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Microstructural characterisation of TiAlTiAu and TiAlPdAu ohmic contacts on AlGaN/GaN

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ABSTRACT: Ti/Al/Ti/Au and Ti/Al/Pd/Au contacts to AlGaN/GaN have been investigated to ascertain the effect of annealing temperature on the structural evolution of the contacts. Ti/Al/Ti/Au contacts become ohmic after rapid thermal annealing at 750°C or higher, corresponding to the formation of an interfacial TiN phase, with inclusions penetrating through the AlGaN layer observed after annealing at 950°C. The Pd layer is shown to be more efficient at inhibiting diffusion of Au to the interface than Ti. Ohmic behaviour was not seen with the Ti/Al/Pd/Au scheme. Either the presence of Au at the interface may improve ohmic behaviour, or the Ti:Al ratio is insufficient in this scheme.

1. INTRODUCTION

AlGaN/GaN heterostructure field effect transistors (HFETs) are attracting attention as high power, high frequency devices. The performance of these devices is limited by the need for reproducible ohmic contacts with low resistance and good thermal stability. It is also desirable to have contacts with a flat surface morphology for processing.

Contacts containing TiAl have become the conventional scheme for n-type GaN and AlGaN. TiAl contacts are believed to become ohmic by the formation of a Ti-nitride interfacial phase during annealing, which depletes N from the surface of the GaN to produce a highly n-type doped layer (Lin et al 1994, Ruvimov et al 1998). In view of the ease with which TiAl layers oxidise, multilayer schemes with Au as the surface layer and materials such as Ni, Pd or Ti acting as a barrier layer between the Au and TiAl layers have been used to obtain improved contacts (Cai et al 1998, Fan et al 1996, Mohammed et al 1996). However, a full understanding of the effect of annealing temperature on the structure of these multilayers and the resultant electrical behaviour is still required. In this work, the effect of annealing temperature on a TiAlTiAu contact to AlGaN/GaN is analysed, and compared to the structure of a TiAlPdAu contact.

2. EXPERIMENTAL

The HFET wafer structure consisted of 30nm of AlGaN (~25%) on 1.2 μm of GaN, grown on an (0001) sapphire substrate by metal organic chemical vapour deposition (MOCVD). Onto this was deposited the device contact structures, either 20nm Ti / 100nm Al / 60nm Ti / 300nm Au, or 10nm Ti / 220nm Al / 200nm Pd / 200nm Au. The TiAlTiAu contact was cleaved into separate sections to be rapid thermal annealed in flowing N_2 at a range of temperatures from

650°C to 950°C. The TiAlPdAu sample was rapid thermal annealed at 950°C. Cross sectional samples were prepared for conventional and high-resolution transmission electron microscopy, energy filtered TEM (EFTEM) and Energy Dispersive X-ray (EDX) analysis.

3. RESULTS AND DISCUSSION

Visual inspection showed that the colour of both TiAlTiAu and TiAlPdAu contact schemes altered from gold to silver-grey after annealing. Transmission Line Method (TLM) measurements showed that the TiAlTiAu contacts became ohmic after annealing at 750°C or higher, while the TiAlPdAu contact did not become ohmic at anneals up to 950°C.

Bright field imaging of the annealed TiAlTiAu contacts (Fig 1a-1c) showed that the layered material in the contact had mixed, resulting in an Au/intermetallic grain structure with grain sizes of up to 200 nm. The TiAlTiAu sample annealed at 850°C (Fig 1b) showed a thin interfacial region comprising small grains approximately 5-10nm wide, which was identified by EFTEM as being TiN (Fay et al 2001). This interfacial phase could not be observed with the TiAlTiAu sample annealed at 650°C (Fig 1a). The TiAlTiAu sample annealed at 950°C showed large inclusions penetrating through the AlGaN layer into the GaN layer below, up to a depth of 100 nm (Fig 1c). There appears to be an association between the size and depth of these inclusions and the presence of extended dislocations. A layer of small grains 10-20 nm wide was again identified between these inclusions and the contact metal. Bright field TEM of the TiAlPdAu sample annealed at 950°C (Fig. 1d) shows a greatly reduced intensity of inclusions compared to that seen in the TiAlTiAu sample annealed at the same temperature, despite a similar defect structure in the GaN/AlGaN layer. The structure of the contact is that of large Au and intermetallic grains in the bulk of the contact, with smaller grains 10-20 nm wide near an

