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OHMIC CONTACTS TO GaN BY SOLID-PHASE REGROWTH

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Ni/Si-based contact schemes based on the solid-phase regrowth process have been developed to form low-resistance ohmic contacts to GaN with a minimum contact resistivity of 1×10^{-3} Ω cm^2 and $\approx 1 \times 10^{-2}$ Ω cm^2 to GaN:Si ($n \approx 2 \times 10^{17}$ cm^{-3}) and GaN:Mg ($p \approx 3 \times 10^{17}$ cm^{-3}). The solid-phase regrowth process responsible for the ohmic contact formation was studied using X-ray diffraction, secondary ion mass spectrometry and Rutherford backscattering spectrometry.

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The formation of low-resistance ohmic contacts to GaN is particularly challenging, relative to other previously studied III–V compounds, because of its large band gap. Moreover, gallium nitride is more ionically bonded than its phosphide, arsenide and antimonide counterparts which implies that the electrical properties of metal/GaN contacts should be dominated by interfacial Schottky barrier height. Such behaviour has indeed been observed, and low resistance contacts to n-type material are possible by choosing metals with a work function approximately equal to GaN electron affinity, $\chi = 3.3$ eV [1]. The fabrication of an ohmic contact to p-GaN, however, would require a metal with work function equal to the sum of the semiconductor band gap and its electron affinity, whereas metal work functions are never much larger than 5 eV [2]. Since selection of a metal with adequate work function is unlikely to lead to ohmic contact to *p*-type GaN, one should consider methods for forming low-resistance contacts by increasing the carrier concentration in the semiconductor subcontact region. From among possible approaches we have chosen the processes based on solid-phase regrowth (SPR) mechanism. The method relies on the low-temperature formation, and further reaction driven-decomposition of intermediate ternary phases involving III–V compounds [3]. It has been extensively studied and successfully used to form non-spiking ohmic contacts to GaAs [4–9] and InP [10], however, no reports on its application to GaN have been published yet.

In this paper we report on the development of SPR process to form ohmic contact to both, *p*- and *n*-type GaN using Ni/Si contact scheme. Such scheme was chosen because (i) Ni is known to penetrate native oxides at the surface of GaN, and to form Ga–Ni and Ni–N compounds already at room temperature [11] (necessary for the first step of SPR reaction) and (ii) Si and Ni form thermally stable silicides [12] (necessary for the final step of SPR reaction). To produce ohmic contact to *p*-type GaN a thin layer of Mg is added into the contact structure, for *n*-type GaN, an additional layer of Si has been interposed in the Ni film.

Contacts under investigation have been made to (0001) oriented GaN epilayers grown by OMVPE on AlN buffer layers predeposited on 6H–SiC [13]. *n*-GaN epilayers were doped with Si to $n \approx 2 \times 10^{17}$ cm^{-3} ($\rho \approx 0.04$ Ω cm), *p*-GaN was doped with Mg and exhibited a net hole concentration of $p \approx 3 \times 10^{17}$ cm^{-3} ($\rho \approx 7$ Ω cm). Prior to metal deposition the surface of GaN was cleaned in organic solvents and by plasma ashering. Next, the samples were soaked in buffered HF, rinsed in H_2O DI, and finally dipped in NH_4OH:H_2O 1:10. The cleaning of the substrates was completed in the deposition chamber by heat treatment at 400°C for 10 min. The contact structures Ni(25 nm)/Si(8 nm)/Ni(25 nm)/Si(240 nm) and Ni(25 nm)/Mg(8 nm)/Ni(25 nm)/Si(240 nm) for *n*- and *p*-type GaN, respectively, were deposited by e-gun evaporation in a universal coating system with a base pressure of 1×10^{-7} torr. Heat treatments were performed in N_2 flow at temperatures up to 650°C for $3 \div 30$ min. During annealings the samples were protected by a piece of oxidized Si as a proximity cap.

The electrical properties of ohmic contacts were characterized by the transmission line method. Samples for these measurements were mesa etched by reactive ion etching with CCl_4/H_2 plasma [14]. The SPR process was analysed by a complementary use of secondary ion mass spectrometry (SIMS), Rutherford backscattering spectrometry (RBS), and X-ray diffraction (XRD).

The Ni/Si-based contacts exhibited ohmic behaviour after annealing at temperatures ranging from 400° to 600°C, with a minimum resistivity for an annealing time 30 min at 400°C. Contacts annealed below and above these temperatures exhibited nonlinear $I-V$ characteristics. The lowest contact resistivity obtained was $\approx 1 \times 10^{-3}$ Ω cm^2 on *n*-GaN, which compares favourably to our previous study using Ti/TiN contacts [14], and $\approx 1 \times 10^{-2}$ Ω cm^2 on *p*-type GaN.

