Ni/Si-BASED CONTACTS TO GaN: THERMALLY ACTIVATED STRUCTURAL TRANSFORMATIONS LEADING TO OHMIC BEHAVIOR

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ABSTRACT

Structural transformations in Ni/Si-based contacts to GaN occurring under heat treatment have been studied using transmission electron microscopy and secondary ion mass spectrometry. Transition from non-ohmic to ohmic behavior correlates with reaction between Ni and Si, and decomposition of the initially formed interfacial Ni:Ga:N layer. Transport of dopant atoms from metallization into GaN testifies in favour of the SPR process of ohmic contact formation

INTRODUCTION

One of the key problems in GaN-based devices is a poor quality of ohmic contacts to p-GaN. The commonly adopted procedure for making ohmic contacts involves the use of high-work-function metallization schemes. These contacts convert from Schottky to ohmic-like after annealing, yielding resistivities of about $10^{-2}\Omega cm^2$ [1].

In order to reduce the contact resistivity, procedures enhancing the concentration of the active dopant in the semiconductor superficial region should be considered. To achieve that, we have adopted the idea of Sands et al. [2] of the incorporation of a dopant into the subcontact region by solid-state dissolution and subsequent regrowth (SPR). We have used Ni/Si metallization, with Mg as a dopant to produce contacts to p-GaN. For n-GaN, Si was the intended donor dopant. It has been shown that these contacts became ohmic after annealing at temperatures ranging from 400 to 600^0C, with resistivity of ~ $1*10^{-3}\Omega cm^2$ on p-type GaN with hole concentration $3*10^{17}$ cm^{-3} [3].

In order to further elucidate structural changes that take place during the formation of ohmic contacts, a study of the microstructure of Ni/Si-based contacts has been performed. We have used transmission electron microscopy (TEM) methods and SIMS. The high spatial resolution of TEM provides details about the morphology of metal/semiconductor interfaces, phase compositions and crystallographic relationships in the contact region. SIMS was applied to probe the elemental depth profiles. The question of dissimilarities in the behavior of p-type and n-type metallizations during the formation of ohmic contacts has been of special concern.

EXPERIMENTAL PROCEDURE

Contacts under investigation have been made to (0001) oriented GaN epilayers, 1-2 μm thick, grown via organometallic vapour phase epitaxy on AlN buffer layers predeposited on 6H-

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SiC substrates [4]. Prior to metal deposition, the samples were etched in buffered HF and in $NH_4OH:H_2O$ (1:10). The cleaning was finished in the deposition chamber by heat treatment at 400^0C for 10 min., under UHV conditions, for thermal desorption of hydrocarbon contaminants. The metallization in the form of sandwich structures Ni/Mg/Ni/Si and Ni/Si/Ni/Si for p- and n-type GaN, respectively, was deposited by e-beam evaporation. The thickness of consecutive metallization films was 25 nm/8 nm/25 nm/240 nm.

In view of a high thermal stability of GaN, contacts were fabricated in a two-step process. The first layer of nickel was evaporated onto the substrate held at 350^0C, then the sample was cooled down to room temperature, and the deposition of the metallization was completed. Finally, heat treatment was carried out in flowing N_2, at temperatures 200-400^0C for 30 min.

The microstructure of contacts was investigated by cross-sectional transmission electron microscopy (XTEM) and high resolution imaging (HREM) combined with energy dispersive x-ray spectroscopy (EDX). TEM observations were performed using a JEOL JEM 3010 microscope operating at 300 keV. A microprobe beam size of ~10 nm was used for EDX analysis.

SIMS profiling was performed in a Cameca 6F instrument with a caesium primary ion beam and detection of CsM_i^+ secondary cluster ions, which enabled the analysis with reduced matrix effects. To follow the thermally activated displacement of nickel and magnesium atoms relative to the contact interface in contacts to p-GaN, Ni-Ga and Mg-Ga cluster ions were analyzed as well. To examine the interaction between GaN and nickel in as-deposited samples, the Ni-Ga-N complex was also monitored with negative secondaries.

RESULTS

TEM micrographs of as-deposited contacts to p-and n-type GaN are presented in Fig.1(a) and Fig.2(a). Both as-deposited contacts consist of four distinct layers. In both contacts the upper Si layers are amorphous, and the intermediate Ni films are polycrystalline. No sign of reaction between these layers was observed.

