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Ohmic contact properties of magnetron sputtered Ti_3SiC_2 on *n*- and *p*-type 4H-silicon carbide

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Epitaxial Ti_3SiC_2 (0001) thin film contacts were grown on doped 4H-SiC (0001) using magnetron sputtering in an ultra high vacuum system. The specific contact resistance was investigated using linear transmission line measurements. Rapid thermal annealing at 950 °C for 1 min of as-deposited films yielded ohmic contacts to *n*-type SiC with contact resistances in the order of 10^{-4} Ω cm^2. Transmission electron microscopy shows that the interface between Ti_3SiC_2 and *n*-type SiC is atomically sharp with evidence of interfacial ordering after annealing. © *2011 American Institute of Physics*. [doi:10.1063/1.3549198]

SiC is an interesting semiconductor for high-power applications and high-temperature operation in harsh and corrosive environments due to its electrical and thermal properties. To achieve reliable, high quality devices, low resistance ohmic contacts to the SiC are necessary. For ohmic contact formation to *p*-type SiC, high-temperature annealed Ti and Al-containing contacts have been reported to give a low contact resistance.[1–4] The reasons why the contacts become ohmic after annealing are not completely understood and different explanations for the low contact resistance have been proposed. One suggestion is that the ohmic behavior arises from the formation of the ternary phase Ti_3SiC_2.[5,6] This has also been suggested for annealed Ti contacts on *n*-type 6H-SiC.[7,8] Ti_3SiC_2 is a material with an unusual combination of metallic properties such as high thermal and electrical conductivity with ceramic properties such as being resistant to oxidation and thermal shock.[9]

We have grown epitaxial Ti_3SiC_2 layers on both *n*- and *p*-type 4H-SiC using magnetron sputtering from three separate targets (see Refs. 9 and 10) and investigated the ohmic contact properties of the films. For this study, 4H-SiC wafers that are *n*-type, Si-face, 4° off axis, and manufactured by SiCrystal[11] were used as substrates. One wafer has a 1 μm thick $p-(4\times10^{15}\ \text{cm}^{-3})$ doped epitaxially grown SiC layer with a 0.8 μm $n-(1.5\times10^{19}\ \text{cm}^{-3})$ doped epitaxially grown SiC layer on top. The other wafer has a 1 μm thick $n-(1\times10^{15}\ \text{cm}^{-3})$ doped epitaxially grown SiC layer with a 0.8 μm $p-(5\times10^{18}\ \text{cm}^{-3})$ doped epitaxially grown SiC layer on top. The doping atoms used for the epilayers were Al and N for the *p*- and *n*-type, respectively, and were grown at the Institute Acreo.[12] Prior to deposition, the substrates were cleaned using acetone for 5 min and isopropanol for 5 min in an ultrasonic bath, and then blown dry in N_2 gas. The Ti_3SiC_2 films were deposited using dc magnetron cosputtering from high purity targets of Ti, C, and Si in an ultra high vacuum system. All depositions were carried out at a constant pressure of ~0.5 Pa in Ar discharge at 800 °C. Before deposition, the substrates were plasma etched for 30 min to remove the native surface oxide on the SiC. Mesa etching for isolation of the highly doped epitaxial top layer and definition of the contact pads for the linear transmission line model measurements (TLMs) was performed using a two-step inductively coupled plasma dry etching system with a 1 μm thick silicon dioxide etching mask. TLM structures consist of five contact pads (100 μm wide) separated by 5, 10, 15, 20, and 25 μm. The contacts were annealed using rapid thermal annealing at 950 °C for 1 min in an Ar atmosphere. Current-voltage (I-V) measurements were performed using a two-probe station connected to an HP4156A analyzer. All TLM measurements were performed in air. $\theta-2\theta$ X-ray diffraction (XRD) measurements on the as-deposited films were performed in a Philips XRD system with a Cu Kα X-ray source operating at 40 kV and 40 mA. Transmission electron microscopy (TEM) was performed using a Tecnai G2 TF20UT FEG Microscope.

