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Transmission electron microscopy assessment of the Si enhancement of Ti/Al/Ni/Au Ohmic contacts to undoped AlGaN/GaN heterostructures

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The microstructure of Si/Ti/Al/Ni/Au was investigated using transmission electron microscopy and energy dispersive x-ray spectroscopy. The dependence of the contact resistance on the silicon layer thickness and the temperature was correlated to the microstructure of the alloyed contacts. The enhancement of the contact resistance by inserting a 30 Å thick Si layer under the Ti/Al/Ni/Au metallization was attributed to diffusion of the contact into the AlGaN layer. Increasing the Si thickness and or the temperature resulted in the formation of Gold (Au)-based silicides, which prevent the formation of low interfacial TiN or AlN layers. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2218262]

I. INTRODUCTION

AlGaN/GaN high electron mobility transistors (HEMTs) have demonstrated excellent performance[1–5] for microwave, high power, and high temperature applications due to the remarkable electrical and physical properties of the III-nitride semiconductors and the AlGaN/GaN heterojunction.[6] However, high performance microwave and power devices for such applications rely on low resistance Ohmic contacts, which directly influence the knee voltage, transconductance, output current density, and resistive heating.[7]

Since the source and drain Ohmic contacts are formed at the top of the AlGaN/GaN epistructure in a HEMT, extensive research has been carried out on developing reliable and low resistance Ohmic contacts to AlGaN/GaN heterostures. Most of low resistance Ohmic contacts to AlGaN or AlGaN/GaN structure have been obtained using a Ti/Al-based metallization, with a Ni,[8] Ti,[9] Pd,[10] Pt,[11] Cu,[12] or Mo (Ref. 13) presumed diffusion barrier overlayer, followed by a Au deposition to reduce the sheet resistance of the contact and limit the oxidation.

Desmaris *et al.*[14] demonstrated further enhancement of the Ti/Al/Ni/Au alloyed Ohmic contacts by inserting a thin Si (30 Å) between the four-layer metallization and the semiconductor, without the need of extra process steps such as regrowth,[15] implantation,[16] plasma preetching,[17] adding an *n*-GaN cap layer,[18] or annealing prior to metallization.[19] Contact resistance of less than 0.25 Ω mm was obtained on undoped AlGaN/GaN structure. However, the exact role of Silicon for the enhancement of the Ohmic contact was undefined. Youn and Kang,[12] observed a similar enhancement of Ti/Al/Cu/Au Ohmic contacts to Si-doped AlGaN/GaN heterostructures. This was attributed to a local increase of the doping in the subcontact AlGaN region and the reduction of the potential offset at the interface due to the formation of a Al–Ti–Si–N intermetallic layer. Recently, Mohammed *et al.*,[20] using a Ti/Si/Al/Si/Mo/Au metallization scheme attributed mainly the Si enhancement of the contact resistance to the formation of an Al–Ti–Si–N intermetallic layer based on Auger electron spectrometry; questioning the occurrence of the local diffusion induced Si-doping mechanism. However, in their study Si was not directly deposited in contact to the semiconductor.

In this work, we investigate the microstructure of Si/Ti/Al/Ni/Au Ohmic contacts to undoped AlGaN/GaN heterostructure, by means of transmission electron microscopy (TEM) and energy dispersive x-ray spectroscopy (EDX), in order to elucidate the role of silicon in the

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enhancement of the contact resistance and investigate its dependence on the silicon layer thickness and annealing temperature.

II. EXPERIMENTAL DETAILS

The AlGaN/GaN heterostructure was grown on sapphire by rf microdevices using metal-organic chemical-vapor deposition. The HEMT structure consisted of a 1 μm thick undoped GaN buffer layer followed by 25 nm undoped $Al_{0.29}Ga_{0.71}N$. The sheet carrier concentration and electron mobility obtained by Hall measurements were $1.2 \times 10^{13}\ cm^{-2}$ and $1100\ cm^2/V\ s$, respectively. Prior to processing, organic contaminants were removed in hot solvents before cleaning the samples using standard RCA methods.