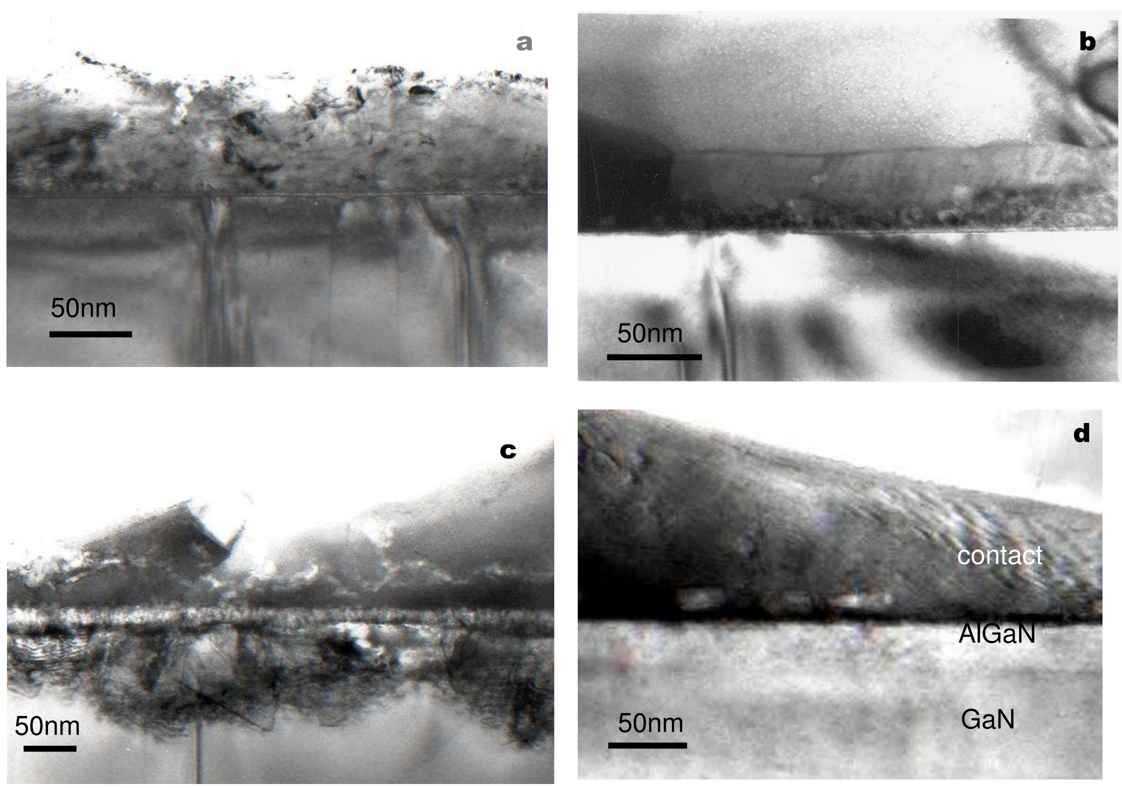


Fig. 1 – Bright field images of contacts to AlGaN/GaN a)-c) TiAlTiAu annealed at 650, 850 and 950°C respectively; d) TiAlPdAu annealed at 950°C

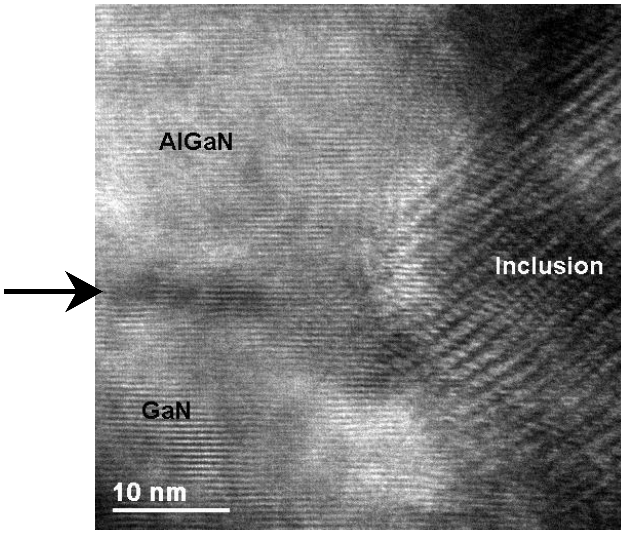
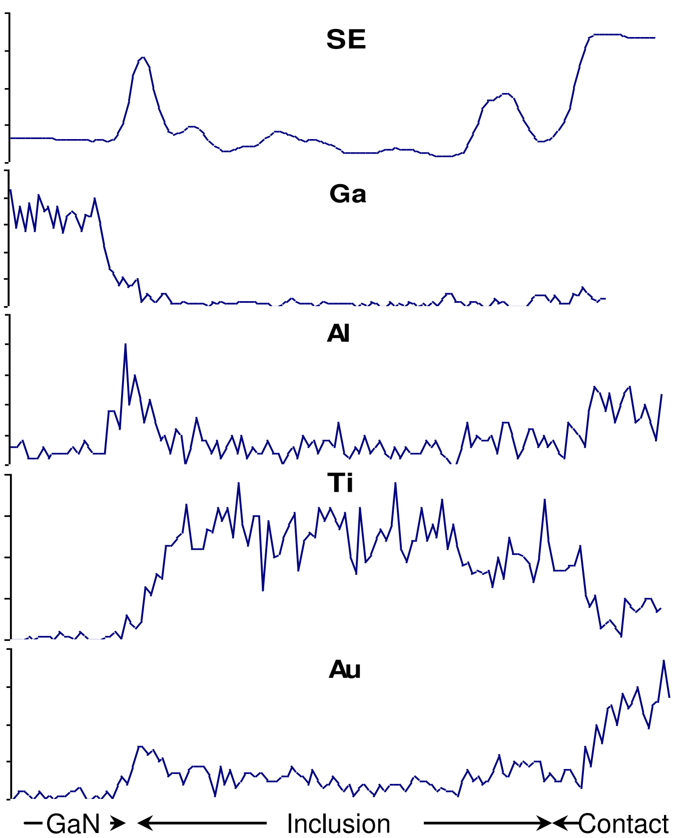


