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Study of the Formation Mechanism of Cu/Ge/Pd Ohmic Contact to *n*-Type InGaAs

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This study investigates electrical characteristics and the formation mechanism of the Cu/Ge/Pd Ohmic contact to *n*-type InGaAs. After annealing the contact at 250°C for 20 min, Cu_3Ge and $Pd_{12}Ga_5As_2$ compounds formed and Ge diffused into the InGaAs layer, achieving a heavily doped InGaAs layer with a low contact resistivity of 1×10^{-6} Ω cm^2. Thermal stability tests were performed on the Cu/Ge/Pd Ohmic contact to InGaAs after Ohmic contact formation, showing no obvious degradation after a 72 h reliability test at 250°C. The results indicate excellent electrical characteristics and thermal stability using Cu/Ge/Pd as an Ohmic contact metal to an *n*-InGaAs layer.

Key words: Copper metalization, Cu/Ge/Pd Ohmic contact, InGaAs

INTRODUCTION

Copper (Cu) metallization has been widely used as an interconnection metal for silicon (Si)-based very large-scale integration (VLSI) in recent years;[1–3] however, few reports on Cu metallization in GaAs-based devices have been published.[4–7] The advantages of using Cu (rather than Au) for metallization in GaAs devices include superior electrical conductivity, improved heat dissipation, and cost reduction. Studies have reported on the Ohmic contact of Cu/Ge/Pd to *n*-GaAs, showing excellent electrical characteristics with good thermal stability.[5] However, InGaAs has been widely used as the Ohmic contact layer for reduction of contact resistance in III–V high-speed devices, such as heterojunction bipolar transistors (HBTs)[8] and high-electron-mobility transistors (HEMTs).[9] This study investigates the feasibility of using Cu/Ge/Pd as an Ohmic contact for the InGaAs layer in GaAs-based devices.

Conventionally, the Au/Ge/Ni Ohmic contact system has been the most widely used in GaAs-based devices.[9] However, this system has a number of drawbacks, such as widely dispersed contact resistivity, poor contact edge definition, and high annealing temperature, due to the eutectic Au/Ge alloy (the Au-Ge eutectic temperature is 361°C).[10,11] This study reports on a system of Cu/Ge/Pd Ohmic contact to *n*-type InGaAs with low contact resistivity and low annealing temperature (250°C). Table I shows the structure of the epitaxial layer in the InGaP/GaAs HBT. This study achieved low contact resistivity (1.0×10^{-6} Ω cm^2) with a standard deviation of 1.1×10^{-7} Ω cm^2 following annealing at 250°C. We also investigated the mechanism behind the formation of the Cu/Ge/Pd Ohmic contact to InGaAs.

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EXPERIMENTAL PROCEDURES

To create an Ohmic contact, the InGaAs mesa was first etched with a solution of $H_3PO_4/H_2O_2/H_2O$. After a conventional cleaning process with an organic solvent, the substrate was chemically cleaned in a HCl:H_2O (1:1) solution, to remove the native oxide layer. The samples were then loaded into an evaporation chamber. Cu (150 nm)/Ge (150 nm)/Pd (15 nm) Ohmic metal was deposited on the substrate using electron-beam evaporation at a pressure of $\sim 1 \times 10^{-6}$ Torr, and formed through a lift-off process. Following metal deposition, the samples were annealed in a conventional tube furnace at various temperatures ranging between 150°C and 450°C for 20 min to attain minimum contact resistance. A thermal stability test of the Cu/Ge/Pd Ohmic contact was performed by a