Figure 1 shows a diffractogram of the as-deposited epitaxially grown Ti_3SiC_2, where, except for the SiC (004) peak from the substrate, only the 000ℓ peaks from the Ti_3SiC_2 can be seen. The SiC (004) overlaps with the TiC (111) peak and traces of intergrown TiC (111) layers were in fact observed in high-resolution TEM of this sample. The contacts were electrically characterized by current-voltage (I-V) and trans-

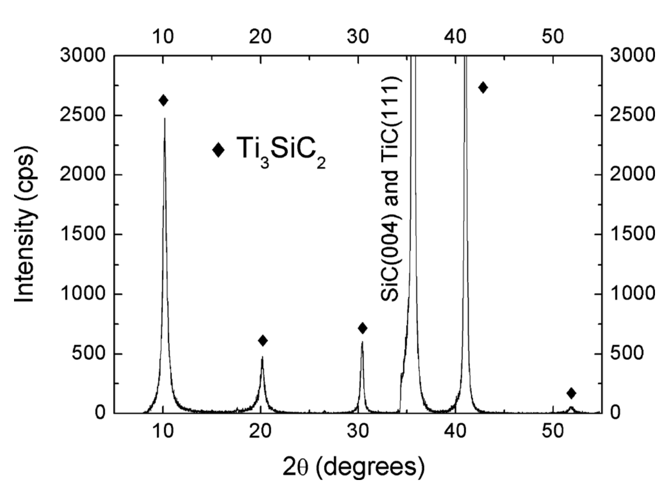

FIG. 1. X-ray diffractogram of epitaxial Ti_3SiC_2 on 4H-SiC.

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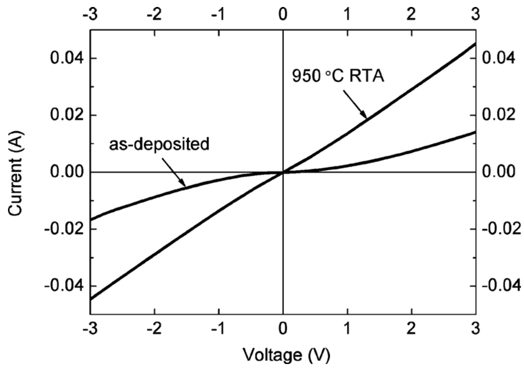

FIG. 2. I-V characteristics of the Ti_3SiC_2 contacts on n-type SiC before and after annealing.

mission line model measurements.[13] I-V measurements of the as-deposited contacts showed no ohmic behavior for the n- or the p-type SiC. Rapid thermal annealing at 950 °C was therefore performed, which resulted in the contacts to the n-type SiC becoming ohmic while no ohmic behavior was seen for the contacts on the p-type SiC.

Figure 2 shows the transition from non-ohmic to ohmic for the Ti_3SiC_2 contact on n-type SiC. The lowest specific contact resistance value obtained from the TLM measurements for the Ti_3SiC_2 contacts to the n-type SiC was $5 \times 10^{-4}\ \Omega\ cm^{-2}$. The interface between the n-type 4H-SiC and the Ti_3SiC_2 was investigated both for the as-deposited and the annealed contacts using TEM. Figures 3(a) and 3(b) display cross-sectional high-resolution TEM images from the interfaces of the as-deposited and the annealed contacts, respectively. The high-temperature annealed film has a more ordered interface where Ti_3SiC_2 is the dominant phase at the area near the interface, while the as-deposited film contains more defects and stacking faults.

The as-deposited Ti_3SiC_2 films on SiC did not yield ohmic contacts until after annealing was performed. The influence of high-temperature annealing on ohmic contact formation to SiC was investigated by Mohammad *et al.* using Pt and Pt/Si contacts.[14] They concluded that alterations in the SiC surface due to the annealing process, and not the phases formed, are primarily responsible for the ohmic behavior and suggest corresponding effects in other SiC contacts during high-temperature annealing. The nature of these changes is, however, unclear. Nevertheless, our results show that annealing is necessary to create an ohmic contact between the Ti_3SiC_2 and the SiC, and that the annealing process causes interfacial ordering.

