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Thermally stable Ru-Si-O gate electrode for AlGaN/GaN HEMT

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We have developed the deposition and studied the electrical characteristics, microstructure and thermal reliability of Ru-based contacts on n-type GaN as well as on AlGaN/GaN HEMT heterostructure. Ru, RuO_2 and Ru-Si-O layers were deposited by reactive magnetron sputtering and annealed up to 900 °C. Amorphous, conducting $RuSiO_4$ contacts with their extremely low reverse currents and thermal stability up to 900 °C, show great potential for use as Schottky contacts to n-type GaN and gate electrodes for AlGaN/GaN HEMT in high temperature, high power applications.

1 Introduction

Reliable Schottky contacts for AlGaN/GaN high electron mobility transistor (HEMT) should use metallisation that is highly conductive, stable in contact with GaN, and capable to withstand treatments at elevated temperatures during device processing and further operation. Targeting high temperature applications we have chosen to study the properties of ruthenium based metallisations: elemental Ru, RuO_2 and Ru-Si-O. Recently several studies have demonstrated the applicability of oxidised Ru and RuO_2 as Schottky contact to n-GaN [1, 2]. Both Ru and RuO_2 are high melting point materials, characterised by low bulk resistivity and large work function. The feasibility of conducting, amorphous ternary Ru-Si-O material has been recently reported by Gasser et al. [3]. If thermally stable, the amorphous microstructure is likely to be the most effective in preventing interfacial reactions in the contact region.

In this paper we compared Ru, RuO_2 and Ru-Si-O Schottky contacts fabricated on n-GaN and AlGaN/GaN HEMT heterostructure. Special attention was paid to the deposition process, which was optimised in order to achieve low resistivity layers and good adhesion to the semiconductor substrate.

2 Experimental details

Thin Ru, RuO_2 and Ru-Si-O films were prepared by reactive magnetron sputtering in DC mode from either Ru (Ru and RuO_2 films) or Ru_1Si_1 (Ru-Si-O film) target in Ar-O plasma. The films were deposited

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on n-type GaN epilayers doped to 2-5x10^{17} cm^{-3} and undoped AlGaN/GaN heterostructures with 30 nm thick AlGaN film grown by MOCVD method on sapphire. Substrates were held at room temperature. Crucial point during the deposition was to optimise the O_2/Ar ratio and the working pressure with regard to the film resistivity and adhesion to the substrate. Film thickness ranged from 50 to 100 nm. The samples were annealed at temperatures up to 900 °C in either N_2 or O_2 flow. For I-V measurements conventional lift-off photolithography was applied. Ti/Al metallisation annealed at 800 °C was used as the ohmic contact. The resistivity of thin metallisation films deposited on semiinsulating GaN was measured using 4-point-probe. 2 MeV $^4He^+$ Rutherford backscattering spectrometry (RBS), secondary ion mass spectrometry (SIMS) and X-ray diffraction (XRD) with Fe K_α radiation were used to analyse the microstructure of the contacts before and after heat treatments, while apparent Schottky barrier height was extracted from I-V measurements. Such procedure enabled us to determine thermal stability of these contacts in terms of microstructure and electrical parameters.