Table I. Epitaxial layer structure of the InGaP/GaAs HBT

Layer	Material	Type	Doping (cm^{-3})	Thickness (Å)
Emitter cap	$In_{0.6}Ga_{0.4}As$	$n+$	1×10^{19}	800
Emitter cap	GaAs	$n+$	4×10^{18}	1250
Emitter	$In_{0.49}Ga_{0.51}P$	n	3×10^{17}	500
Base	GaAs	$p+$	4×10^{19}	800
Collector	GaAs	$n-$	4×10^{16}	7500
Etch-stop layer	$In_{0.49}Ga_{0.51}P$	n	1×10^{18}	200
Subcollector	GaAs	$n+$	4×10^{18}	5000
	$Al_{0.3}Ga_{0.7}As$		Undoped	1800
	GaAs		Substrate	

high-temperature annealing test (250°C) in a N_2-ambient tube furnace for 72 h. The Ohmic contact resistance (R_C) and sheet resistance (R_{sh}) of the samples were measured using the transmission line method (TLM).[12]

RESULTS AND DISCUSSION

Figure 1 shows x-ray diffraction (XRD) data regarding the structure of the Cu (150 nm)/Ge (150 nm)/Pd (15 nm) as-deposited Ohmic contact, following annealing at 250°C and 450°C for 20 min. The x-ray diffraction data clearly exhibit the diffraction peaks of Ge and Cu, indicating that the Cu/Ge/Pd layers did not react with each other in the as-deposited sample. However, the diffraction peaks show the occurrence of Cu_3Ge and the disappearance of the Cu peak when the annealing temperature exceeded 250°C. In addition, $Pd_{12}Ga_5As_2$ peaks were observed following annealing at 250°C. The Ohmic contact behavior is related to the formation of Cu_3Ge compounds following annealing at 250°C. Figure 1 shows the x-ray diffraction peaks following annealing at 450°C, wherein the InGaAs peak weakened, and $Pd_{12}Ga_5As_2$ strengthened substantially. These results, combined with the data from Auger electron spectroscopy (AES) and energy-dispersive spectrometry (EDX), (see below) indicate a significant interaction between the Ohmic metals and InGaAs.

Figure 2 shows depth profiles from AES depth profiles of the Cr/Cu/Ge/Pd/n-InGaAs as-deposited samples, following annealing at 250°C, and 450°C for 20 min. The data in Fig. 2a show the slight interaction between the Ohmic metals and the InGaAs layer in the as-deposited sample. However, after annealing at 250°C, Pd began diffusing into the InGaAs layer, as shown in Fig. 2b. In addition, Ge diffused into the InGaAs layer, possibly causing Ge doping of high concentration on the surface of the InGaAs layer. Interdiffusion of Cu and Ge occurred at an annealing temperature of 250°C, which was in agreement with the XRD analysis. However, as Fig. 2c shows, after annealing at 450°C, the Cu and Ge atoms penetrated through the Pd layer to diffuse into the InGaAs layer. Furthermore, In atoms also diffused to accumulate near the surface of the sample.

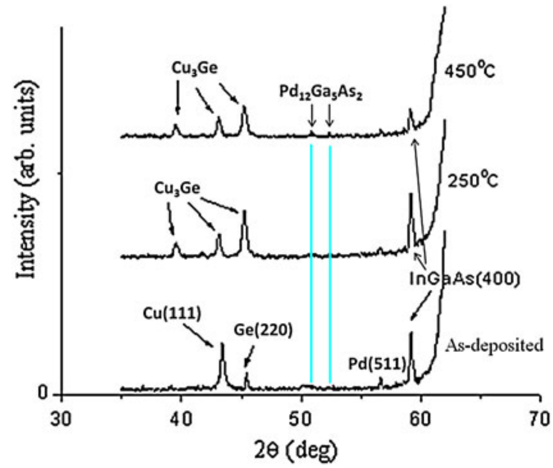

Fig. 1. X-ray diffraction patterns for the Cu (150 nm)/Ge (150 nm)/Pd (15 nm) contact after annealing at 250°C for 20 min, 450°C for 20 min, and the as-deposited sample.

