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Germanium/Ni-InGaAs Solid-State Reaction for Contact Resistance Reduction on n^+ $In_{0.53}Ga_{0.47}As$

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ABSTRACT

We report the first demonstration of solid state reaction between Ge and Ni-InGaAs to form mono nickel germanide contact on n^+ $In_{0.53}Ga_{0.47}As$. This reaction was performed by isochronous annealing of Ge on Ni-InGaAs at temperatures ranging from 400 to 600 ˚C in N_2 ambient. Detailed materials study on the reaction mechanism is described here. Compared with Ni-InGaAs contact, more than 60% reduction in contact resistance on n-$In_{0.53}Ga_{0.47}As$ was achieved using this new contact formation scheme.

INTRODUCTION

High mobility III-V compound semiconductors are attractive candidates to replace strained Si channel for future high performance logic applications [1]-[4]. To realize the full potential of III-V MOSFETs, S/D engineering to achieve low series resistance R_{SD} is required. A self-aligned metallization analogous to the salicide process in Si CMOS technology is desired for deeply scaled III-V MOSFETs. In this regard, Ni-InGaAs compound has been reported as a promising self-aligned contact for InGaAs MOSFETs [5]-[7]. However, these contacts suffer from high contact resistance R_C which severely degrades device performance at small gate length. Therefore, R_C needs to be reduced.

In this paper, we report the demonstration of significant R_C reduction for Ni-InGaAs contact through the solid state reaction of Ge and Ni-InGaAs. This was achieved by annealing the material stacks and mono nickel germanide is formed on a layer of solid phase regrown InGaAs.

DEVICE DESIGN AND FABRICATION

2" p-type InP wafers were used as starting substrates, on which a 1 μm p-type $In_{0.53}Ga_{0.45}As$ (Be-doped, doping concentration N_A of 2×10^{16} cm^{-3}) was grown. Si^+ ion implant (1×10^{14} cm^{-2} at 25 keV and 1×10^{14} cm^{-2} at 70 keV) and mesa etching was done to form n^+ InGaAs well for forming transfer length method (TLM) test structures. Active contact regions were opened by Photoresist (PR) patterning. Ni (~30nm) was deposited and lift-off was done to form contact pads. The 1st Rapid Thermal Anneal (RTA) at 250 ˚C for 30 s forms Ni-InGaAs contact on the n-InGaAs well. The complete process flow for TLM device fabrication is illustrated in Fig. 1(a). The key steps to form NiGe contact is illustrated in Fig. 1(b) where Ge (~70 nm) was evaporated on the Ni-InGaAs pad by lift-off after a 1 min DHF (HF:H2O=1:100) clean. The process was completed by the 2nd annealing at various temperatures for 10s.

Blanket samples were also prepared for the study of the solid state reaction between Ge and Ni-InGaAs at temperatures ranging from 300 ˚C to 600 ˚C.

RESULTS AND DISCUSSION

The Secondary Ion Mass Spectroscopy (SIMS) analysis in Fig. 2 shows the elemental distributions of Ni and Ge for as-deposited sample and annealed samples. Similar to as-deposited sample, there is little reaction between Ge and Ni-InGaAs at 300 ˚C as seen from the sharp interface between Ge and Ni signal. However, after 400 ˚C anneal, Ge intermixes with Ni to form a layer of NiGe compound.

Therefore, we further studied samples annealed above 300 ˚C in TLM samples. Fig. 3 shows the sheet resistance measured by micro-four-point-probe. The sheet resistance of formed metal layer reduces dramatically after thermal annealing compared with Ni-InGaAs. TLM test structures were used to evaluate the contact resistance. Fig. 4(a) plots the total resistance versus contact spacing between two adjacent pads. R_C for each split is statistically summarized by the box chart in Fig. 5. The control is Ni-InGaAs samples without Ge deposition. On the average, R_C is reduced by 64% for samples annealed at 600 ˚C for 10 s.

Fig. 6 shows the SIMS signals for samples annealed at 400 ˚C. From the Ge and Ni distributions, it is clear that the top layer consists of a nickel-germanium compound and the sublayer is unconsumed Ni-InGaAs alloy. This was also confirmed by the cross-sectional TEM images of the formed layer in Fig. 7. Fig. 7(b) is the magnified view of the contact materials with Energy-Dispersive X-Ray Spectroscopy (EDX) results labeled, showing two metal layers: a top NiGe layer (~66 nm) over a Ni-InGaAs layer (~27 nm). ~24 nm InGaAs regrew at this anneal temperature. It is calculated that the Ge/Ni-InGaAs reaction ratio is around 1.94~2.36. Fig. 8 shows that at 600 ˚C, Ge fully consumes the Ni-InGaAs to form only NiGe on top. TEM images of this condition in Fig. 9 show that the NiGe (~57 nm) layer and the solid phase regrown InGaAs (~49 nm) below the contact material. The NiGe film is continuous and smooth though interface over growth of NiGe was observed at a few spots.