3 Results and discussion

3.1 Resistivity and composition of Ru-based films

In this study the correlation between the resistivity and phase structure of Ru-based films was of primary concern. As deposited Ru films were polycrystalline. The resistivity of Ru film was 2.0x10^{-5} Ωcm and stabilised at a value 3.5x10^{-4} Ωcm at 20 % of oxygen. A plot of resistivity of Ru-O metallisation versus oxygen partial pressure is shown in Fig. 1. The total pressure during the deposition was 1x10^{-2} mbar. Figure 2a shows the RBS spectra of the corresponding Ru-O films. Changing the oxygen content form 20 to 50 % did not influence the reading. The atomic concentration of each element was calculated from RUMP simulation of RBS spectra (Fig. 2b). These showed that with only 20% of O_2 the RuO_2 structure was formed and the increase in oxygen's concentration did not change the situation much. It should be pointed out that the lower oxygen concentration resulted also in a better adhesion of the film. With the 50% of oxygen the films were peeling off. XRD analysis indicated that RuO_2 films were nanocrystalline. The resistivity of oxygen-free Ru-Si film was 4.5x10^{-4} Ωcm. It turned out that the resistivity of the Ru-Si-O after the initial increase, with the increase of O_2 content in the gas mixture, got saturated at the level of 1.3x10^{-2} Ωcm (Fig. 1). The depositions of Ru-Si-O films were made at a pressure 5x10^{-2} mbar. The films exhibited excellent adhesion to the substrate. Figures 2c and 2d show the results of RBS measurements and RUMP calculations for Ru-Si-O films. The composition of the oxygen-free film corresponds roughly to that of Ru_1Si_1 target. It can be clearly noticed that only with 10% of O_2 in the sputtering gas, the obtained film was actually $RuSiO_4$. The oxygen-saturated phase was XRD amorphous. Our results are in agreement with those of Gasser [3].

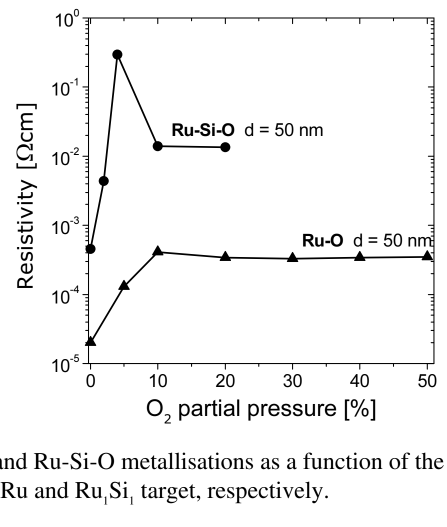

Fig. 1 The resistivity of Ru-O and Ru-Si-O metallisations as a function of the oxygen partial pressure during reactive sputter deposition from Ru and Ru_1Si_1 target, respectively.

3.2 Thermal stability

In order to investigate thermal stability of obtained films SIMS and resistivity measurements of annealed Ru/GaN, RuO_2/GaN, $RuSiO_4$/GaN structures were carried out. Furthermore I-V characteristics of (Ru, RuO_2, $RuSiO_4$)/AlGaN/GaN heterostructures were measured. Such approach enabled us to observe changes at a film/substrate interface and electrical parameters of the junction that took place while increasing the temperature. Figure 3 presents SIMS profiles of as-deposited and annealed contact structures. Ru/GaN and RuO_2/GaN structures demonstrated no signs of the interfacial reaction up to 800°C while $RuSiO_4$/GaN interface was stable up to 900 °C. The resistivity of Ru-based films displayed only small fluctuations, as shown in Fig. 4. Basing only on this information it can be stated the Ru-based films exhibit excellent thermal stability both in terms of microstructure and resistivity. In order to determine the suitability of these films for a gate electrode for AlGaN/GaN HEMT devices, I-V measurements were carried out (Fig. 5).

