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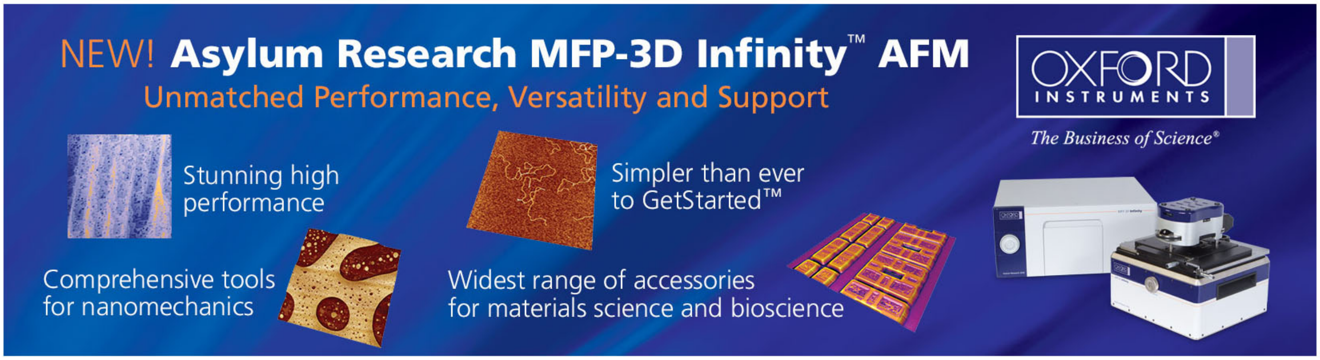

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A Cu-based alloyed Ohmic contact system on *n*-type GaAs

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An alloyed Pd/Ge/Cu Ohmic contact to *n*-type GaAs is reported for the first time. The Pd/Ge/Cu Ohmic contact exhibited a very low specific contact resistance of $5.73\times10^{-7}\ \Omega\,\text{cm}^2$ at a low annealing temperature of 250 °C. This result is comparable to the reported Pd/Ge and Au/Ge/Ni Ohmic contact systems to *n*-type GaAs with doping concentrations about $1\times10^{18}\ \text{cm}^{-3}$. The Ohmic contact formation mechanisms and microstructure evolution were investigated using secondary ion mass spectrometry, x-ray diffraction, transmission electron microscopy, and energy dispersive spectrometer. The Ohmic contact behavior was related to the formation of Cu_3Ge and $PdGa_xAs_y$ compounds after annealing. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2819687]

Copper has been widely used in metallization for the silicon based very-large scale integration because of its lower electrical resistivity, higher electromigration resistance, and lower cost.[1–3] However, there are only a few reports on the copper metallization of GaAs devices.[4,5] In previous studies, some applications of the copper metallization in metal semiconductor field-effect transistors, high electron mobility transistors and heterojunction bipolar transistors have been reported.[6–8]

The objective of this study is to develop the Cu-metallized Ohmic contact system for the GaAs devices to implement a fully copper metallized GaAs-based device.[9] Conventionally, Au/Ge/Ni Ohmic contact system is the most widely used material system for the *n*-type Ohmic contacts of the GaAs-based devices. However, the Au/Ge/Ni Ohmic contact system has several drawbacks, such as large spread of the contact resistance, poor contact edge definition, and the annealing temperature was high due to the eutectic Au/Ge alloy. In this paper, we report a low resistance alloyed Pd/Ge/Cu Ohmic contact system to *n*-type GaAs with a wide annealing temperature range of 220–350 °C. And a very low specific contact resistance of $5.73\times10^{-7}\ \Omega\,\text{cm}^2$ was achieved at a low annealing temperature of 250 °C. The low contact resistance was due to the formation of the Cu_3Ge compound and the $PdGa_xAs_y$ compound layer. In this article, the Ohmic contact formation mechanisms of the Pd/Ge/Cu Ohmic contact system will be discussed.