The high resolution micrographs of metal/semiconductor interfaces are shown in Fig.1(b) and Fig.2(b). In p-type metallization, the Mg film is polycrystalline and, as proved by EDX analysis, accommodates some amount of Ni, while in n-type contacts, a thin film of Si in-between Ni layers, is amorphous.

In both contacts the layer adjacent to GaN is very uniform, 20-25 nm thick, and crystalline in nature. Fourier transforms of the lattice fringes are consistent with a face-centred cubic phase with lattice parameter a=0.341 nm, which, within the resolution of our measurements, suggests Ni. In our previous publication [3] we speculated on the formation of a highly textured Ni_3Ga_2 phase. This work gives evidence for the presence of nickel. Because of the small lattice expansion for the Ni-Ga and Ni-N solid solutions [5], the incorporation of a few atomic percent of Ga and N into the Ni film is below the detection limit of the applied method.

No oxide at metal/semiconductor interface was observed.

The progress of the contact reaction, as registered by SIMS, is shown in Fig.3. SIMS analysis reveals evidence for the expected interaction in as-deposited contacts between Ni and semiconductor. The Ni-Ga cluster peak, Fig.3.(a), and Ni-Ga-N complex, Fig.3.(b), apparently coincide with the superficial region of GaN.

Annealing at 350^0C, which is 50^0C below the onset of the ohmic behavior, causes migration of Mg towards the contact interface and movement of Ni in the opposite direction, Fig.3.(c). This trend is preserved after annealing at 400^0C. The concentration of Mg in the interfacial layer has further increased, while the position of Ni, which now forms only one distinct layer, coincides with that of Si, Fig.3(d).

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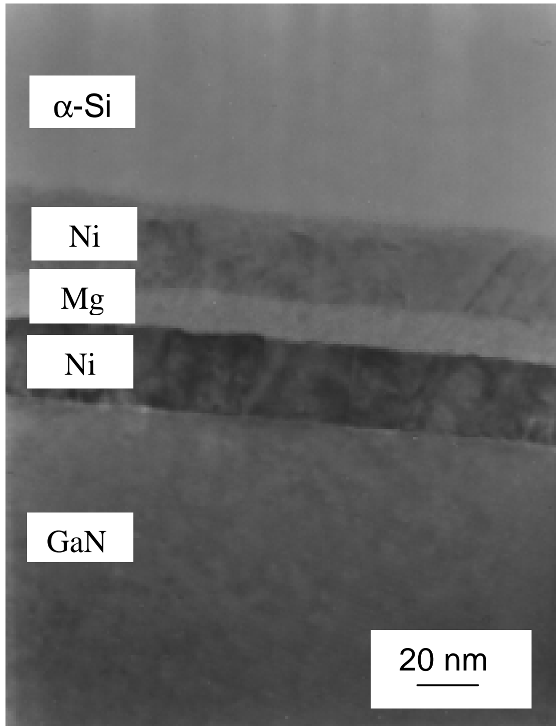

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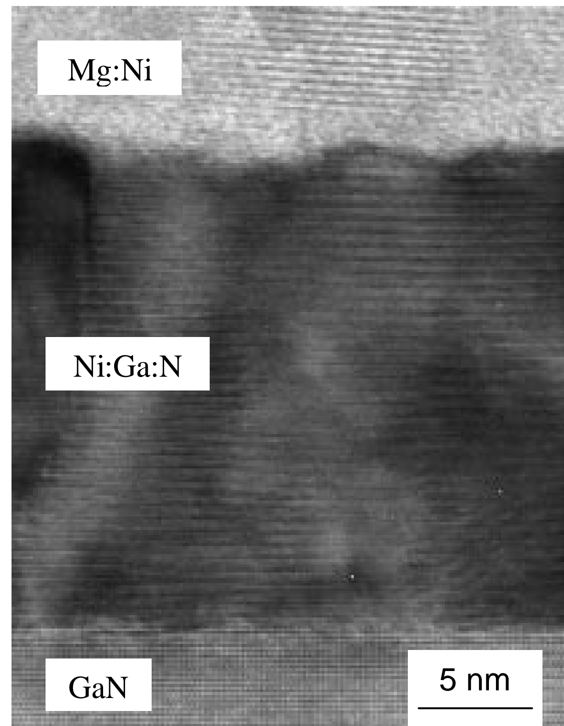

