Low resistance, thermally stable ohmic contacts to n-GaAs
for low-cost high-density interconnections

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ABSTRACT

We successfully achieved thermally-stable NiGe(In) ohmic contacts with a very low contact resistance ($R_C$) of 0.08 Ωmm ($\rho_C = 3.6 \times 10^{-7} \Omega cm^2$), which is comparable to that of conventional AuGeNi contacts, by using ammonium sulfide treatment and rapid thermal annealing in a pure H$_2$ ambient. The excellent thermal stability at 400°C up to 10 h was also obtained. These results show that NiGe(In) contacts are very suitable for GaAs ICs and LSIs with Al-based high-density interconnections. The mechanism of the $R_C$ reduction, related to residual oxide layers at the metal/GaAs interface, has been successfully demonstrated by using XRD, AES, SIMS, and TEM/EDS analysis. The different mechanisms in thermally-stable Pd-based contacts PdIn(Ge) and Au-based contacts AuGeNi are also discussed.

INTRODUCTION

Advanced Al- or Cu-based high-density multilevel interconnections rather than conventional Au-based wiring are the key technology in the high-volume manufacturing of low-cost GaAs ICs and LSIs. Technologies such as reflow sputtering, metal chemical vapor deposition, and low dielectric-constant spin-on-glass film deposition require thermally-stable (≥ 400°C) ohmic contacts. However, conventional Au-based contacts to n-GaAs are not suitable for GaAs ICs and LSIs because they have poor thermal stability (= 350°C), rough surfaces, deep diffusion depths, and are difficult to fabricate by dry etching. One of the best candidates for thermally-stable non-gold contacts is NiGe contacts [1-3]. In these ohmic contacts, reduced contact resistances ($R_C$) and excellent thermal stability obtained by adding a small amount of In have been reported [4]. These NiGe(In) ohmic contacts are expected to displace thermally-unstable AuGeNi contacts. However, the $R_C$ of the NiGe(In) contacts is about three times higher than that of AuGeNi contacts ($R_C \approx 0.1 \Omega$ mm).

In this study, for the first time, the discovered dependence of $R_C$ on alloy ambient gases is discussed by comparing these Ni-based contacts with Pd-based contacts PdIn(Ge) [5,6] and Au-based contacts AuGeNi. On the basis of these results, we tried the novel approach of reducing $R_C$ by sulfur-treatment and rapid thermal annealing (RTA) in a pure H$_2$ ambient, and obtained thermally-stable NiGe(In) ohmic contacts with a very low $R_C$.

EXPERIMENTAL PROCEDURE

N-GaAs layers (100 nm-thick, Si: 2 × 10$^{18}$ cm$^{-3}$) grown on semi-insulating (100) GaAs wafers were used as the conducting channels. Prior to metal deposition, wafers were cleaned by the following two methods.

Method I: Wafers were dipped in a H$_3$PO$_4$ solution at 60°C for 1 min, followed by a deionized water rinse and N$_2$-blow dry.

Method II: After the H$_3$PO$_4$ treatment mentioned in Method I, wafers were immediately dipped in an ammonium sulfide ([NH$_4$]$_2$S$_2$) solution at room temperature for 30 min, followed by a deionized water rinse of 10 sec and N$_2$-blow dry.

After these treatments, wafers were immediately introduced into an electron-beam metal deposition system, and the structures of n-GaAs/Ni (75 nm)/In (6 nm)/Ge (100 nm), n-GaAs/Pd (15 nm)/Ge (1.5 nm)/Pd (15 nm)/In (120 nm)/Pd (30 nm), or n-GaAs/AuGe (100 nm)/Ni (50 nm) were fabricated. Wafers were annealed by RTA or furnace (FA) under various ambient gases (H$_2$, N$_2$, or mixed) and temperature profiles. After annealing, Au or Al pad metals were deposited on these contacts for the transmission line model (TLM) measurements. TLM patterns were fabricated by using optical lithography and the lift-off method. The microstructures of alloyed samples were analyzed by using x-ray diffraction (XRD), Auger electron microscopy (AES), quadrupole-type secondary ion mass spectroscopy (SIMS), and cross-sectional transmission electron microscopy with energy dispersive spectroscopy (TEM/EDS). To investigate the thermal stability, isothermal annealing was also carried out at 400°C after contact formation.

RESULTS AND DISCUSSION

Dependence of contact resistance on annealing ambient gas

The TLM measurements of Method I samples indicated that annealing ambient gases affect $R_C$, and this effect depends on the metals used, as shown in Fig. 1 (NiGe(In) > PdIn(Ge) > AuGeNi). The $R_C$ of the NiGe(In) contacts depends mostly on the ambient gases. The annealing,
NiGe(In) contacts annealed in N\textsubscript{2} ambient, the residual oxide layers at the interfaces act as potential barriers and cause high contact resistances, while the residual oxide layers are deoxidized by annealing in H\textsubscript{2} ambient. The analysis of the as-deposited sample revealed that these oxide layers originated in the GaAs native oxide. Cross-sectional TEM images (Fig. 3) show that thicker oxide layers and a larger number of voids exist around the NiGe/GaAs interface of the N\textsubscript{2}-ambient-annealed contacts than those in the H\textsubscript{2}-ambient-annealed contacts.

