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# Evaluation of Ni–In–Ni multi-layers for thermally stable ohmic contacts to n-GaAs

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## Abstract

A thermally stable, low resistance ohmic contact system Ni–In–Ni to n-GaAs was investigated. The lowest value of the specific contact resistance $\rho_c$ was $1.71 \times 10^{-4}\ \Omega\ \mathrm{cm}^2$. Heating the contact up to 400 °C for 5 h did not obviously change the value of $\rho_c$. It was observed by Auger electron spectroscopy and X-ray diffraction that Ni–In compounds, Ga–Ni and InAs formed at the metal–GaAs interface. It was noted that In reacted with GaAs and formed a heterojunction ohmic contact (such as InAs–$In_xGa_{1-x}As$–GaAs) and due to the low melting point (156 °C) of In, additions of Ni are needed to completely react the remaining In to form a high melting point compound.

*Keywords*: Auger electron spectroscopy; Gallium arsenide; Contact resistance; Nickel

## 1. Introduction

In the fabrication of GaAs high speed integrated circuits (ICs), it is crucial to find low resistance ohmic contacts which can withstand subsequent heat treatments (up to 400 °C) after the contact formation. Thermal limitations on currently used Au–Ge–Ni ohmic contacts due to the existence of low melting temperature phases at the metal–GaAs interface showed that these contacts are inadequate for GaAs IC developments. Murakami and Price [1] first proposed that a structure of W(30 nm)–Ni(15 nm)–In–Ni(5 nm–5 nm)–Ni(5 nm)–GaAs had successfully formed a thermally stable ohmic contact. In this work, a simpler multi-layered W(30 nm)–Ni(10 nm)–In(5 nm)–Ni(5 nm)–GaAs contact structure with different thickness was evaluated.

## 2. Experimental details

The material used was n-GaAs wafers with a carrier concentration of $10^{17}\ \mathrm{cm}^{-3}$. A resistivity of 25 mΩ cm was determined from the van der Pauw method. The (100)-oriented wafers, having a thickness of 365 μm were cut into $1 \times 1\ \mathrm{cm}^2$. All these samples were boiled in TCE (10 min), ACE (5 min), rinsed in deionized water, and dried in a nitrogen stream. The native surface oxide was etched away with a hot solution of $HCl:H_2O$ (1:1). The samples used for electrical study were then masked with photoresist AZ1350J to provide patterns of circular dots having a diameter of 200 μm and a spacing of 750 μm. Before development, the samples were soaked in toluene for 10 min to harden the photoresist surface. This step provides a negative slope for the developed pattern and helps the subsequent lift-off process. The Ni and In films were deposited by E-beam evaporation. In the sample preparation, two types of samples were fabricated: (a) sample A, 3 nm Ni was first deposited onto the GaAs surface, followed by 20 nm In and the top layer was 60 nm Ni; (b) sample B, 5 nm Ni was first deposited onto the GaAs surface, followed by 17 nm In and the top layer was 40 nm Ni.

In certain cases, a W layer with thickness 30 nm was also deposited by E-beam evaporation before the annealing; the samples were encapsulated with 50 nm SiN film deposited by r.f. sputtering. These contacts

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were treated by rapid thermal annealing (RTA) with various temperatures and time profiles (800–950 °C, 2–16 s) under nitrogen ambient. Capless annealing of the contact was also done at 800 °C for 2 s.

After removal of the SiN films, the 4-point method was used to determine the specific contact resistance $\rho_c$ [2–3]. The surface reaction were mainly characterized by X-ray diffraction (XRD) and Auger electron spectroscopy (AES) depth profile measurements.

The annealed contacts were first examined by HP4145 to check the ohmic behaviors. The $\rho_c$ measurement technique included probing four adjacent ohmic dots—two with the constant current leads and two with the digital voltmeter leads. To monitor the linearity, the measurements were made at 1 mA and 10 mA. Each dot was measured several times to reduce errors due to probing, and $\rho_c$ was calculated by an iteration method.