Figure 3 shows an image obtained by transmission electron microscopy (TEM), showing the structure of the as-deposited Cu (150 nm)/Ge (150 nm)/Pd (15 nm) on the InGaAs layer. Conventional mechanical polishing followed by Ar-ion milling were used to prepared the TEM sample, for cross-sectional analysis (JEOL 2010F, 200 kV). The figure clearly shows the Pd, Ge, and Cu layers without mixing. The study used a Cr covering layer to prevent oxidation of the Cu surface during the preparation of the sample.

Figure 4 shows TEM images and EDX profiles of the Pd/Ge/Cu Ohmic metal structure following annealing at 250°C for 20 min. Figure 4a shows a TEM image of the structure of the Cu/Ge/Pd Ohmic metal after annealing at 250°C for 20 min. From the figure, it is clear that the Cu/Ge compound began forming vertical grains, which were also observed in the literature.[13] EDX analysis of the composition of the grains shown in Fig. 4a indicates that the grains are the compound Cu_3Ge. A previous study reported that the compound Cu_3Ge has low resistivity and Ga has lower chemical potential in Cu_3Ge than in the GaAs compound. Therefore, Ga atoms could diffuse into the Cu_3Ge layer.[13] Furthermore, Fig. 4b shows a high-resolution transmission electron microscope (HRTEM) image of the near-interfacial region between the InGaAs layer and the Ohmic metal after annealing at 250°C. A $Pd_{12}Ga_5As_2$ phase began appearing on the surface of InGaAs after annealing at 250°C. Formation of the $Pd_{12}Ga_5As_2$ compound created many Ga vacancies in the InGaAs layer. The Ge atoms diffused easily into the vacancies left by the Ga near the surface of the InGaAs, resulting in a heavily doped n^+-InGaAs layer. Ohmic contact