Fig. 2 HRTEM image of TiAlTiAu sample annealed at 950°C, showing the location of the 2DEG layer between the AlGaN and GaN (arrowed) and a TiN inclusion.

interfacial region ~5 nm thick. It was also observed that the surface morphology of this sample is smoother than with TiAlTiAu contacts annealed at the same temperature.

High resolution TEM performed on the TiAlTiAu sample annealed at 950°C demonstrated that the inclusions were crystalline, with a dominant lattice spacing of 0.25nm, consistent with {111} TiN. An HRTEM image, taken down the <11-20> axis shows the integrity of the AlGaN/GaN 2DEG interface appears to be unaffected beyond a few nm of the inclusion (Fig 2). The region of the inclusion in this image shows moiré fringes due to the superposition of the inclusion material with the AlGaN/GaN matrix.

An EDX line profile taken across the TiAlTiAu sample annealed at 950°C, from the GaN to the contact crossing an inclusion, shown in Fig. 3. It can be seen clearly that the Ga has been completely displaced in the region of the inclusion, with an Al and Au rich layer separating the TiN of the inclusion from the GaN layer. The layer of small grains between



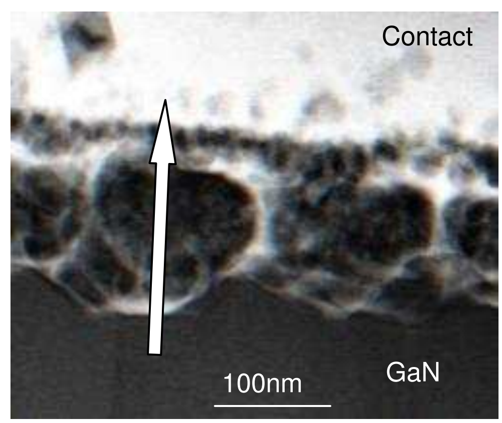


Fig. 3 EDX linescans taken across an inclusion within a TiAlTiAu sample annealed at 950°C, along the arrow indicated in the secondary electron image. The inclusion can be seen to be rich in Ti, with the Ga completely displaced. An Al/Au layer can be seen between the inclusion and GaN layer. The contact adjacent to this region can be seen to be rich in Al and Au.

the inclusion and contact was also identified by EDX spot spectra (not shown) as being a Ti-rich layer, most likely TiN, as there is no corresponding peak in Al or Au. The contact grains are also separated from the inclusions by a diffuse region richer in Al and Au.

Analysis of the TiAlTiAu sample annealed at 950°C concludes that the inclusions are TiN, which is a semi-metal with a low work function, and would therefore satisfy the requirement for ohmic contacting to n-type GaN. However, despite the significant change in interfacial morphology observed between TiAlTiAu samples annealed at 850°C and 950°C, the electrical behaviour showed only a slight improvement. This indicates that it is the formation of the interfacial TiN phase that is the key to ohmic behaviour in this contact. The TiAlPdAu contact annealed at 950°C showed a much lower density of inclusions than the TiAlTiAu sample. It is believed that the Al/Au diffusion front is essential to the formation of the inclusions, indicating that the Pd layer is more effective than the second Ti layer at inhibiting the diffusion of Au to the interfacial region. However, the lack of ohmic behaviour in the TiAlPdAu contact suggests that this sample contained inadequate activities of Ti at the interfacing to form adequate levels of interfacial TiN, which is necessary for the formation of an ohmic contact in these schemes.

4. CONCLUSIONS

Rapid thermal annealing temperatures of 750°C or higher are required to establish ohmic behaviour from TiAlTiAu contact schemes, corresponding to the formation of an interfacial TiN phase. At anneals of 950°C, large inclusions are formed that consume the AlGaN layer, but do not significantly affect the electrical characteristics of the layer. The TiAlPdAu scheme investigated produces a superior contact morphology, but does not become ohmic. The Pd is more effective at inhibiting the diffusion of Au to the contact/AlGaN interfacial region than the Ti barrier.

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