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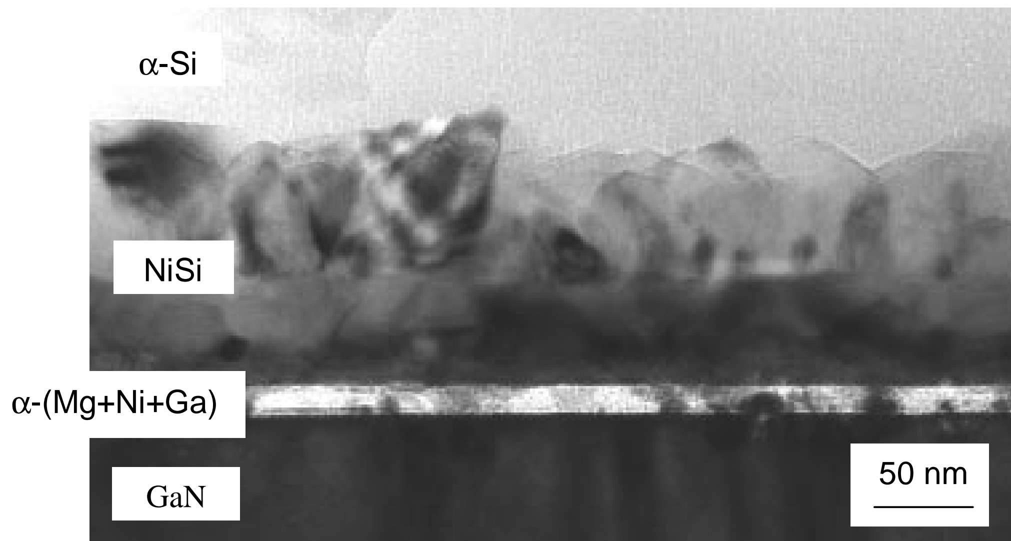

Fig. 1. XTEM micrographs of p-GaN/Ni/Mg/Ni/Si contacts:
a) as-deposited contact, b) HREM lattice image of the interface of the as-deposited contact, c) contact annealed at 400°C.

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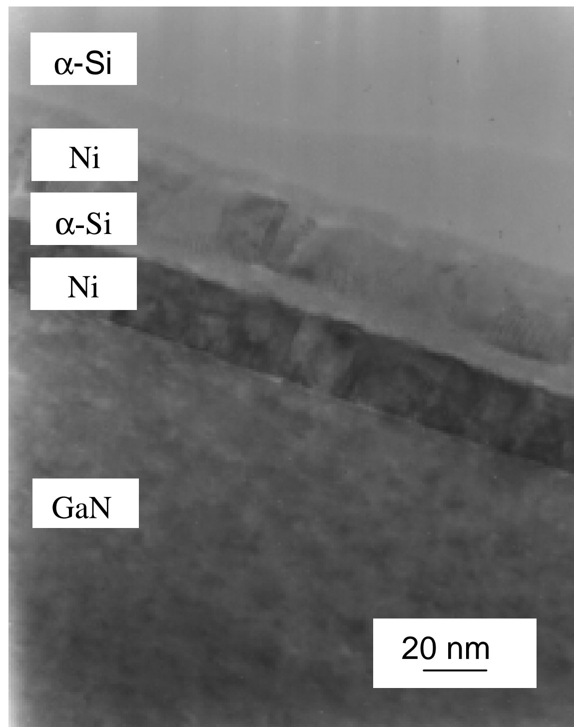

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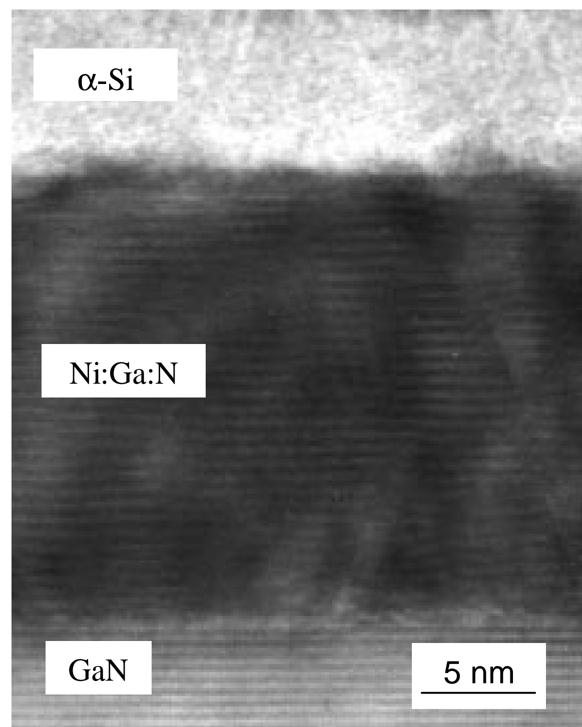