## 3. Results and discussion

The $I-V$ characteristics of the as-deposited samples were non-ohmic. When samples were annealed for a short time (about 2 s), the $I-V$ characteristics showed a linear relationship, but the linearity was lost for a longer time annealing (greater than 6 s). The specific contact resistances for samples with structure Ni(40 nm)–In(17 nm)–Ni(5 nm(–GaAs and Ni(60 nm)–In(20 nm)–Ni(3 nm)–GaAs were annealed at 800, 850 and 950 °C. The lowest $\rho_c$ was $1.71 \times 10^{-4}$ Ω cm$^2$ obtained for samples with structure 60 nm–20 nm–3 nm–GaAs annealed at 800 °C for 2 s. Samples annealed at 800 and 850 °C for 2 s were mostly in the range 10 Ω cm$^2$. The $\rho_c$ was increased as the annealing temperature increased.

Thermal stability of these samples was studied during annealing at 400 °C subsequent to the contact formation; the result is shown in Fig. 1. The contacts of sample A (60 nm–20 nm–3 nm–GaAs) annealed at 800 and 850 °C for 2 s showed good thermal stability, and the contacts annealed at 900 °C for 2 s showed slight change after the heat treatment. It is noted that the samples with thicker Ni films showed better thermal stability than those with thinner Ni films. Nevertheless the $\rho_c$ of samples with thinner Ni film (40 nm–17 nm–5 nm–GaAs) was lowered by the subsequent heat treatment.

The XRD patterns of the as-deposited samples showed no significant peaks except those corresponding to GaAs. After annealing at 800 °C for 2 s, the peaks of the compounds of Ni and In appeared; the InAs and Ga–Ni peaks were also found in the XRD data.

The compounds corresponding to Ni and In at high temperature [4] exhibit high melting point and behave in a stable manner during the subsequent 400 °C heat treatment. The Ga–Ni is also formed at high temperature, which could not influence the microstructure of this Ni–In–Ni contact system after the ohmic formation. The detected InAs coincides with the results of Lakhani [5]. The $In_xGa_{1-x}As$ phase could not be observed by our XRD, because the peaks of $In_xGa_{1-x}As$ can be masked by the peaks of GaAs due to their similar lattice constants. The lattice constant of InAs is 0.606 nm and the corresponding value of GaAs is 0.565 nm, mismatch of only 7%. Such a large lattice mismatch is likely to hinder the epitaxial growth of

