Structural characterization of V/Al/V/Au Ohmic contacts to n-type $Al_{0.4}Ga_{0.6}N$*

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(Received 17 July 2010; revised manuscript received 25 October 2010)

This paper investigates the temperature dependence of the specific resistance in annealed V/Al/V/Au (15 nm/85 nm/20 nm/95 nm) contacts on n-$Al_{0.4}Ga_{0.6}N$. Contacts annealed at 700 °C and higher temperatures show Ohmic behaviour. Annealing at 800 °C produces the lowest contact resistance. Samples annealed at 800 °C have been analysed by using cross-sectional transmission electron microscopy and an energy dispersive x-ray spectrum. Limited reaction depths are observed between V-based contacts and n-AlGaN. The VN grains are found to form in the contact layer of the annealed samples, which can be considered as the key to the successful formation of Ohmic contact. The contact layer adjacent to AlGaN material consists of V–Al–Au–N, AlN and AlAu alloys.

Keywords: Ohmic contact, vanadium, transmission electron microscopy, energy dispersive x-ray spectrum

PACS: 61.05.jh, 68.37.Lp, 61.72.uj, 73.40.Cg **DOI:** 10.1088/1674-1056/20/4/046101

1. Introduction

AlGaN material has generated great interest in the last decade because of its potential application in ultraviolet emission and detection devices.[1,2] The $Al_xGa_{1-x}N$ material forms a continuous and direct-band-gap alloy from 3.42 eV (GaN) to 6.2 eV (AlN). With a large band gap, high breakdown voltage, and high carrier mobility, high Al fraction AlGaN materials are excellent candidates for short wavelength optoelectrical devices. However, one of the limitations to the performance of these devices is the need for good Ohmic contacts with low resistance.

Recently, it has been reported that V-based contacts can produce lower specific contact resistance at lower annealing temperatures than traditional Ti-based contacts. The Ti/Al/X/Au contact is usually annealed above 850 °C to achieve Ohmic behaviour.[3−7] However, annealing at such a temperature often causes degradation in device performance.[8] The V-based metallizations have been reported recently to form good Ohmic contacts with n-AlGaN.[9] The V has a work function of 4.3 eV, which is close to n-GaN, and could react with N at 600 °C to form VN, which has a low work function of 3.56 eV.

A significant amount of work has been performed on V-based Ohmic contacts n-AlGaN. The interface between the metal contact layer and semiconductor layer after heat treatment has previously been investigated by glancing-angle x-ray diffraction,[10] Auger electron spectroscopy sputter depth profiling, and x-ray photoelectron spectroscopy.[11−14] Despite this, very little work on transmission electron microscopy (TEM) of V-based contacts to n-AlGaN bas been published. Mohney *et al.*[15] performed some TEM analysis and reported that V–Al–Au–N and Al–Au phases formed at the metal/AlGaN interface. In this article, TEM and energy dispersive x-ray (EDX) techniques have been used to investigate chemical information at the interface of a metal contact to nitride layer.

2. Experiment

The $Al_{0.4}Ga_{0.6}N$ layers used in this work were grown on sapphire by metal organic chemical-vapour deposition. The layer structure consists of an AlN buffer layer, a 1-μm unintentionally doped $Al_{0.4}Ga_{0.6}N$, and a 450-nm n-$Al_{0.4}Ga_{0.6}N$ with a carrier concentration of 3.7×10^{18} cm^{-3}.

Samples were ultrasonically cleaned for 10 min

*Project supported by the National Natural Science Foundation of China (Grant Nos. 10774001, 60736033, 60876041 and 60577030), National Basic Research Program of China (Grant Nos. 2006CB604908 and 2006CB921607), and the National Key Basic Research and Development Program of China (973 Project) (Grant No. TG2007CB307004).

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in acetone, 10 min in methanol, and rinsed in deionized water to remove organic contamination. The substrates were then etched in 50% HCl solution for 10 min to remove native oxides from the sample surface and then immediately loaded into a DC magnetron sputtering system. The composite metal layers V/Al/V/Au (15 nm/85 nm/20 nm/95 nm) were then deposited. After metallization, the samples were rapidly thermally annealed sequentially at various temperatures from 600 °C to 900 °C under N_2 ambience for 150 s in each case. Contact resistances were then measured using the conventional linear transmission line method by a parameter analyser (HP 4155A) at room temperature.