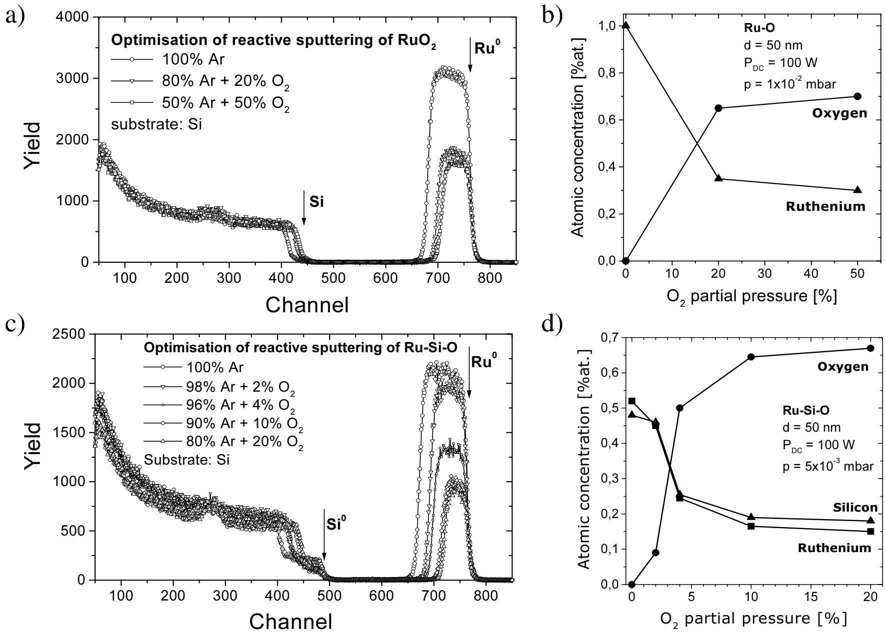

Fig. 2 RBS spectra and percent concentration of elements in Ru-O (a, b) and Ru-Si-O (c, d) films deposited on silicon.

3.3 Electrical properties

The apparent barrier heights were calculated from I-V characteristics and the results are presented in Table 1. The values of ϕ_B obtained in our work compare well with the values previously reported for Ru and RuO_2 metallisations [1]. The highest barrier height values were observed for RuO_2 contact for both GaN and AlGaN/GaN substrates, however the lowest leakage currents were obtained for $RuSiO_4$ contacts. On the another hand it should be noted that the reverse current of Ru/AlGaN/GaN and RuO_2/AlGaN/GaN structures was decreasing with increasing temperature. In case of $RuSiO_4$/AlGaN/GaN structure further improvement was observed after annealing at 700 °C. Generally, all three structures showed suitability of Ru-based films for Schottky contacts to AlGaN/GaN heterostructure. Of the investigated contacts, $RuSiO_4$ showed superior thermal stability, which combined with low resistivity and stability of the contact/substrate region at high temperatures, makes it the perfect choice for AlGaN/GaN HEMT devices targeting high-temperature applications.

Further investigations will focus on the optimisation of the semiconductor surface treatment to increase the effective Schottky barrier height.