The structure of the substrates used for the microstructure evolution and phase transformation studies of the Pd/Ge/Cu Ohmic contact system was semi-insulating GaAs wafers with a Si-doped GaAs epitaxial layer (2000 Å and $1\times10^{18}\ \text{cm}^{-3}$). The specific contact resistances of *n*-GaAs/Pd/Ge/Cu contacts were determined by the transmission line method (TLM). Standard photolithography was used to pattern the substrates for TLM measurements. The dimension for each pad is $74\times110\ \mu\text{m}^2$. The GaAs mesa was etched by $H_3PO_4/H_2O_2/H_2O$ solutions. After the conventional organic solvent cleaning process, the substrates were chemically cleaned in a solution of HCl:H_2O (1:1 by volume) to remove the native surface oxide layer and then loaded into the evaporation chamber. Several metal compositions were deposited on the substrates using an electron-beam evaporator in a pressure of $\sim1\times10^{-6}$ Torr. After the lift-off process, the samples were annealed in a conventional N_2-ambient tube furnace at various temperatures from 150 to 450 °C for 20 min. The Ohmic contact resistance (R_C) of the samples after annealing was measured using the TLM with interspacings between the metal pads of 3, 5, 10, 20, and 36 μm.

In order to understand the formation mechanism of the Pd/Ge/Cu Ohmic contact, several analytic tools were used to study the phase transformation of the material system. Atomic distribution was examined by the secondary ion mass spectrometry (SIMS). Phase identification was analyzed by the x-ray diffraction (XRD). The interfaces of the Pd/Ge/Cu/*n*-GaAs Ohmic contact were observed by transmission electron microscopy (TEM). The compositions of the elements in the microstructure were analyzed by energy dispersive spectrometer (EDX).

The results of the specific contact resistance (ρ_c in $\Omega\,\text{cm}^2$) and the contact resistance (R_C in Ω mm) of the Pd/Ge/Cu Ohmic contact extracted from the TLM method as a function of annealing temperature after annealing in a traditional tube furnace at different temperatures for 20 min are shown in Fig. 1. Very low Ohmic contact resistance can be obtained when the Pd/Ge/Cu Ohmic contact structure was annealed at 220–350 °C for 20 min, and the correlation coefficient (r^2) of the linear curve fit used to calculate the contact resistance are in the range of 0.9995–1.0000. The lowest specific contact resistance was $5.73\times10^{-7}\ \Omega\,\text{cm}^2$ (which corresponds to the contact resistance of 0.034 Ω mm and the correlation coefficient of 0.9999) after the sample Pd (15 nm)/Ge (150 nm)/Cu (150 nm) was annealed at 250 °C for 20 min. Figure 1(a) shows the contact resistance of the Pd/Ge/Cu samples with different Pd thicknesses. As these results indicate, the Pd/Ge/Cu sample with 15 nm Pd layer has the lowest contact resistance and the thickness of the Pd layer has a significant effect on the Ohmic contact resistance.