Phase identification was carried out using X-Ray diffraction (XRD) in θ-2θ geometry. The XRD spectra in Fig. 10 for annealed samples shows that, for annealing temperatures above 400 ˚C, mono nickel germanide is the dominant phase formed.

The surface morphology was characterized by Scanning Electron Microscope (SEM) (Fig. 11). Relatively smooth surface was observed for 400 ˚C and 600 ˚C, while the 500 ˚C sample has a rougher surface. Table I is a summary of the two contact schemes. The novel contact scheme in this work shows superior properties to that of Ni-InGaAs. Future work is needed to integrate this contact technology into InGaAs nMOSFETs in a self-aligned manner.

CONCLUSION

Solid state reaction between Ge and Ni-InGaAs was demonstrated for the first time on $In_{0.53}Ga_{0.47}As$ substrate. Electrical data from TLM structures shows significant R_C reduction. The reaction starts at temperatures above 300 ˚C. The contact material formed is found to be mono nickel germanide. Solid phase regrowth of InGaAs was also observed during the reaction. This novel contact formation scheme could be a promising self-aligned contact for InGaAs nMOSFETs.

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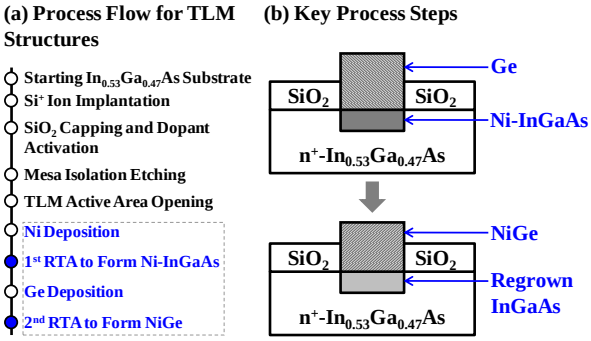

Fig. 1. (a) Process sequence employed in the fabrication of TLM test structures. (b) Highlights of the key process steps.

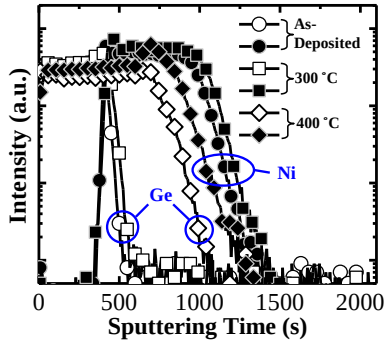

Fig. 2. SIMS analysis shows that Ge and Ni-InGaAs react at 400 ˚C.

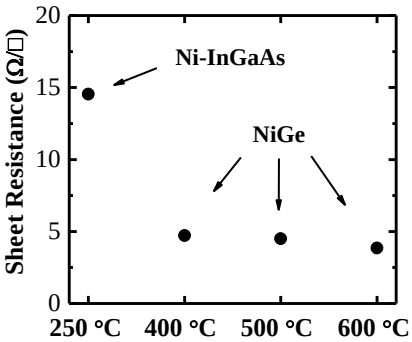

Fig. 3. Metal sheet resistance comparison for Ni-InGaAs and NiGe formed on p-$In_{0.53}Ga_{0.47}As$.

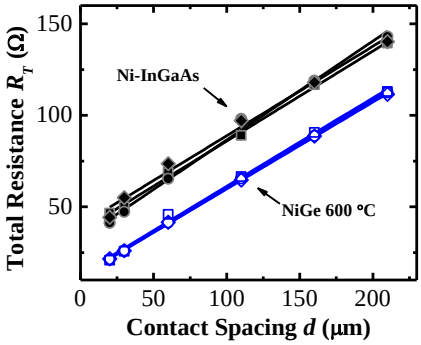

Fig. 4. Total Resistance as a function of contact spacing d ranging from 20 μm ~ 160 μm.

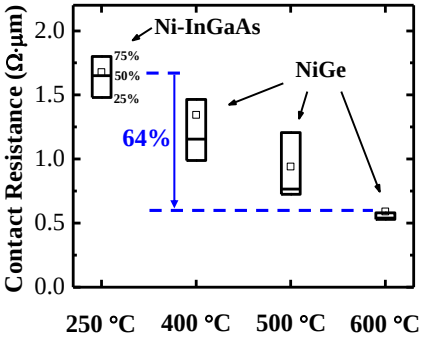

Fig. 5. R_C values for Ge/Ni-InGaAs/InGaAs annealed at different temperatures. Ni-InGaAs is the control.

