclusions

By comparing Ti/Al/Ti/Au and Ti/Al contacts to AlGaN/GaN heterostructures, the effect of microstructure on ohmic contact formation and characteristics was investigated. The thickness and uniformity of the

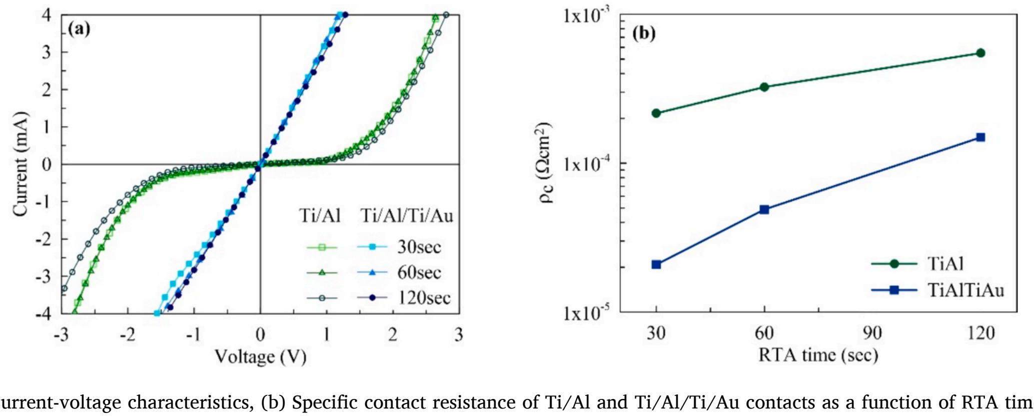
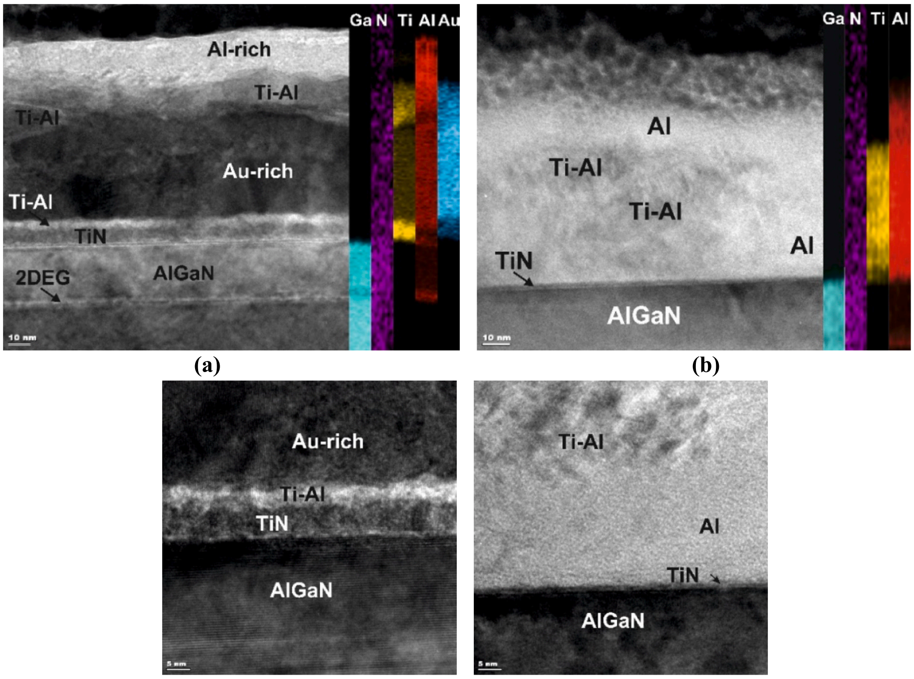


Fig. 1. (a) Current-voltage characteristics, (b) Specific contact resistance of Ti/Al and Ti/Al/Ti/Au contacts as a function of RTA time at 850 °C.



(a) (b)

(c) (d)

Fig. 2. Cross-sectional TEM images and elemental mappings of (a),(c) Ti/Al/Ti/Au and (b),(d) Ti/Al contact.

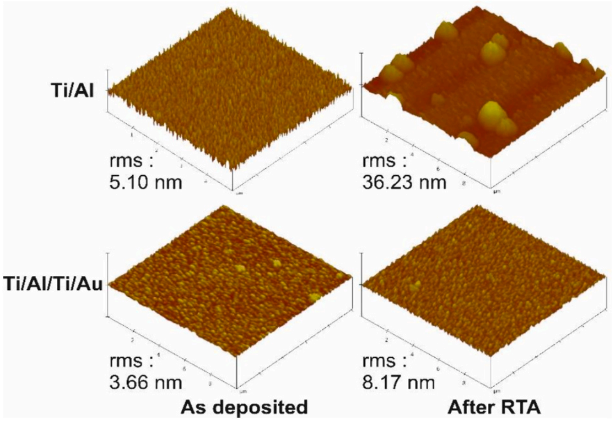


Fig. 3. AFM surface images and surface roughness analyses in 10x10 μm^2 area.

TiN layer formed at the metal–semiconductor interface during RTA were demonstrated to improve ohmic contact characteristics. The Ti/Al/Ti/Au contact with a 4 nm thick uniform TiN layer, exhibited superior ohmic contact behaviour than the Ti/Al contact with an excellent linear I-V curve and a specific contact resistance of $2.09\text{x}10^{-5}$ Ωcm^2. Moreover, with 8.17 nm rms, it has at least 4 times smoother surface than the Ti/Al contact. These results showed that the Ti/Al/Ti/Au multilayer contact scheme is an improvement in comparison to the Ti/Al double layer contact scheme in achieving lower contact resistance as well as higher reliability and uniformity of AlGaN/GaN HEMTs.

CRediT authorship contribution statement

Ayse Canbolat: Writing – original draft, Visualization, Data curation. **Abdullah Akkaya:** Validation, Methodology, Data curation. **Enise Ayyıldız:** Writing – review & editing, Supervision, Project administration.

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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