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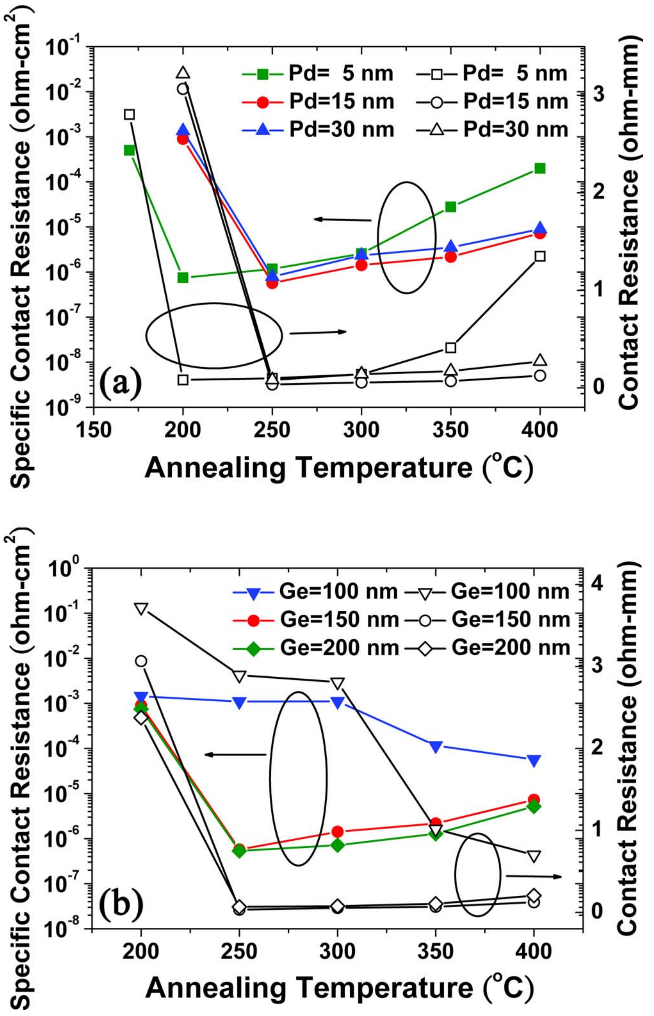

FIG. 1. (Color online) Specific contact resistance (color) and contact resistance as a function of annealing temperature for the Pd/Ge/Cu (150 nm) Ohmic contact structure to n-type GaAs with (a) different Pd thicknesses and (b) different Ge thicknesses.

The thin Pd layer in this structure enhances the adhesion of the Ohmic metals and helps the Ge atoms (donor) diffusing into the Ga vacancies in the vicinity of the GaAs surface, resulting in a heavily doped n^+-GaAs layer.[10] The Cu_3Ge compound formed after the annealing process also showed a low contact resistance. The Cu_3Ge compound has lower chemical potential for Ga, thus causing Ga atoms to outdiffuse from the GaAs substrate into the Ohmic metal layers and results in the observed Ohmic behavior. There are a few reports on Cu-metallized Ohmic contact to GaAs devices published in the past. The Ge/Cu Ohmic system proposed by Aboelfotoh *et al.* had a specific contact resistance of $6.5 \times 10^{-7}\ \Omega\ \mathrm{cm}^2$.[11] For comparison, the Ge (150 nm)/Cu (150 nm) Ohmic structure was also investigated in this study; however, the Ge/Cu Ohmic structures peeled off easily due to the weak adhesion between the Ge/Cu Ohmic metal and the GaAs surface. The Pd/Ge/Cu Ohmic structure in this study does not have the peeling off problem, because the thin Pd layer enhances the adhesion between the Ohmic contact metal and the GaAs surface. Based on the previous studies of the Pd-GaAs system,[12] we believe a ternary phase $PdGa_xAs_y$ had formed after annealing at 250 °C for 20 min. The $PdGa_xAs_y$ compound formed on the GaAs surface caused more Ga vacancies near the GaAs surface and made it easier for Ge atoms to diffuse into the Ga vacancies at the interface region and resulted in a lower contact resistance.[10] Figure 1(b) shows the Ohmic characteristics of the Pd/Ge/Cu samples with different Ge thicknesses. As these results indicate, the thickness of Ge layer also has a significant effect on the Ohmic contact resistance. The Pd/Ge/Cu sample with 150 and 200 nm Ge layers has similar low specific contact resistance, but the Pd/Ge/Cu Ohmic contact with 100 nm Ge layer has no Ohmic characteristic. It may be because there was not enough Ge atoms to react with Cu and diffuse into the GaAs. The specific contact resistance ρ_c, the contact resistance R_C, and the correlation coefficient r^2 of the Pd/Ge/Cu Ohmic contact with different Pd or Ge thicknesses as a function of annealing temperature after 20 min annealing are shown in Table I.