Mesas were formed using a chlorine based inductively coupled plasma reactive ion etching (ICP-RIE) to isolate the active areas previous to contact deposition. Linear transfer length measurements (TLMs) test structures were later patterned using photolithography. To eliminate surface oxide buildup, the samples were dipped into a buffered oxide etchant solution immediately before depositing the Ohmic contacts by electron beam evaporation and lifted-off to form a TLM patterns with spacings of 4, 8, 12, 16, 20, 25, and 30 μm. Two silicon layers of different thickness were deposited (30 and 90 Å) under the same Ti/Al/Ni/Au multilayer. A third sample without any silicon layer was also processed for reference. The samples were diced before one sample of each Si thickness was annealed at the same time in a N_2 atmosphere at temperatures ranging from 700 to 850 °C for 30 s. Based on the contact resistance measurements, four additional samples were prepared for TEM measurements.

The contact resistances of the different Ohmic metallizations were calculated[21] from the current-voltage measurements of the TLM test structure using a HP4145B semiconductor parameter analyzer. Although the material sheet resistance was assumed to be constant on a given mesa structure, variations of the latter material property over the whole sample were considered.

The TEM specimens were prepared by using manual lapping before finely polishing by Ar-ion milling using Gatan precision ion polishing system. TEM measurements were carried out on a JEOL JEM-2010F FEG. *In situ* EDX spectrometry was used in order to semiquantatively analyze the chemical compositions by means of an Oxford x-ray dispersive spectrometer. The smallest electron beam spot size was 0.5 nm, allowing a very accurate spatial resolution of the analyzed areas.

III. RESULTS AND DISCUSSION

A. Ohmic contact resistance

The temperature dependence of the contact resistances was first investigated for the three different metallizations. The different Ohmic contact resistances, extracted from the TLM measurements are presented in Fig. 1. The lowest Ohmic contact resistance of 0.23 Ω mm was observed for the Si(30 Å)/Ti/Al/Ni/Au metallization revealing the electrical Si enhancement of the standard Ti/Al/Ni/Au Ohmic metallization. However, increasing further the Si thickness did not improve the contact resistance. Moreover, the contact resistances of the Si/Ti/Al/Ni/Au metallizations show a different temperature dependences to the annealing temperature than the standard Ohmic contacts. In fact, the contact resistance degenerated rapidly after reaching a minimum at about 780 °C.

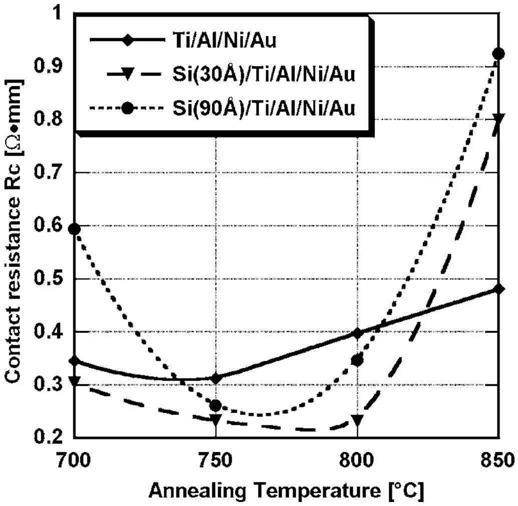

FIG. 1. Annealing temperature dependence of the contact resistance for the three metallization schemes.