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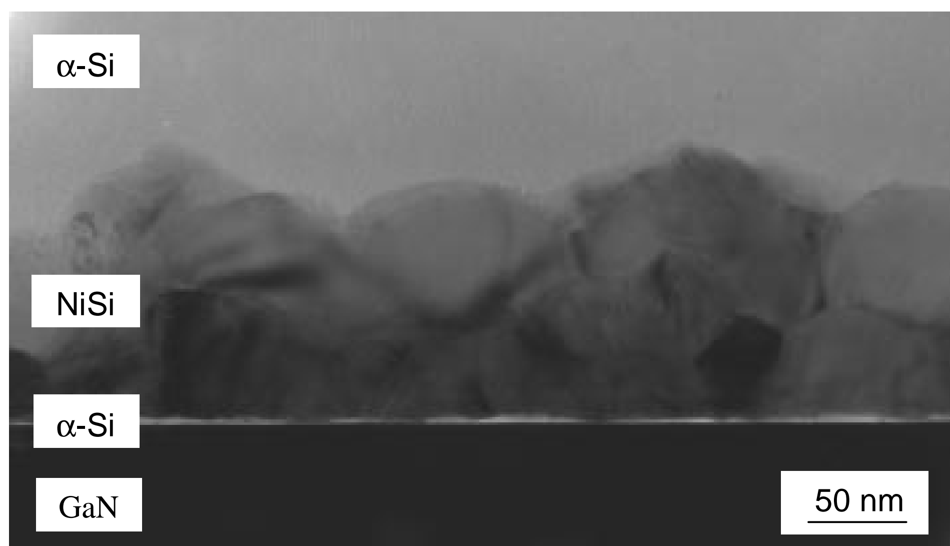

Fig. 2. XTEM micrographs of n-GaN/Ni/Si/Ni/Si contacts:
a) as-deposited contact, b) HREM lattice image of the interface of the as-deposited contact, c) contact annealed at 400°C.

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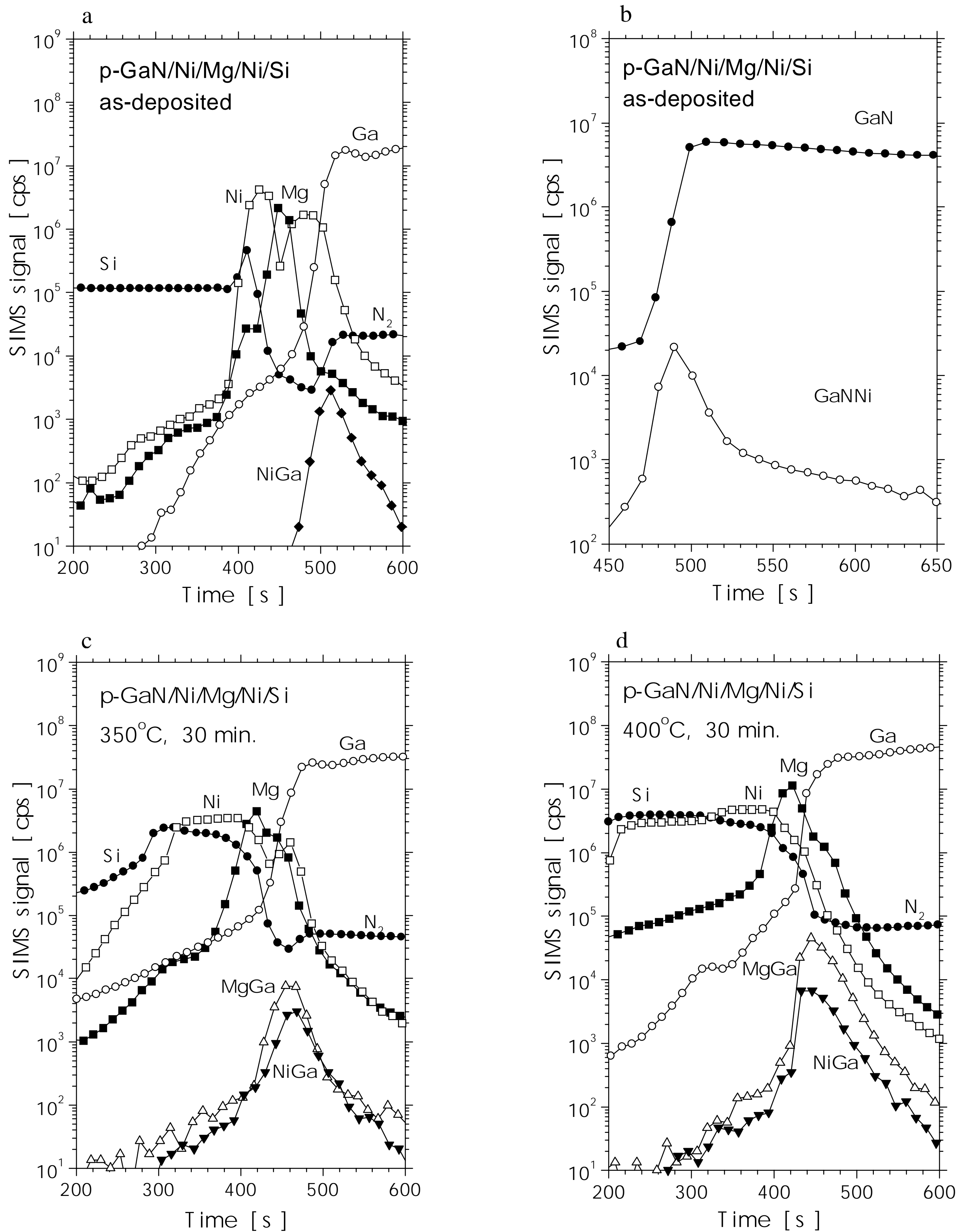