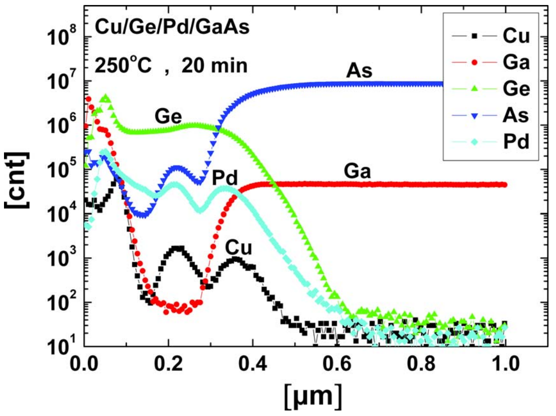

FIG. 2. (Color online) SIMS profiles of the Pd (15 nm)/Ge (150 nm)/Cu (150 nm) Ohmic contact structure after annealing at 250 °C for 20 min.

TABLE I. Specific contact resistance (ρ_c in $\Omega\ \mathrm{cm}^2$), contact resistance (R_c in Ω mm), and correlation coefficient (r^2) as a function of annealing temperature for the Pd/Ge/Cu (150 nm) Ohmic contact structure to n-type GaAs with different Pd or Ge thicknesses.

Annealing temperature (°C)	Pd/Ge/Cu 5/150/150 (nm)			Pd/Ge/Cu 15/150/150 (nm)			Pd/Ge/Cu 30/150/150 (nm)			Pd/Ge/Cu 15/100/150 (nm)			Pd/Ge/Cu 15/200/150 (nm)		
	R_c (Ω mm)	ρ_c ($\Omega\ \mathrm{cm}^2$)	r^2	R_c (Ω mm)	ρ_c ($\Omega\ \mathrm{cm}^2$)	r^2	R_c (Ω mm)	ρ_c ($\Omega\ \mathrm{cm}^2$)	r^2	R_c (Ω mm)	ρ_c ($\Omega\ \mathrm{cm}^2$)	r^2	R_c (Ω mm)	ρ_c ($\Omega\ \mathrm{cm}^2$)	r^2
200	0.08	7.43×10^{-7}	0.9993	3.066	9.01×10^{-4}	0.9435	3.219	1.35×10^{-3}	0.9827	3.723	1.43×10^{-3}	0.9636	2.375	7.45×10^{-4}	0.9918
250	0.098	1.17×10^{-6}	0.9997	0.034	5.72×10^{-7}	0.9999	0.081	7.88×10^{-7}	0.9999	2.894	1.10×10^{-3}	0.9989	0.068	5.34×10^{-7}	1.0000
300	0.138	2.55×10^{-6}	0.9999	0.054	1.42×10^{-6}	0.9997	0.139	2.35×10^{-6}	0.9999	2.810	1.11×10^{-3}	0.9988	0.077	7.14×10^{-7}	1.0000
350	0.410	2.78×10^{-5}	0.9999	0.069	2.17×10^{-6}	0.9998	0.171	3.51×10^{-6}	1.0000	1.016	1.16×10^{-4}	0.9968	0.105	1.28×10^{-6}	09999
400	1.349	1.99×10^{-4}	0.9986	0.124	7.26×10^{-6}	0.9995	0.270	8.99×10^{-6}	0.9998	0.701	5.70×10^{-5}	1.0000	0.205	5.17×10^{-6}	0.9995

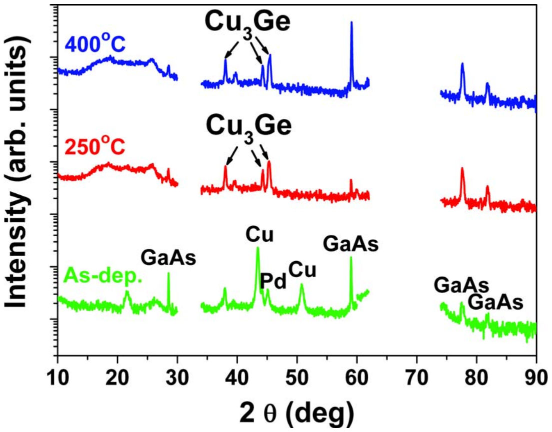

FIG. 3. (Color online) X-ray diffraction patterns for the Pd (15 nm)/Ge (150 nm)/Cu (150 nm) Ohmic contact structure as deposited and after annealing at 250 and 400 °C for 20 min.