SIMS measurements also show that the hydrogen accumulated at the NiGe/GaAs interfaces of the H\textsubscript{2}-ambient-annealed contacts is higher than that in the N\textsubscript{2}-ambient-annealed contacts. This may also affect R\textsubscript{C}; for example, crystal defects in the GaAs layer may be passivated by hydrogen, resulting in reduced R\textsubscript{C}.

For the PdIn(Ge) contacts, SIMS measurements show that even in N\textsubscript{2} ambient, the oxide layers can be removed from the interface more effectively than those in the NiGe(In) contacts, which is due to high reactivity between Pd and GaAs (Fig. 4(1)). This allows a low dependence on the ambient gases. In the AuGeNi contacts, very high reactivity between Au and GaAs promotes the diffusion of oxygen from the interface, resulting in the R\textsubscript{C} independence of the ambient gases (Fig. 4(2)). The dependence on metals is related to the difficulty in removing oxide layers, which originates in the reactivity between metals and GaAs (Ni<Pd<Au).

PdIn(Ge) contacts annealed at temperatures higher than 550\degree C have been reported to have excellent thermally stability [5]. However, the NiGe(In) contacts are superior to the PdIn(Ge) contacts because of low contact resistances.
Fig. 4. SIMS depth profiles of (1) PdIn(Ge) and (2) AuGeNi contacts annealed by RTA in H₂ and N₂ ambient (Method I samples). In all samples, poor surface morphology degrades the accuracy of the depth.

wide process windows, and smooth surface morphology. The poor morphology of the PdIn(Ge) contacts is due to In agglomeration.

Contact resistance reduction

On the basis of the results obtained, we tried to reduce the R_c by effectively removing oxide layers. By using the simple treatment of Method II (sulfur-treatment) and RTA in a pure H₂ ambient with a high flow rate and steeper temperature profile, the R_c of NiGe(In) ohmic contacts was reduced to 0.08 Ωmm (ρ_s = 3.6 × 10⁻⁷ Ωcm²), which is comparable to that of AuGeNi contacts (R_c = 0.09 Ωmm), as shown in Fig. 5. This is the lowest value ever obtained in thermally stable alloyed ohmic contacts. A low R_c was even obtained in the N₂ ambient when this process was used. SIMS measurements show that a high level of sulfur accumulated around the interfaces and diffused into the GaAs layer (Fig. 6). Therefore, the R_c reduction should not only be due to the removal of oxide layers but also due to sulfur doping to n-GaAs layers.

Thermal stability

As shown in Fig. 7, the isothermal annealing experiment at 400°C shows that the NiGe(In) contacts have excellent electrical and morphological thermal stability, compared with AuGeNi contacts. The R_c values are unchanged up to 10 h. When Al or Au pad metals were deposited on the contact

Fig. 5. Dependence of the contact resistances of NiGe(In) ohmic contacts on the H₂ flow ratio in annealing ambient gas.

Fig. 6. SIMS depth profiles of sulfur-treated (Method II) NiGe(In) contacts annealed by RTA in H₂ and N₂ ambient.

Fig. 7. (1) Changes of the contact resistances of NiGe(In) and AuGeNi ohmic contacts during isothermal annealing at 400°C. The NiGe(In) samples used were sulfur-treated and annealed by RTA (600°C, 5 sec, H₂). (2) Surface morphology after 10 h annealing. The ohmic metal surfaces without pad metals are shown. Morphological degradation was only observed in the AuGeNi contacts.
metals, the NiGe(In) contacts have low $R_C$ values of less than 0.2 $\Omega$mm after 2 h annealing. This indicates that NiGe alloy metal acts as a good barrier to the diffusion of the Al and Au pad metals. The thermal stability of NiGe(In) contacts is enough for the processing of Al- and Au-based multilevel interconnections.

To investigate the NiGe(In) contacts to the 2-dimensional electron gas (2DEG) channels, we also fabricated the AlGaAs/InGaAs pseudomorphic heterojunction field-effect transistor (HJFET) structures. We obtained almost the same source resistances as those of AuGeNi contacts and excellent thermal stability at 400°C.

CONCLUSION

We found that residual oxide layers strongly affect the contact resistances of NiGe(In) ohmic contacts to n-GaAs compared with Pd-based and Au-based contacts. By using the developed processes to efficiently remove oxide layers, we achieved a very low contact resistance comparable to that of conventional AuGeNi contacts. The NiGe(In) contacts developed have very low $R_C$, wide process windows, excellent thermal stability, smooth surfaces and interfaces, and shallow diffusion depths. This shows the high potential of these contacts for low-cost GaAs metal-semiconductor FET (MESFET) and HJFET ICs and LSIs with high-density multilevel interconnections, as well as for high-power and high-temperature devices.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution of Shuji Asai and Michihisa Kohno in the wafer preparation. The authors would also like to thank Dr. Kazuhiko Honjo and Dr. Hidenori Shimawaki for their valuable discussions and encouragement.

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