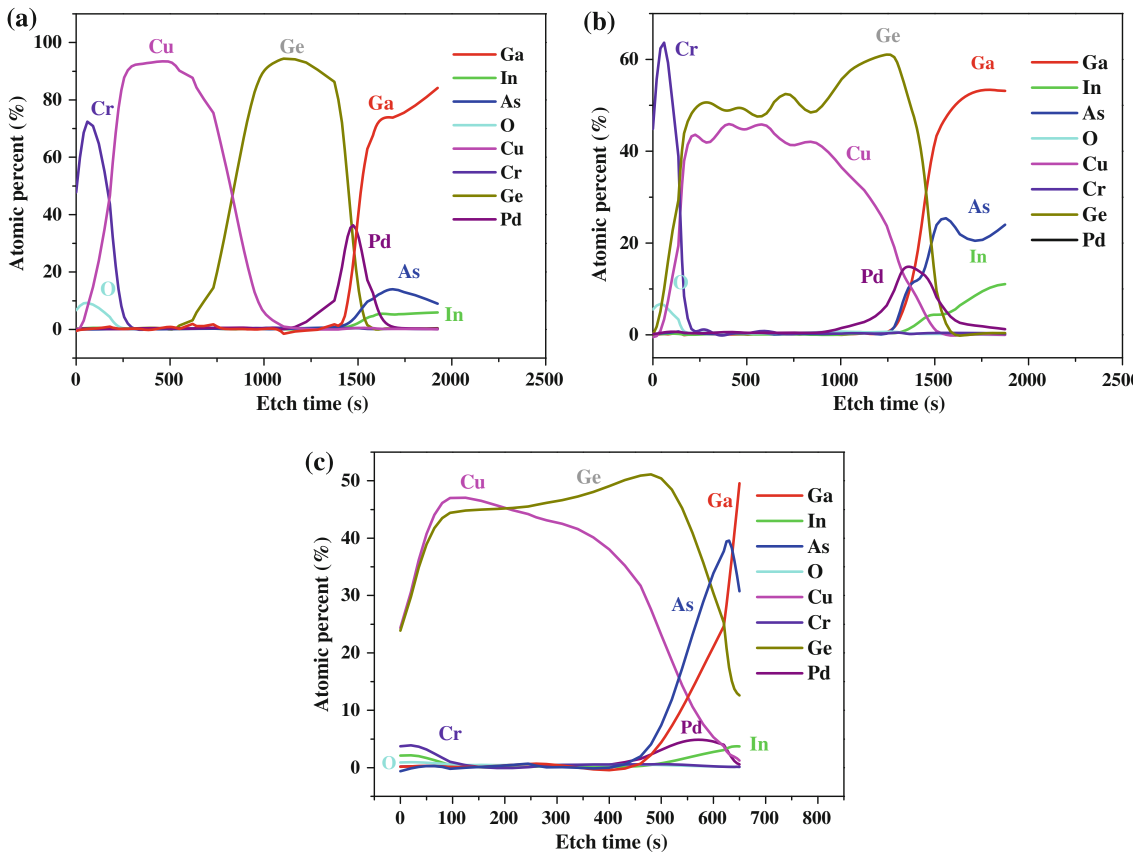

Fig. 2. AES depth profiles of the Cu (150 nm)/Ge (150 nm)/Pd (15 nm)/n-InGaAs contact: (a) as-deposited sample, (b) after annealing at 250°C for 20 min, and (c) after annealing at 450°C for 20 min.

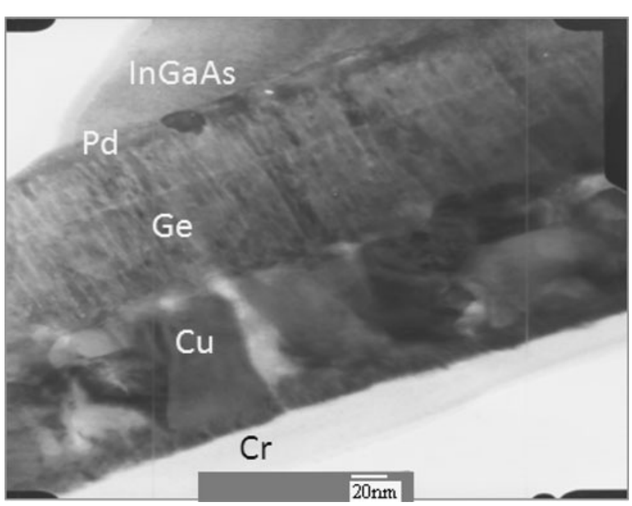

Fig. 3. TEM image of the Pd/Ge/Cu contact for the as-deposited sample.

characteristics appeared following furnace annealing at 250°C for 20 min. The EDX profiles in Fig. 4b indicated no diffusion of Cu atoms into the InGaAs layer after annealing at 250°C. However, atomic interdiffusion and interfacial reactions became obvious after annealing at 450°C for 20 min, as shown in Fig. 4c. The Ohmic contact characteristics of the Cu/Ge/Pd Ohmic system began degrading after 450°C annealing, due to the diffusion of Cu and Ge into the InGaAs layer. Figure 4c shows EDX profiles of the surface of the sample after annealing at 450°C. A thin layer of Cr was deposited to protect the Cu layer from oxidation. The data indicate that In, Ga, and As atoms had diffused through the Pd, Ge layers and mixed with Pd, Ge atoms on the surface of the sample.

Figure 5 is an atomic force microscope (AFM) image showing the surface morphology of the as-deposited sample, as well as samples after annealing at 250°C and 450°C. The root-mean-square (rms) roughness of the as-deposited sample was 1.597 nm. The roughness of the samples after annealing at 250°C and 450°C was 2.058 nm and 2.918 nm, respectively. The results of AFM clearly indicate that the roughness of the surface increased with increasing annealing temperature.