B. Microstructure of the Ohmic contacts

The microstructure of Ti/Al/Ni/Au, Si(30 Å)/Ti/Al/Ni/Au and Si(90 Å)/Ti/Al/Ni/Au Ohmic contacts to AlGaN/GaN undoped epistructures alloyed at 780 °C are presented in Figs. 2–7. The microstructure observed for the Ti/Al/Ni/Au metallization on the bright field TEM image (Fig. 2.) is similar to the one described by Bright *et al.*[22] Au diffused through the Ni layer and large islands made of Al–Au compounds were formed during annealing. TiN and Al–Ti–N were clearly identified at the interface and are commonly believed to be responsible for the low resistance Ohmic contact to the nitrogen depleted AlGaN layer. In fact, the formation of the interfacial TiN and Al–Ti–N alloy[23,24] is

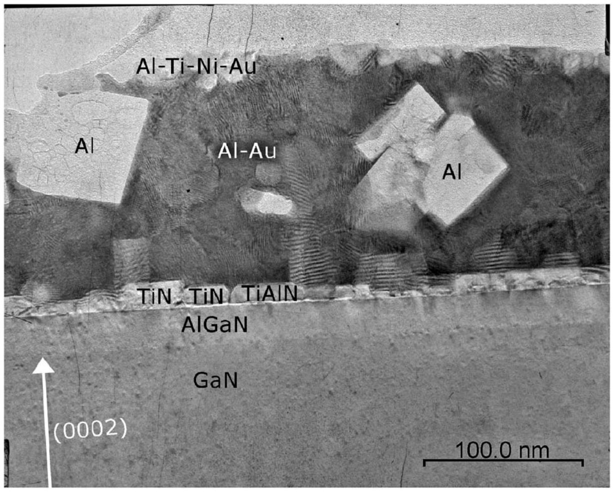

FIG. 2. Bright field TEM picture of the microstructure of the Ti/Al/Ni/Au contacts annealed at 780 °C.

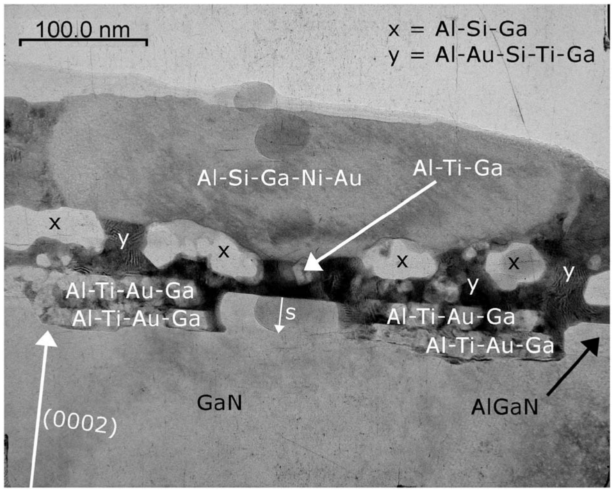

FIG. 3. Bright field TEM picture of the microstructure of Si(30 Å)Ti/Al/Ni/Au contacts annealed at 780 °C.

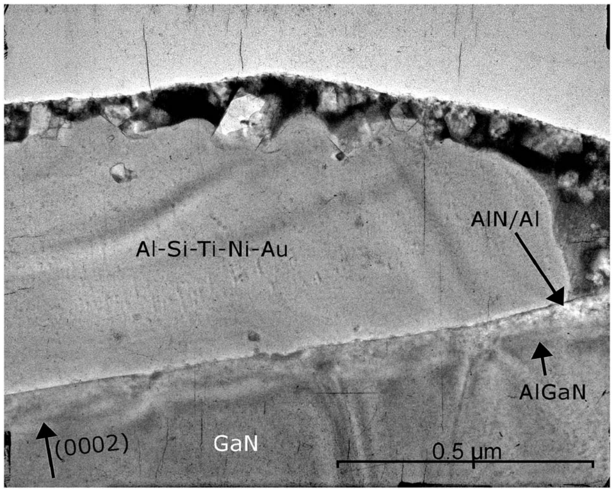

FIG. 4. Bright field TEM picture of the segregated Si-rich islands formed when annealing the Si(90 Å)Ti/Al/Ni/Au metallization 830 °C.