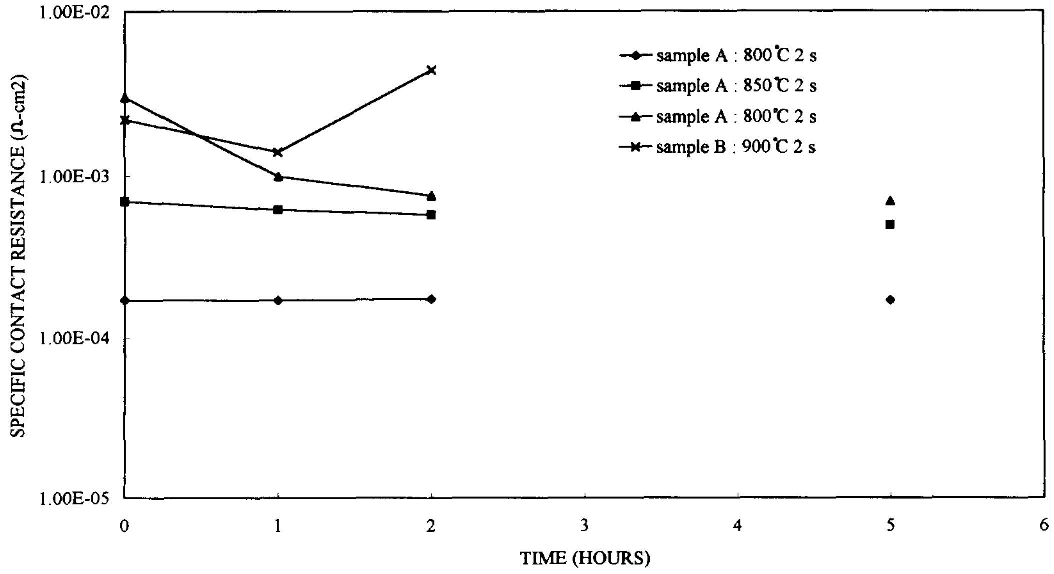

Fig. 1. Heat tests at 400 °C on Ni–In–Ni ohmic contact system.

InAs on GaAs. The existence of $In_xGa_{1-x}As$ phase was proven by Lakhani by AES [5]. Furthermore, the conduction band discontinuity of the heterojunction of InAs-n-GaAs should be about 0.8 eV. Such a large barrier would be rectifying and not ohmic. However, the Ni-In-Ni contact system does act as an ohmic contact to n-GaAs.

The AES depth profile of 800 °C, 2 s RTA treated sample A is shown in Fig. 2; the profiles of the Ni-In-Ni-GaAs contact showed the mixture of Ni, In, Ga and As at the surface after the heat treatment. The AES depth profile of the sample subjected to a 400 °C treatment for 1 h is shown in Fig. 3.

In and Ni were found to diffuse into GaAs, and Ga and As out-diffusion were also observed. The XRD data also showed the Ni-Ga phases existing at the surface. The results of the subsequent 400 °C, 1 h heat treatment did not seem to show any obvious difference to the profiles before the 400 °C, 1 h treatment. This may be explained by the existence of stable phases at the contact surface, as was found by XRD. The profile of sample B annealed at 800 °C for 2 s showed that its Ni concentration is lower than that of sample A annealed at the same conditions. On the surface a large amount of As could be detected, and it is retarded by the encapsulated SiN film.

We also tried to deposit the structure W(30 nm)-Ni(10 nm)-In(5 nm)-Ni(5 nm)-GaAs and successfully formed a thermally stable ohmic contact. The Rutherford backscattering (RBS) data shown in Fig. 4 presents evidence of In diffusion towards both the GaAs substrate and the top W layer. The top W layer is believed to act as a diffusion barrier for In and As. However, the W layer could be replaced by SiN film in the Ni-In-Ni-GaAs contact system.

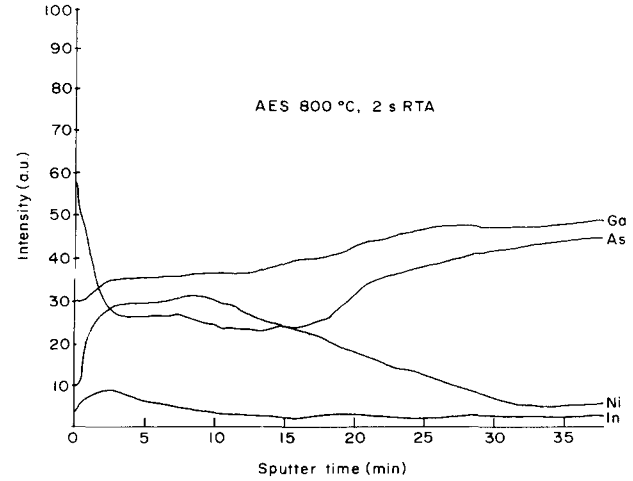

Fig. 2. AES depth profile of 800 °C, 2 s RTA sample.