Detailed TEM analyses were carried out to investigate the microstructure of the contact layer. The cross-sectional TEM specimens were prepared by mechanical grinding and then by Ar^+ milling with 4.0 eV at 5° glancing incidence by a Gatan model 691 precision ion polishing system. The specimens were examined by using a JEOL-200CX TEM operated at 160 keV. The chemical composition of the contact layer was analysed by an EDX detection system.

3. Results and discussion

3.1. Electrical characterization

The variation of specific contact resistance as a function of annealing temperature ranging from 700 °C to 900 °C is shown in Fig. 1. As the annealing temperature increased, the specific contact resistance decreased until 800 °C. The lowest specific contact resistance of $3.4\times10^{-5}\ \Omega\cdot\mathrm{cm}^2$ was obtained when the V/Al/V/Au contact was annealed at 800 °C for 150 s. Further increase in annealing temperature resulted in overannealing. It is considered that the electrical characteristic is related to the interfacial phases and interfacial reaction of the contacts. In order to gain insights into the physical mechanism of Ohmic contact formation in the annealed V/Al/V/Au system, samples annealed at 800 °C were observed using TEM and EDX analyses.

3.2. Structure characterization

The electrical behaviour of the annealed contacts was correlated to the structural characteristics of the samples determined by means of TEM analyses. To obtain an insight into the structural properties of the contact layers after annealing, we perform bright field TEM images and EDX line profiles to obtain information about the phase formation and the chemical composition of the reacted layers.

Bright field cross-sectional TEM images prepared from V/Al/V/Au contact samples annealed at 800 °C are shown in Fig. 2. Analyses were performed on the samples annealed at 800 °C since it is the optimal annealing condition at which the lowest contact resistance is obtained. After annealing, the original contact metal layers are considerably intermixed, showing a complex grain structure with grain sizes up to 100 nm. The EDX line scans of the contact layer taken along the contact/AlGaN interface indicate that the V atoms have agglomerated into grains instead of an original continuous layer structure. The contact material between these grains comprises the Al–Au phase. The contact/nitride interface appears relatively smooth, indicating that a deep reaction depth is not necessary to form a low resistance Ohmic contact. This is in contrast to a Ti-based contact, where the Ti-rich consumption layer penetrated into the nitride semiconductor layer.[16]

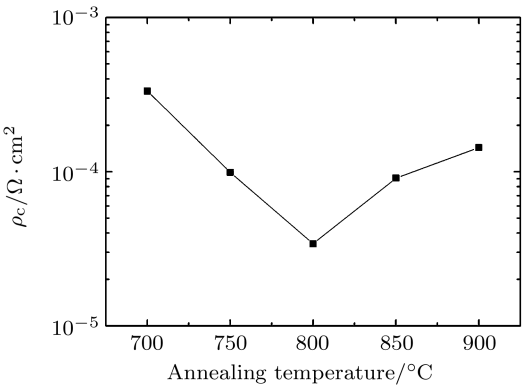


Fig. 1. Specific contact resistivity of V/Al/V/Au contacts at different annealing temperatures.