supposed to consume some N of the AlGaN layer during alloying, leaving N vacancies in this layer which act as unintentional dopants facilitating the Ohmic contact formation. An Al–Au phase was also observed between and above the TiN and Ti–Al–N grains, which was suspected to aid the Ohmic contact formation.[22]

Introducing the 30 Å thick Si layer resulted in the penetration of the contacts into the AlGaN and its partial consumption under almost the entire contact region, reducing the tunneling distance between the Ohmic alloyed metallization and the two dimensional electron gas[25] (2DEG) (Fig. 3). The contact inclusion in the AlGaN layer mainly consisted of small (10–15 nm) Ti–Al–Ga–N and Ti–Al–Ga–Au grains. Similar inclusion was also observed by Fay *et al.* in the case of Ti/Al/Ti/Au contacts, and the penetration of the contact in the layer was found to be correlated to the presence of Al–Au and being responsible for the low Ohmic contact.[26] Moreover, relatively large Si(3%–4%)–Al–Ga and Si(2%)–Al–Ga–Ti–Au grains located just above the the original contact/AlGaN interface were identified, suggesting the Si enhanced the consumption and outdiffusion of Ga from AlGaN layer, allowing the penetration of the Ohmic metallization. Similar Ga outdiffusion enhancements were earlier reported for Pt and Pd (Ref. 27) and we believe that Si might have the same effect. Very large grains made of Si–Al–Ni–Ga–Au (Fig. 3) were also observed on the top of the alloyed contacts, revealing the outdiffusion of Si and Ga up to the surface, unlike the published results about confinement of Si between the Ti and Mo layer by other authors.[20]

Furthermore, careful EDX analysis also the *s* axis on Fig. 3 of some remaining AlGaN show a gradient of Si concentration from the surface into the semiconductor, showing the possible diffusion induced Si doping of the AlGaN Schottky layer, as suggested by Desmaris *et al.*[14] and Youn and Kang.[12] Even though Si was present in small percentages (2%) in the top of the AlGaN matrix, the resulting doping would be considerable, hence enhancing the Ohmic contact resistance.

Increasing the thickness of the Si layer resulted in a drastic modification of the microstructure of the contacts. The Ohmic contact did not penetrate the AlGaN layer and the formation of very large Ti–Ni–Si(10%)–Al–Au segregation islands (Fig. 4) and pure Al crystallites in an AlN/Al matrix was observed (Fig. 5). Si and Ti were also found to diffuse out to the contact surface forming principally Al–Si(5%–10%)–Au, Ti–Al–Au, and Ti–Al compounds above the AlN/Al continuous layer. Nitrogen consumption from the AlGaN layer is thus observed, which would result in a local increase of the semiconductor doping and the enhancement of the Ohmic contact. We believe that in this case, the larger amount of Si diffused out to the surface, alloyed with the down diffusing Au forming the observed Si–Al–Au which hinders the formation of the Al–Au layer. The absence of this Al–Au alloy in turn allowed the outdiffusion of Ti through the Al layer.[28,29] Therefore Ti–Al–Au and Ti–Al alloys were observed above the AlN/Al layer.

Furthermore our results clearly show that the absence of the Al–Au layer is detrimental to the contact resistance, as suspected by Fay *et al.*[26] and Wang *et al.*,[29] who also observed the importance of the Al–Au diffusion front in the formation of the Ohmic contact to AlGaN and GaN, respectively.