Figure 6 shows that the optimized Cu (150 nm)/Ge (150 nm)/Pd (15 nm) metal structure formed an Ohmic contact to n-type InGaAs with low contact resistivity in a low annealing temperature range (from 150°C to 450°C). The lowest specific contact resistivity achieved was $1.0 \times 10^{-6}\ \Omega\ \mathrm{cm}^2$ with a

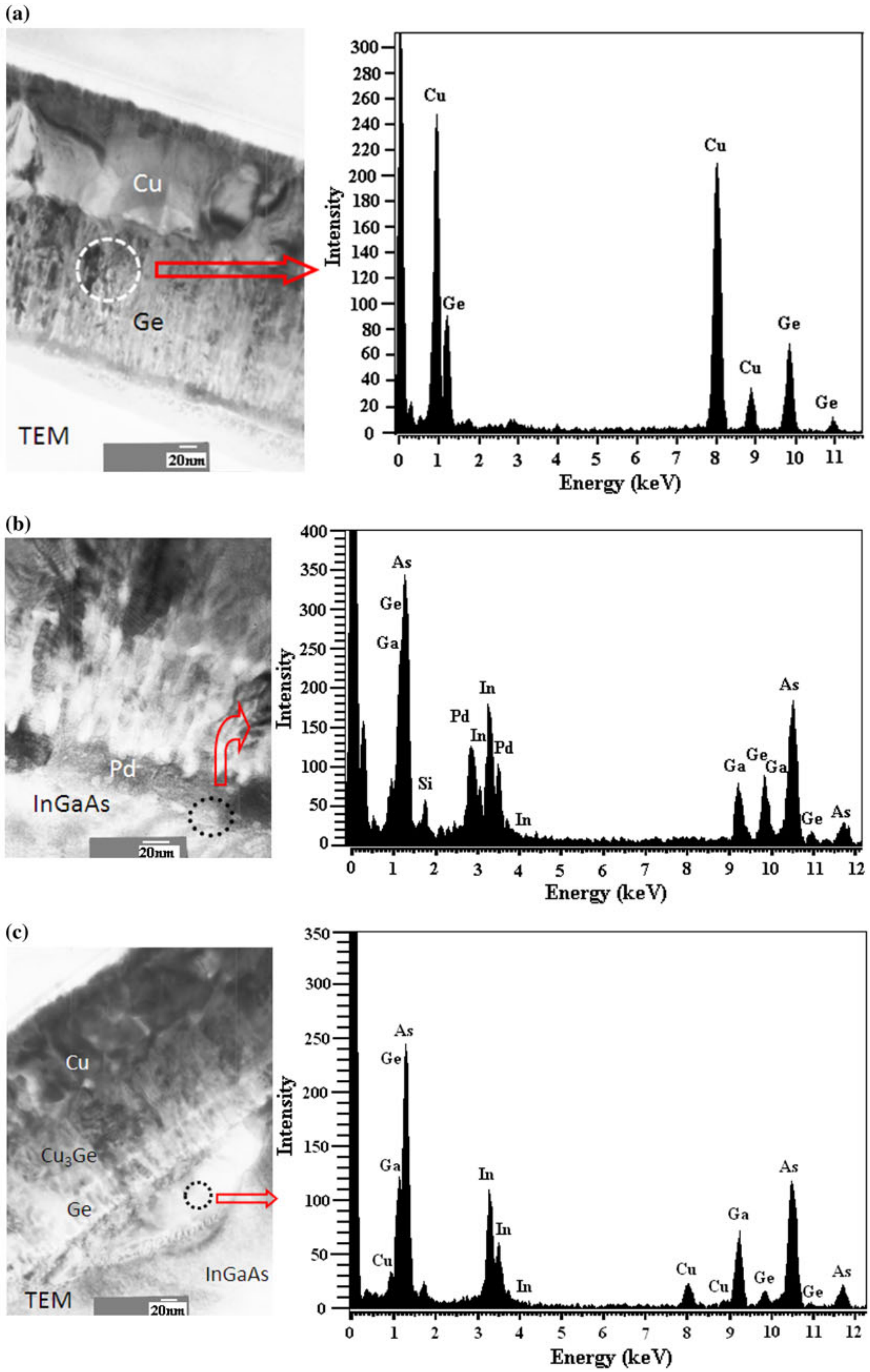

Fig. 4. TEM images of the Pd/Ge/Cu contact cross-section and the EDX profiles of the Ge/Cu compound grains: (a) after annealing at 250°C for 20 min, (b) the near-interface region between InGaAs layer and Ohmic metal after 250°C annealing, and (c) EDX profiles near the surface of InGaAs after annealing at 450°C for 20 min.