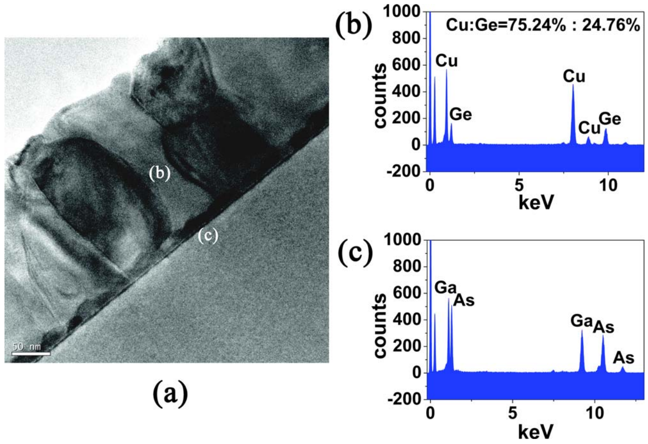

FIG. 4. (Color online) (a) The TEM image of the Pd (15 nm)/Ge (150 nm)/Cu (150 nm) Ohmic contact. (b) The EDX profiles of the Cu_3Ge compound grain. (c) The EDX profiles of the GaAs substrate near the Pd/GaAs interface after annealing at 250 °C for 20 min.

Figure 2 shows the SIMS depth profiles after the sample was annealed at 250 °C for 20 min. From the SIMS profiles, it can be seen that the Ge atoms diffused into GaAs and diffused out into the Ohmic layer. As mentioned above, the formation of the Cu_3Ge compound and the Pd_xGaAs compound after annealing helped the interdiffusion of the Ga and Ge atoms. The diffusion of the Cu atoms into the GaAs substrate is a very important issue for the copper metallization process. In the Pd/Ge/Cu Ohmic metal system, most of the Cu atoms in the Pd/Ge/Cu Ohmic metal structure were consumed due to the formation of Ge/Cu compounds after annealing. Figure 3 shows the x-ray diffraction profiles for the Pd (15 nm)/Ge (150 nm)/Cu (150 nm) Ohmic contact structure as deposited and after annealing at 250 and 400 °C for 20 min. It is obvious from these data that the Cu_3Ge compounds started to form when the annealing temperature was higher than 250 °C. Thus, the Ohmic contact behavior was related to the formation of Cu_3Ge compounds when the annealing temperature was above 250 °C.

The TEM images and the EDX profiles of the Pd/Ge/Cu Ohmic metal structure after 250 °C annealing are shown in Figs. 4(a) and 4(b), the Cu_3Ge compound started to form with vertical grain boundary. Literature shows that the Cu_3Ge metallic compound has low resistance and the Ga atoms have lower chemical potential in Cu_3Ge than that in GaAs.[11] The EDX profiles in Fig. 4(c) also show that there was still no Cu atom diffusion into the GaAs substrate near the Pd/GaAs interface after 250 °C annealing.

A Pd/Ge/Cu Ohmic contact structure to *n*-type GaAs is reported in this study. The optimized Pd (15 nm)/Ge (150 nm)/Cu (150 nm) metal structure exhibits a low specific contact resistance of $5.73 \times 10^{-7}\ \Omega\,\mathrm{cm}^2$ to *n*-type GaAs after annealing at 250 °C for 20 min. From the SIMS, XRD, TEM, and EDX studies, the mechanisms for the Pd/Ge/Cu Ohmic contact formation were identified. The low contact resistance for this Ohmic structure was due to the formation of the Cu_3Ge and $PdGa_xAs_y$ compounds and the outdiffusion of Ga into the Ohmic metal in conjunction with the diffusion of Ge into the Ga vacancies.

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