Fig. 3. SIMS in-depth profiles for p-GaN/Ni/Mg/Ni/Si contacts:
a) and b) as-deposited contact - profiles obtained with positive and negative secondary ions, respectively, c) annealed at 350°C, d) annealed at 400°C.

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The microstructures of contacts after annealing at 400^0C for 30 min. are presented in Fig.1(c) and Fig.2(c). In both contacts, amorphous planar interlayers, ~10 nm thick, are formed along the interface separating the semiconductor and the metallization. Careful EDX analysis revealed that in p-type contact this layer contains Mg, and some amount of Ni and Ga. Small crystalline voids of Ni are present throughout this film. In the n-type contact, Si is the only component of the interfacial film. The main constituent of each contact consist of nickel silicide. Excess of unreacted amorphous Si is detected in the outermost layer. The contact interfaces are sharp and abrupt.

DISCUSSION AND CONCLUSIONS

From the experimental observations of two Ni/Si-based contacts to GaN some common structural transformations are apparent. During the deposition, Ni reacts with GaN and forms a highly ordered Ni layer containing some amount of Ga and N. This reaction provides a very good oxide-free interface. Upon annealing the interfacial film decomposes, and Ni is transported toward the outer Si layer. At the same time, the dopant atoms (Mg or Si) move in the direction of the semiconductor substrate and finally form a continuous film at the interface.

As for electrical properties, the transition from non-ohmic to ohmic behavior in GaN/NiSi contact system takes place when the initial interface interlayer Ni:Ga:N decomposes as a result of Si-Ni reaction. The NiSi phase is not in direct contact with GaN when the contact become ohmic, so it can not be responsible for the ohmic behavior. On the other hand, the presence of Mg in the superficial film of the semiconductor, in the applied temperature range, can not be explained in terms of diffusion. The contact reaction is probably accompanied by a regrowth of the decomposed volume of the semiconductor. Since the semiconductor surface layer reacted with Ni is very thin, the observed ohmic behavior must be due to a few monolayers thick regrown GaN film. The growth of an amorphous layer at the surface of GaN could lower the barrier height across the metal/semiconductor interface, and thus facilitate the formation of the low-resistance contact. The interface of Ni/Si-based contacts to GaN appears to be sharp as opposed to a continuous diffuse interface, characteristic of the presently used alloyed contacts. In terms of electronic properties, interface and surface morphologies, the Ni/Si contact scheme appears to be promising for device applications.

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