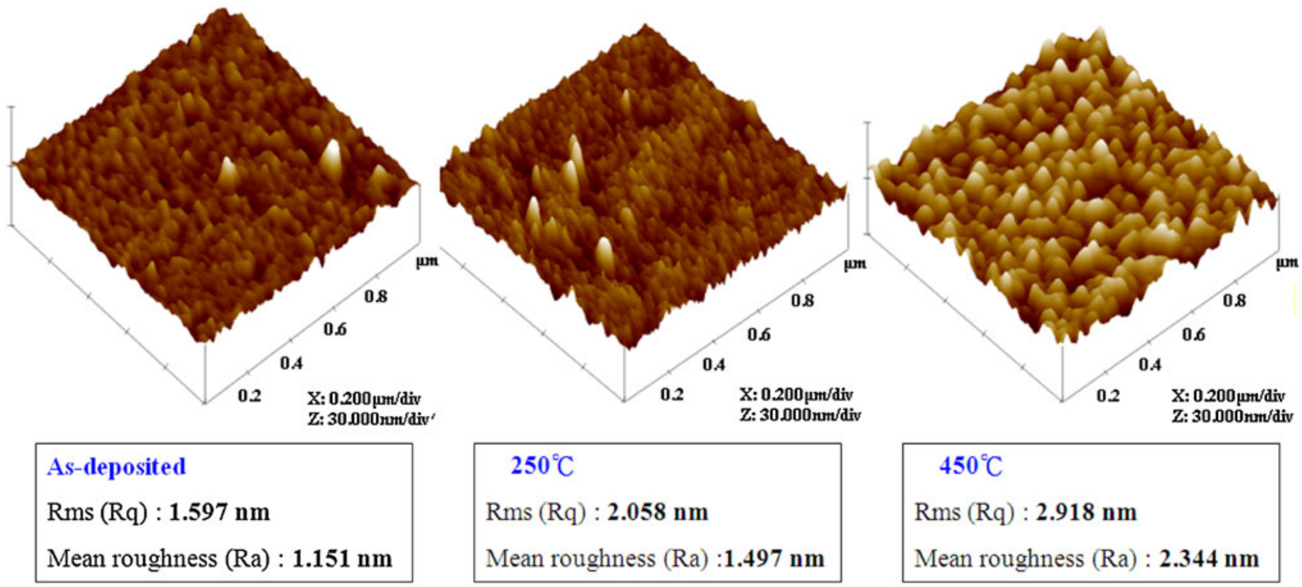

Fig. 5. AFM surface morphology of the as-deposited sample and samples after annealing at 250°C and 450°C.

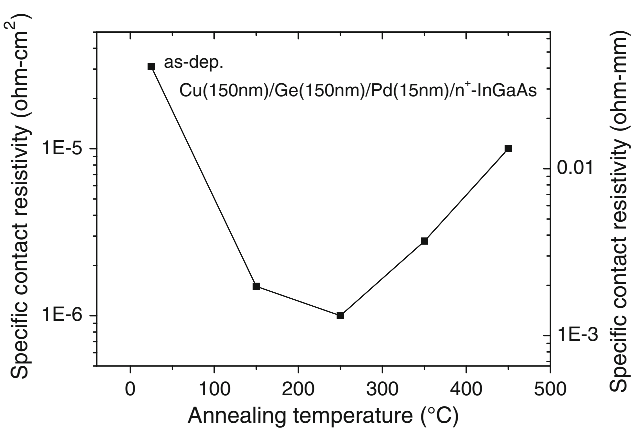

Fig. 6. Specific contact resistivity of the Pd (15 nm)/Ge (150 nm)/Cu (150 nm) contact on n-type GaAs as a function of annealing temperature after annealing (from 150°C to 450°C) for 20 min.

standard deviation of $1.1 \times 10^{-7}\ \Omega\ \mathrm{cm}^2$ following annealing at 250°C for 20 min.