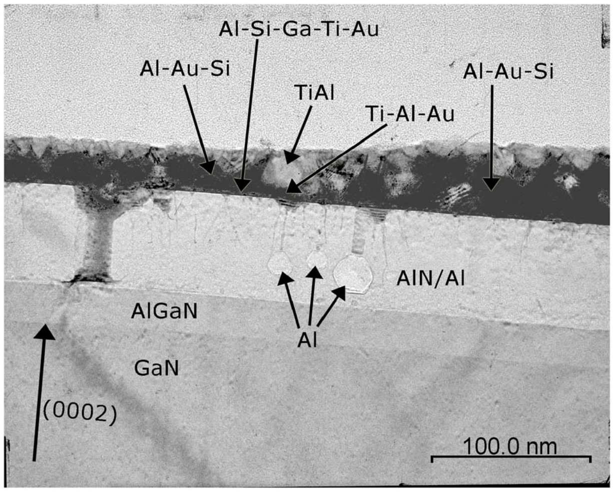

FIG. 5. Bright field TEM picture of the microstructure of the Si(90 Å)Ti/Al/Ni/Au contacts annealed at 830 °C.

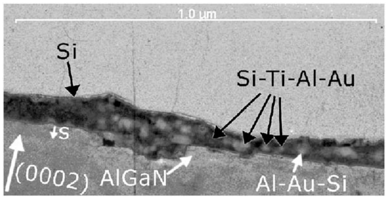

FIG. 6. Bright field TEM picture of the microstructure of Si(30 Å)Ti/Al/Ni/Au contacts annealed at 830 °C.

After annealing the Si(30%)/Ti/Al/Ni/Au Ohmic contacts at 830 °C (Fig. 5), silicon could still be detected in the underlying AlGaN layer at a very low atomic percentage (1%–2%), when performing an EDX scan along the *s* axis on Fig. 6. The contact penetration into the semiconductor was much scarcer than when annealed at 780 °C. Formation of Si–Ti–Al–Au and Si–Al–Au islands with rather high silicon content (5%–8%) was also observed in the Al–Au matrix, but no continuous thick Al or gold-silicide based layer was observed. This could be ascribed to the faster Si outdiffusion due to the higher temperature and limited Si supply because of the thin Si layer, which act as a getter for part of the down diffusing Au, hence preventing the formation of Al–Au alloy. Nevertheless a thin (1–2 nm) continuous contact layer with very low Si content consisting of Ti–N and Al–N was observed for the formation of the Ohmic contact (Fig. 7).

IV. CONCLUSION

We demonstrated that the Si enhancement of Ti/Al/Ni/Au Ohmic contacts to undoped AlGaN/GaN heterostuctures was due to penetration of the Ohmic contact alloyed metallization into the AlGaN Schottky layer. The optimal Si thickness resulted from the tradeoff between the Ga outdiffusion and consumption induced by the presence of Si and the prevention of the formation of the Ti encapsulating Al–Au layer due to the formation of Si–Al–Au and Si–Ti–Al–Au compounds. Increasing the annealing temperature for the Si(30 Å)/Ti/Al/Ni/Au is believed to result in a larger outdiffusion of silicon to the contact surface and the formation on the undesired gold-silicide regions.

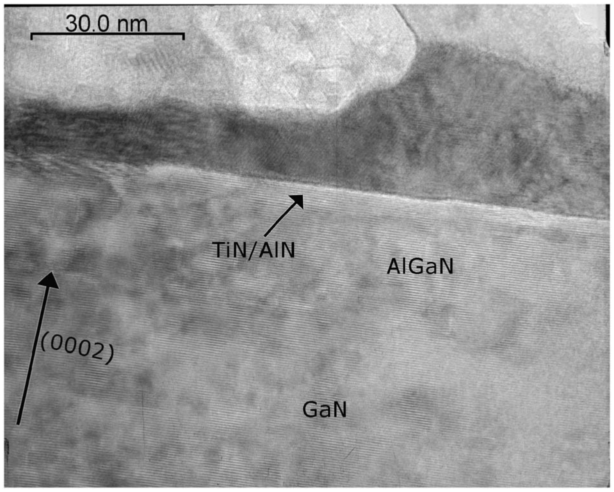

FIG. 7. HRTEM picture of the Si(30 Å)Ti/Al/Ni/Au contacts annealed at 830 °C.

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