The formation of ohmic contacts to p-type SiC is difficult due to its large work function, larger than 6 eV.[15] We did not see ohmic behavior for the as-deposited or annealed Ti_3SiC_2 contacts on p-type SiC. However, ohmic contact formation for high-temperature annealed Ti/Al-based contacts on p-type SiC with a doping level comparable to our substrates ($5 \times 10^{18}\ cm^{-3}$) has been reported.[2,4,6] In these studies, the main phase formed in the contacts was Ti_3SiC_2, but other phases such as Al_4C_3 and Al_3Ti were also present. Gao *et al.* investigated the role of Al-distribution, interface layers, and localized states in Ti/Al-based ohmic contacts on p-type 4H-SiC.[16] They found that the main role of Al in the contacts was to aid the formation of a liquid alloy that promotes the reaction between the SiC and the Ti. The work function of Ti_3SiC_2 was determined to be 5.07 eV ± 0.1 eV. This value

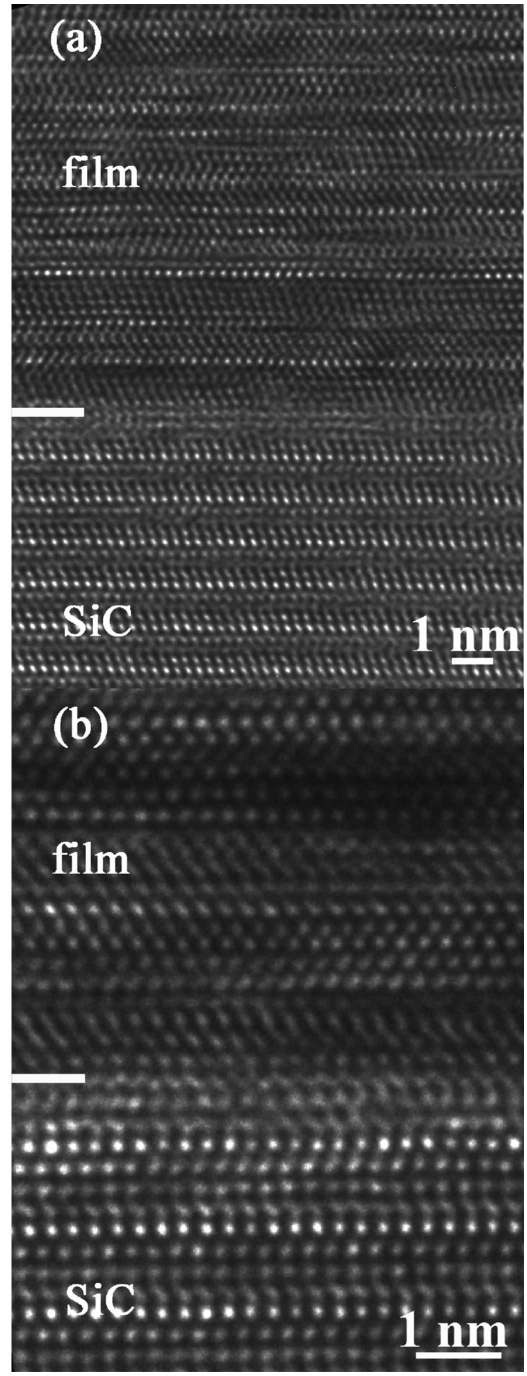

FIG. 3. Interface between the SiC and the Ti_3SiC_2 film in (a) as-deposited and (b) annealed states.

is intermediate between Ti and p-SiC giving a reduced Schottky barrier height. Reaction induced interfacial defect states in the near-interface SiC were also observed by Gao *et al.* and were believed to further reduce the barrier height and cause the ohmic contact formation. Further investigations by Wang *et al.* on the SiC/Ti_3SiC_2 interface after annealing of Ti/Al contacts suggest the emergence of interfacial C layers, which would reduce the Schottky barrier significantly.[17] The Ti_3SiC_2 contacts in this study were processed using a different synthesis route than for Ti/Al contacts, which might influence the non-formation of ohmic contacts to p-type SiC, possibly through differences in interfacial reactions/states. This, however, requires further investigations.

In summary, we have grown Ti_3SiC_2 films on both *n*- and *p*-type 4H-SiC using magnetron sputtering and studied the contact properties using TLM measurements. Ohmic contacts were achieved to the *n*-type SiC after a high-temperature anneal at 950 °C with a lowest specific contact resistance value of $5\times10^{-4}\ \Omega\ cm^{-2}$ while no ohmic behavior was seen for the contacts to *p*-type SiC. TEM showed interfacial ordering with an atomically sharp interface between the Ti_3SiC_2 and the *n*-type SiC after annealing.

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