To investigate the thermal stability of the Cu (150 nm)/Ge (150 nm)/Pd (15 nm) Ohmic contact, we annealed a Cu/Ge/Pd multilayer Ohmic metal at 250°C for 72 h and measured the specific contact resistivity using TLM patterns. Figure 7a shows the contact resistivity data for the samples annealed at 250°C for various durations. Figure 7b shows the sheet resistance of the Ohmic metal after long-term annealing at 250°C. From these figures, this study concluded that there was no obvious degradation in the Cu/Ge/Pd Ohmic system following annealing at 250°C for 72 h.

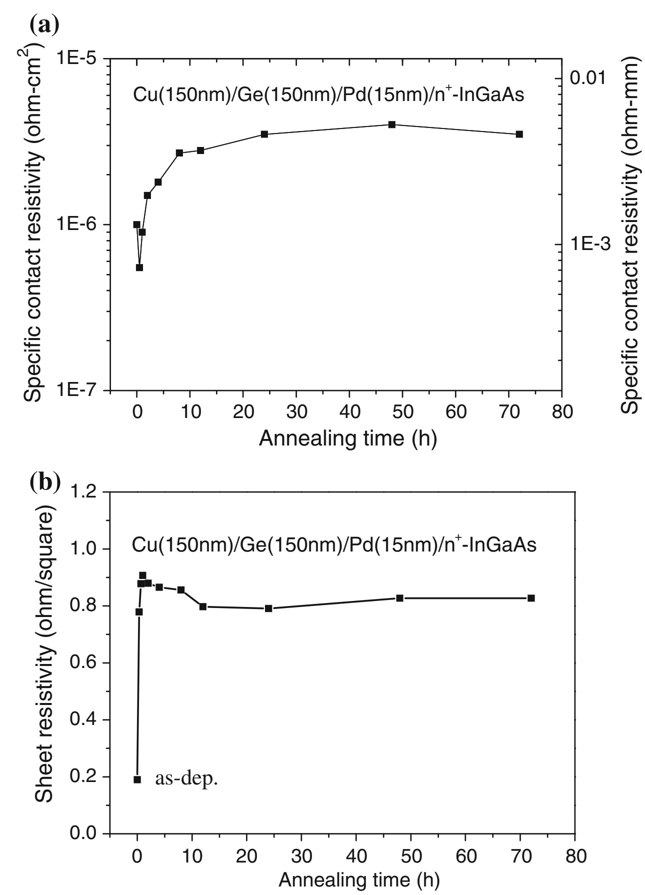

Fig. 7. (a) Specific contact resistivities and (b) sheet resistance of the Cu/Ge/Pd/n^+-InGaAs structure annealed at 250°C for long annealing time.

CONCLUSIONS

Based on our investigation employing XRD, AES, AFM, TEM, and EDX, we determined that the low contact resistivity of the Cu/Pd/Ge Ohmic contact to InGaAs was due to the formation of Cu_3Ge and $Pd_{12}Ga_5As_2$ compounds as well as the dispersion of Ga into the Ohmic metal and the diffusion of Ge into the vacancies left by the Ga. The lowest contact resistivity achieved was $1.0 \times 10^{-6}\ \Omega\,\mathrm{cm}^2$ with a standard deviation of $1.1 \times 10^{-7}\ \Omega\,\mathrm{cm}^2$ following annealing at 250°C for 20 min. The contact resistivity of the Cu/Ge/Pd–InGaAs Ohmic contact was very stable after annealing at 250°C for 72 h. Overall, the Pd/Ge/Cu Ohmic contact to InGaAs showed low contact resistivity, good thermal stability, and excellent surface morphology, making it useful for practical applications in devices.

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