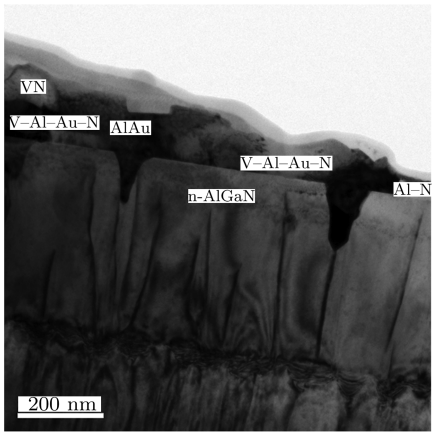
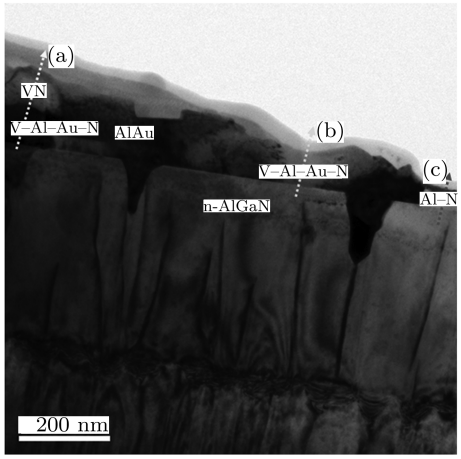
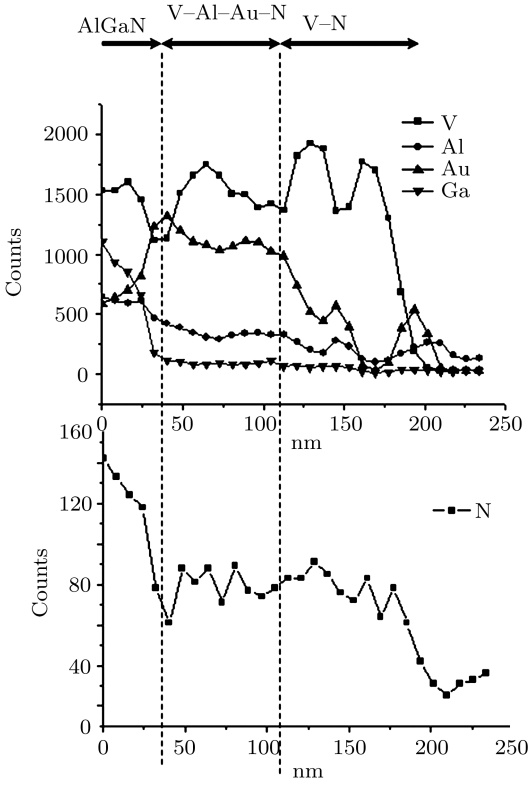


Fig. 2. The TEM cross section of V/Al/V/Au contact annealed at 800 °C on n-AlGaN.

Detailed EDX line profiles across cross sections obtained from V/Al/V/Au contact samples annealed at 800 °C can be seen in Fig. 3. Elemental analysis of the grains in Fig. 3(a) strongly indicates the formation of a well-defined V-based nitride phase, most probably VN. The presence of VN, with a low work function of 3.56 eV, would satisfy the requirement to form an Ohmic contact with n-AlGaN. Just beneath the VN grains, a nonuniform layer containing V, Al, and Au was detected in contact with the n-AlGaN. The occurrence of such a mixture is mainly related to the high diffusivity of gold atoms through the contact. Mohney *et al.*[17] reported the formation of V–Al–Au–N.



(a)



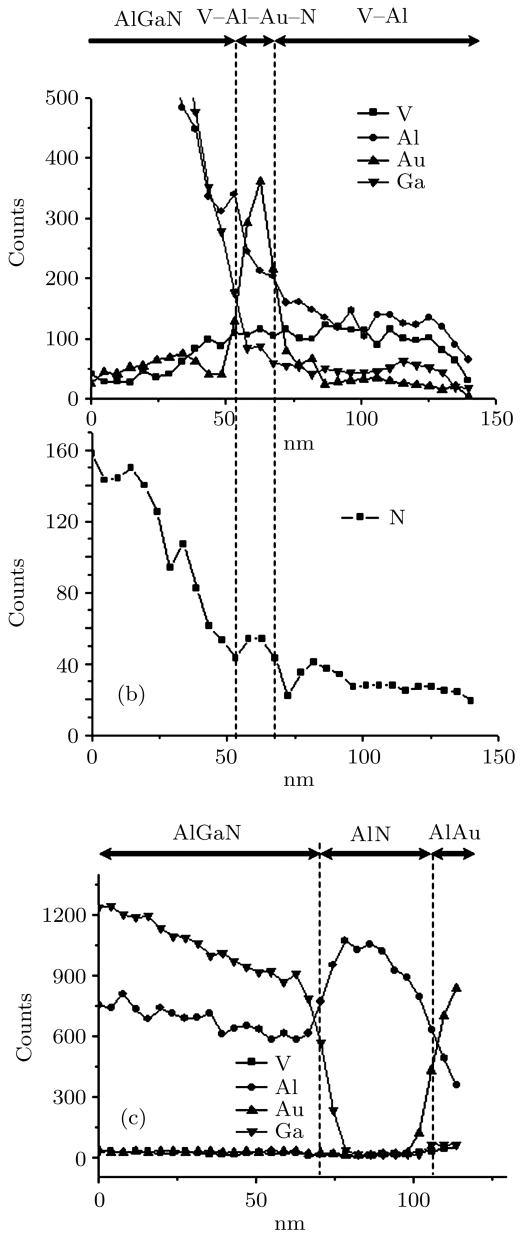


Fig. 3. The EDX elemental line scans taken across the contact layer in an AuVAlV/AlGaN contact annealed at 800 °C. The line scans are taken in the direction of the arrow, from AlGaN to the contact. (a) The location of VN-rich grains; (b) the location of V–Al–Au–N; (c) the location of Al–N.