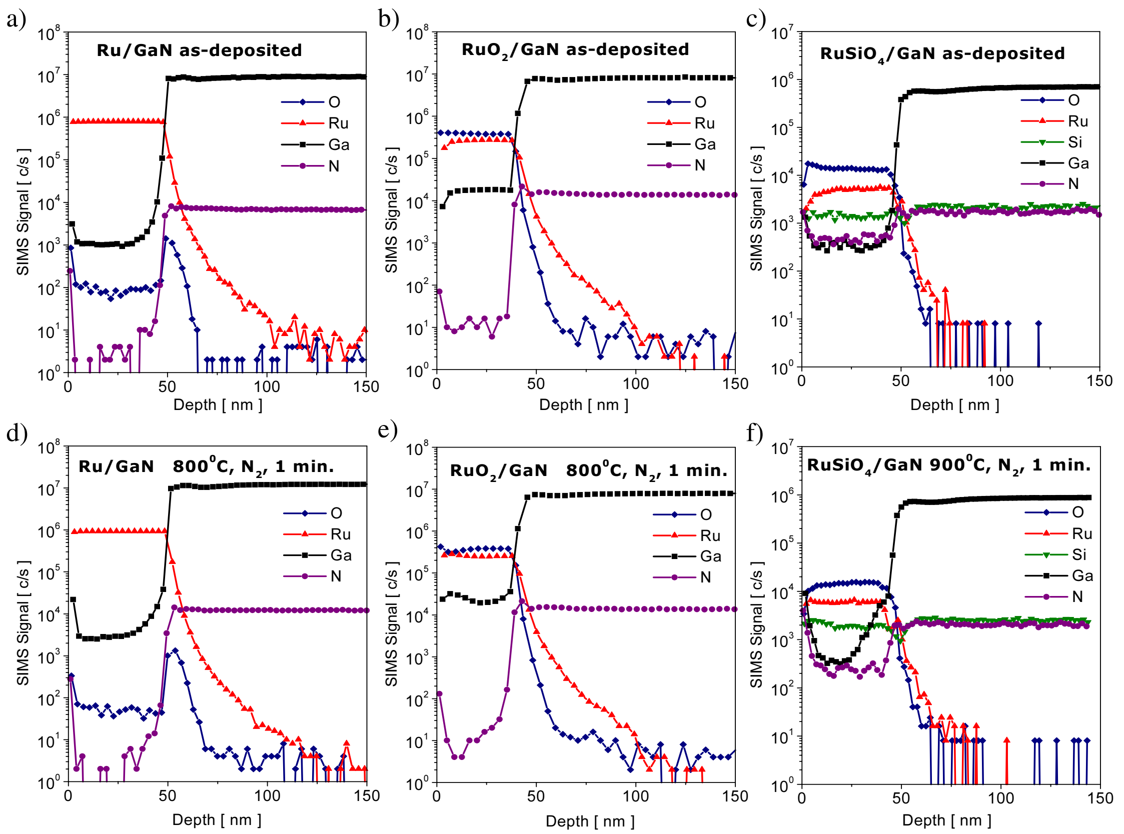

Fig. 3 SIMS depth profiles of Ru-based metallisations on GaN: a) as-deposited Ru film, b) as-deposited RuO_2 film, c) as-deposited $RuSiO_4$ film, d) Ru contact annealed at 800 °C, e) RuO_2 contact annealed at 800 °C, f) $RuSiO_4$ contact annealed at 900 °C.

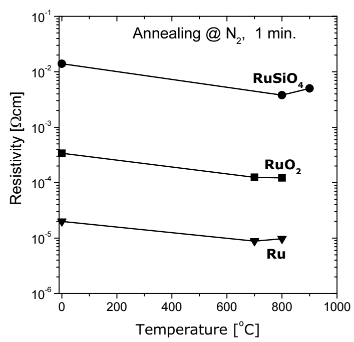

Fig. 4 The resistivity of Ru, RuO_2 and $RuSiO_4$ films as a function of annealing temperature.

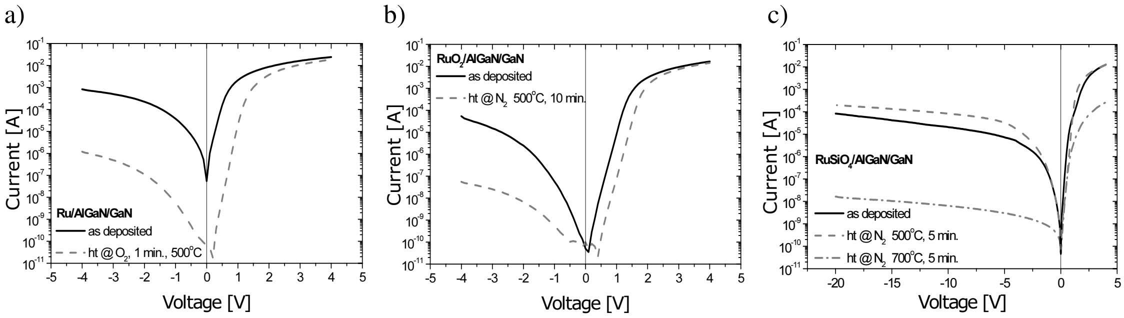

Fig. 5 I-V characteristics of Ru-based contacts to AlGaN/GaN HEMT heterostructures: a) Ru contact, b) RuO_2 contact and c) $RuSiO_4$ contact.

Table 1 The apparent Schottky barrier heights of Ru-based contacts to n-GaN and AlGaN/GaN structures.

Contact	The apparent ϕ_B [eV]
Ru/GaN	0.74
RuO_2/GaN	0.82
$RuSiO_4$/GaN	0.71
Ru/AlGaN/GaN	0.60
RuO_2/AlGaN/GaN	0.89
$RuSiO_4$/AlGaN/GaN	0.72

4 Conclusions

It has been demonstrated that Ru-based metallisations are thermally stable in contact with GaN-based compounds. In particular, amorphous, conducting $RuSiO_4$ films show extremely low reverse currents and thermal stability up to 900 °C, which makes them attractive candidates for thermally stable Schottky contacts to n-type GaN and gate electrodes for AlGaN/GaN HEMT in high power devices.

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