Figures 1 and 2 show a SIMS depth profiles and RBS spectra of the as-deposited and annealed GaN/Ni/Mg/Ni/Si contacts. In order to evaluate the compositional changes in the contact region during annealing, the computer simulations of RBS spectra using RUMP code [15] were performed. SIMS and RBS analysis

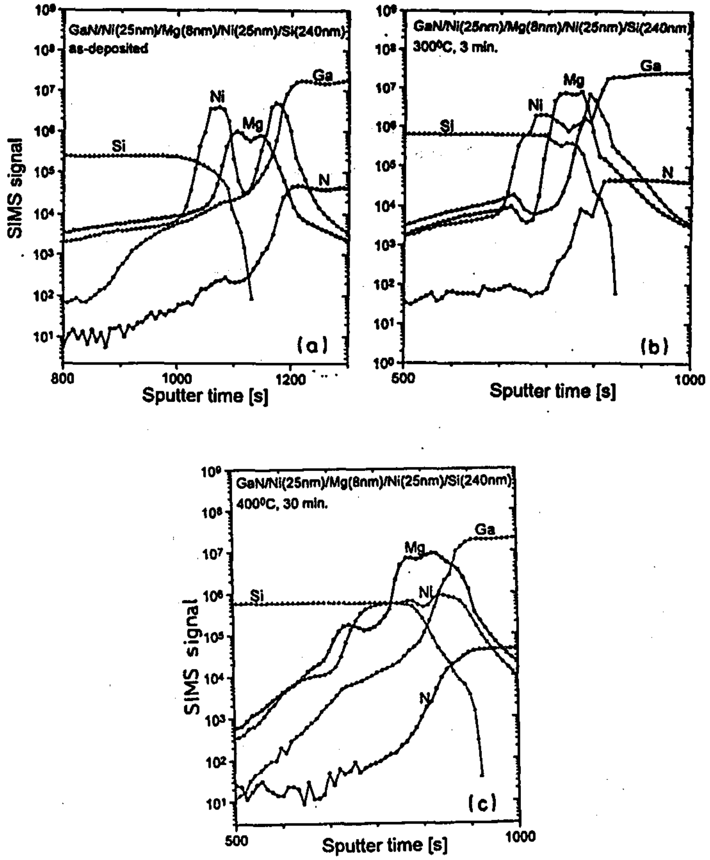

Fig. 1. SIMS in-depth profiles for GaN/Ni/Mg/Ni/Si contacts: (a) as-deposited, (b) annealed at 300°C, (c) annealed at 400°C.

indicate that in the unprocessed metallization a limited solid state reaction takes place between Ni and GaN, leading to the formation of about 10 nm thick Ni_2GaN phase. Also a *ca.* 15 nm thick Ni_2Si film was detected at the interface between upper Ni layer and Si. The XRD pattern showed Ni reflections only, indicating that as-deposited Ni was polycrystalline with ⟨001⟩ preferred orientation, whereas Si layer was amorphous. After annealing at 300°C, the SIMS profiles of the first Ni layer, Ga and N, as well as the profiles of the upper Ni film and Si, clearly coincide indicating the formation of Ni–GaN and Ni–Si phases, respectively. These two phases are separated by Mg layer, which acts as a diffusion barrier to reaction at both interfaces. Ni_2Si phase was found to show a preferred orientation ⟨011⟩. Upon annealing at 400°C, which is necessary to form an ohmic contact, the Ni signal at the Ni/GaN interface decreases. This could be a hint that the decomposition of the Ni_2GaN phase took place, and a regrown layer of GaN doped with Mg was formed. The upper Ni layer has reacted with Si to form an about 30 nm thick NiSi compound. Annealing at higher temperatures enhances the decomposition of GaN which is evidenced by the presence of few percent of Ga in the Si film. This

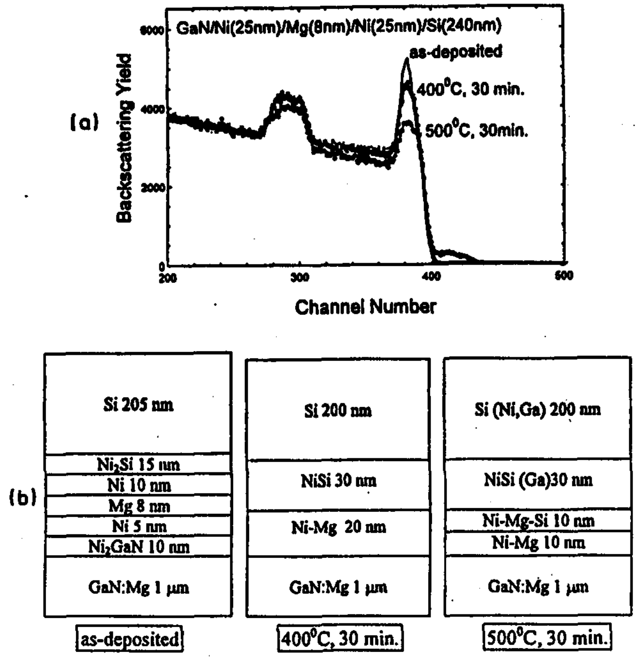

Fig. 2. (a) RBS spectra from as-deposited and annealed at 400°C and 500°C GaN/Ni/Mg/Ni/Si contacts, (b) schematic representation of the layer composition and thickness evaluated through the RUMP analysis.

thermally activated decomposition of the semiconductor is very likely the cause of the degradation of ohmic contact properties at temperatures exceeding 600°C. Microstructural changes which occur during annealing are summarized in Fig. 2b.

In summary, we have presented a novel way of fabricating ohmic contacts to n-type and p-type GaN using the Ni/Si-based metallization scheme. Low contact resistivities have been achieved by adding the proper dopant interlayer into the contact structure and heat treatment at 400°C for 30 min. The obtained results prove that the mechanism responsible for the ohmic contact formation of these contacts is associated with the solid-phase regrowth of a highly doped semiconductor layer, as a result of the decomposition of a ternary phase formed during the early stage of annealing.

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