In this work, clear evidence of the VN phase was obtained. Figure 3(b) also showed that the V–Al–Au–N phase was in contact with n-AlGaN. The material between arrow (a) and arrow (b) (Fig. 3) was identified as Al–Au. An Al-rich area was observed in Fig. 3(c), which was identified probably as AlN. However, the formation of AlN, with a band gap of 6.2 eV, might act as an electrical barrier layer. The formation of VN or AlN would be expected to result in the outdiffusion of nitrogen atoms from the adjacent AlGaN region, producing strongly n-type doped material. Neverthe-

less, the loss of nitrogen atoms from AlGaN was not detected by EDX analysis because of the low sensibility of the technique for the light elements. VN is metallic in nature and has a low work function. The formation of VN, accompanied by the generation of nitrogen vacancies, caused heavy doping of AlGaN, and hence the effective barrier was thinned. Therefore, the current conduction of tunneling effect was facilitated through the junction (see Fig. 4).

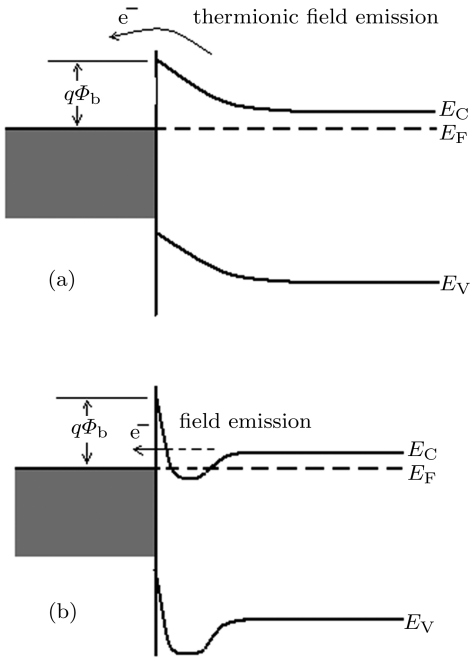


Fig. 4. Schematic energy-band diagram for the metal-semiconductor interface showing the band bending due to the presence of nitrogen vacancies: (a) conduction and valence bands without band bending; (b) conduction and valence bands with band bending due to the presence of nitrogen vacancies.

The EDX ananlysis showed that Au diffused through metal layers and made contact directly with AlGaN, indicating that the deposited V isolation layer was ineffective at stopping the indiffusion of Au at an annealing temperature of 800 °C. The region of contact adjacent to the AlGaN can be considered to consist of grains of V–Al–Au–N, AlN and a continuous layer of AlAu. It is indicated that electrons would preferentially flow from the metal layer to the AlGaN material through these VN grains. With a low work function, VN could be a more efficient carrier transport means than tunneling through the AlN and AlAu. Within the metal contact layer, no Ga signal was identified throughout the annealed samples, which again indicated a very limited reaction between the V-based contact and n-AlGaN. In our previous work on the V/Al/V/Au system, combining x-ray diffraction with TEM analyses, we showed that V atoms react with N and Al, forming $VN_{0.81}$ and VAl_{10} phases, and that Au atoms react with Al, forming an $AlAu_2$ phase.

4. Conclusion

Ohmic contacts with $Al_{0.4}Ga_{0.6}N$ material have been investigated by TEM. The variations in contact resistance as a function of annealing temperature have been established. In samples annealed at 800 °C, VN grains were observed with a lateral size of about 100 nm. The metal/semiconductor interface was relatively smooth, which indicated that consumption of the $Al_{0.4}Ga_{0.6}N$ was very limited for V-based contacts. The EDX analysis showed that the interfacial layer adjacent to AlGaN consisted of V–Al–Au–N, AlN, and AlAu alloys. It is indicated that the formation of the interfacial VN phase is the key to Ohmic behaviour in the contact.

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