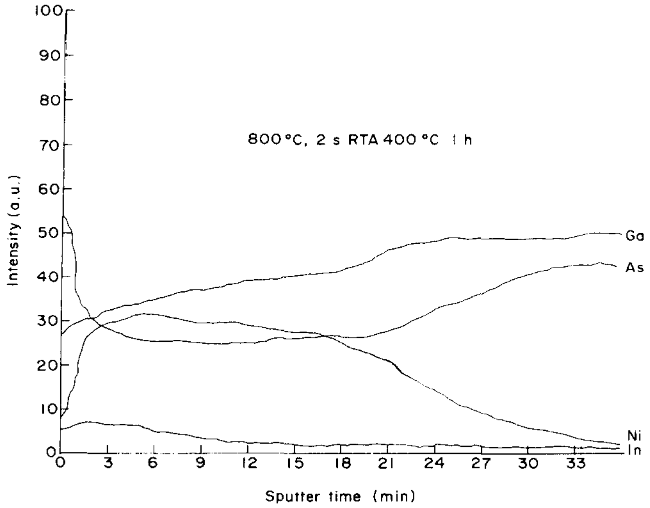

Fig. 3. AES depth profile of 800 °C, 2 s RTA sample after heat treatment at 400 °C for 1 h.

## 4. Conclusions

In this work, simpler multi-layered W(30 nm)-Ni(10 nm)-In(5 nm)-GaAs contacts with different thickness were fabricated. We have obtained a $\rho_c$ as low as $1.77 \times 10^{-4}$ Ω $cm^2$ on n-GaAs ($n = 10^{17}$ $cm^{-3}$); after a subsequent 5 h heat treatment at 400 °C, it still had a value of $4.63 \times 10^{-4}$ Ω $cm^2$. Comparing the results of both samples (sample A: Ni(60 nm)-In(20 nm)-Ni(3 nm)-GaAs and sample B: Ni(40 nm)-In(17 nm)-Ni(5 nm)-GaAs), it was found that the structure with thicker Ni films had a better thermal stability performance than that with thinner Ni films. The samples annealed at a lower temperature (800 °C) had both better ohmic behavior (low $\rho_c$) and better thermal stability than the higher temperature annealed samples.

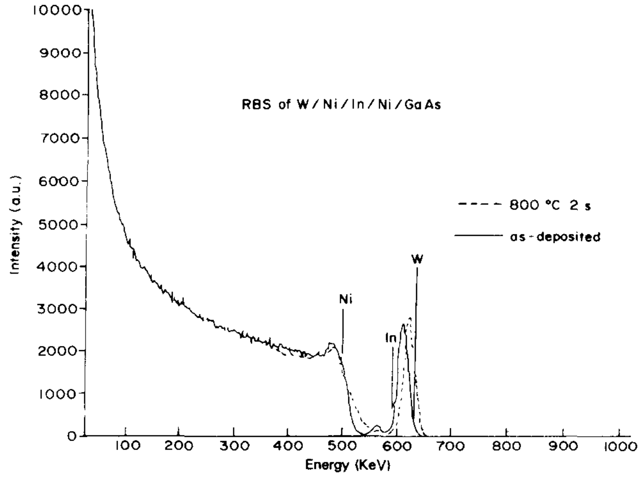

Fig. 4. RBS profiles of as-deposited sample and 800 °C, 2 s RTA sample.

The samples annealed at shorter times also had better thermal stability.

Analysis of the RBS data presents evidence of In diffusion towards both the GaAs substrate and the top W layer. The top W layer is used to act as a diffusion barrier for In and As. Furthermore, the feasibility of replacing W layer by SiN film on Ni–In–GaAs contact system was also studied. The surface structure was studied by AES and XRD. It was observed that Ni–In, Ga–Ni and InAs compounds were formed at the metal–GaAs interface. It was also found that In reacted with GaAs to form heterojunction ohmic contacts (as $InAs-In_xGa_{1-x}As$). In the study, the first Ni film deposited above GaAs was used to provide a more uniform reaction of In–GaAs; the top Ni layer was used to totally react with the residual In, otherwise, since In has a melting point at 156 °C and it might deteriorate the ohmic behavior of the contacts. To have In completely reacted is the most important requirement to achieve thermal stability. The addition of certain amounts of Ni are needed to completely react the remaining In to form a high melting point compound, and the amounts of In and Ni are crucial in building the stable surface structure.

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