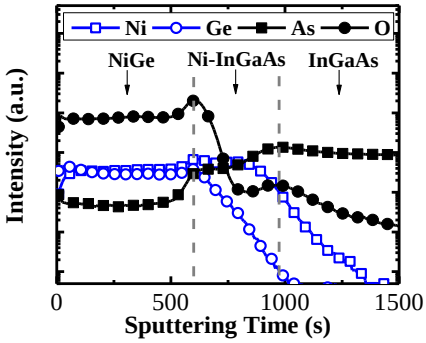

Fig. 6. SIMS analysis reveals that Ni-Ge coumpound forms on top and a unconsumed Ni-InGaAs layer below.

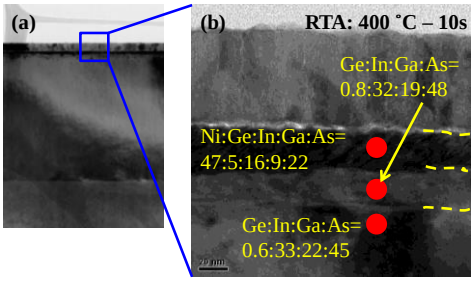

Fig. 7. (a) Cross-sectional TEM image of the TLM sample. (b) Zoomed-in view of the contact layers with compositions labeled from EDX.

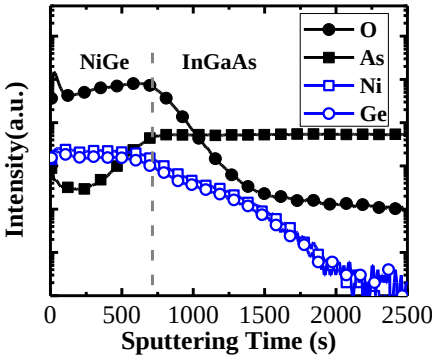

Fig. 8. 600 ˚C anneal completely consumes all the Ni-InGaAs and leaves Ge-rich InGaAs layer below the NiGe contact.

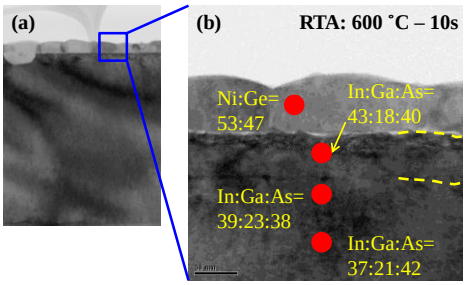

Fig. 9. (a) TEM of 600 ˚C annealed sample. (b) Zoomed-in view of the contact region with EDX spot scan results labeled.

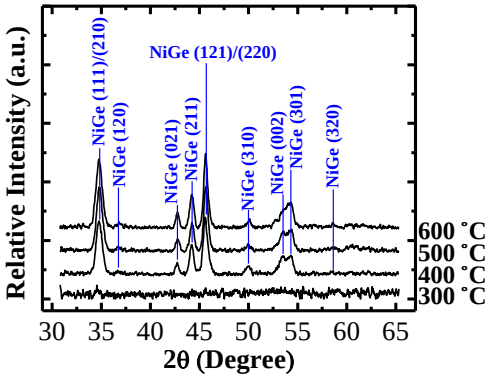

Fig. 10. XRD spectra for annealed samples. It is found that mono nickel-germanide is the dominant phase for anneal temperatures of 400 ˚C or higher.

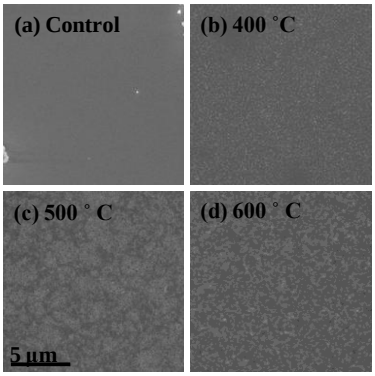

Fig. 11. SEM images of the surface morphology for control and annealed samples. Surface roughness is observed for (c).

Table I. Comparison of key properties between Ni-InGaAs contact and our proposed NiGe contact in this work.

	Ni-InGaAs	NiGe
Self-Aligned Design	✓	✓
Process	Simple	Simple
Contact Resistance (kΩ·μm)	1.68	0.59
Contact Resistivity ($\Omega\cdot cm^2$)	$6.32\times10^{-4*}$	$8.52\times10^{-5*}$
Contact Sheet Resistance	Medium	Small
Thermal Stability	Poor**	Good**
$In_{0.53}Ga_{0.47}As$ Consumption Rate	1.7-2	Very little***

*Assuming the sheet resistance to be identical under the contacts and between contacts;
**NiGe forms stably at anneal temperatures above 400 ˚C;
***NiGe mainly formed above the original InGaAs surface during solid phase regrowth of InGaAs.