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Novel Cu/Cr/Ge/Pd Ohmic Contacts on Highly Doped n-GaAs

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The thermal stability of the Cu/Cr/Ge/Pd/n$^+$-GaAs contact structure was evaluated. In this structure, a thin 40 nm layer of chromium was deposited as a diffusion barrier to block copper diffusion into GaAs. After thermal annealing at 350°C, the specific contact resistance of the copper-based ohmic contact Cu/Cr/Ge/Pd was measured to be $(5.1 \pm 0.6) \times 10^{-7}\ \Omega\ \text{cm}^2$. Diffusion behaviors of these films at different annealing temperatures were characterized by metal sheet resistance, X-ray diffraction data, Auger electron spectroscopy, and transmission electron microscopy. The Cu/Cr/Ge/Pd contact structure was very stable after 350°C annealing. However, after 400°C annealing, the reaction of copper with the underlying layers started to occur and formed Cu_3Ga, Cu_3As, Cu_9Ga_4, and Ge_3Cu phases due to interfacial instability and copper diffusion.

Key words: Thermal stability, annealing, ohmic contact, diffusion

INTRODUCTION

Low-resistance ohmic contacts that are thermally stable are essential for GaAs-based microwave and millimeter-wave devices.[1] Since IBM first engaged in the copper interconnection technology,[2–4] copper metallization has attracted great attention in the silicon integrated circuit (IC) industry. Conventionally, gold is used as the contact and interconnect metal for GaAs microwave devices and circuits. Using copper in place of gold as the metallization metal for the GaAs devices has the advantages of lower resistivity, higher thermal conductivity, and lower cost. Copper diffuses very quickly into silicon without any diffusion barrier.[5] It is generally confirmed that the rapid diffusion results from singly ionized interstitial copper that migrates as a positively charged ion in silicon.[6] Similarly, copper is known to diffuse rapidly into GaAs via a kick-out mechanism in the absence of a diffusion barrier[7] to create deep traps that degrade device characteristics. Even though copper metallization has played an important role in the silicon IC industry, there are few papers related to copper metallization for GaAs devices.[8–10]

The AuGeNi alloyed ohmic contact was commonly used as the ohmic contact to n-GaAs in the past. In this study, the feasibility of using novel Pd/Ge-based copper ohmic contacts on highly doped n-GaAs is investigated. In comparison with the AuGeNi ohmic system, the PdGe-based ohmic contact has the following advantages: (1) a better surface morphology, and (2) a better contact edge definition due to the solid phase regrowth.[11] In this Cu/Cr/Ge/Pd structure, Ge/Pd was used to reduce the contact resistance. The refractory metal chromium was used as the diffusion barrier between Cu and the underlying materials due to its high melting point and low solubility in copper even at high temperatures.[12] The thick Cu metal on the top was used to reduce the sheet resistance of the metal layers.

EXPERIMENTAL

The ohmic contact structure of Cr/Cu/Cr/Ge/Pd/n$^+$-GaAs was prepared for electrical and materials characterizations. The substrates were semi-insulating (100) GaAs wafers with Si-doped layers

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($\sim 5 \times 10^{18}$ cm^{-3}, 0.2 μm) grown by metalorganic chemical vapor deposition (MOCVD). After an ohmic contact pattern was defined by photolithography, the ohmic metals were deposited by electron beam evaporation. A palladium film of 50 nm thickness was evaporated on top of the n$^+$-GaAs substrate first, and 125 nm germanium was evaporated on the Pd film. To avoid copper contamination in the Au metallized process, the substrate was transferred to another electron beam chamber for evaporation of Cr(40 nm)/Cu(150 nm)/Cr(15 nm) thin-film stacks. Note that for the test samples, a top Cr (15 nm) layer was deposited on the surface of Cu to prevent the copper layer from oxidizing during further study. After metal deposition, the samples were annealed in a nitrogen ambient, and followed by a series of material analyses. X-ray diffraction (XRD), Auger electron spectroscopy (AES), transmission electron microscopy (TEM), and four-point probe measurements were used to identify the phases formed and the interfacial reactions of the contact metals.

DISCUSSION

The specific contact resistances of the Cr/Cu/Cr/Ge/Pd/n$^+$-GaAs ohmic contacts were obtained by the transmission-line method (TLM) using a Keithley 2400 source meter. The TLM pattern, as illustrated in Fig. 1, was designed in the process control monitor (PCM) in order to measure the ohmic contact resistance and to identify the ohmic contact characteristics. In our measurements, the distances between TLM electrodes were 3 μm, 5 μm, 10 μm, 20 μm, and 36 μm, respectively. Figure 2 shows specific contact resistance as a function of annealing temperature after a 10-min anneal of the Cr/Cu/Cr/Ge/Pd/n$^+$-GaAs structure. The lowest specific contact resistance was achieved after 350°C annealing for 10 min. At this annealing temperature, the specific contact resistance of the Cr/Cu/Cr/Ge/Pd/n$^+$-GaAs contact was measured to be $(5.1 \pm 0.6) \times 10^{-7}$ Ω cm^2. In order to evaluate the metal sheet resistances during thermal processing, n$^+$-GaAs substrates with Cr/Cu/Cr/Ge/Pd metal stacks on top of the entire surface were prepared. Four-point probe measurements (collinear structure, Napson RT-7) were used to measure the metal sheet resistances of the ohmic metal structure at different annealing temperatures, and a 10×10 mm^2 square sample size was used. Figure 3 shows the metal sheet resistances of the Cr/Cu/Cr/Ge/Pd/n$^+$-GaAs structure after annealing at 300°C, 350°C, and 400°C for 30 min. The lowest metal sheet resistance was also achieved after the sample was annealed at 350°C, which was mainly due to grain growth and a decrease in the defect density in the ohmic metals. The metal sheet resistance of the ohmic contact increased drastically after annealing at 400°C, implying that significant atomic diffusion and the interfacial reactions between the Cu layer and the underlying films had occurred. To confirm that the low metal sheet resistance obtained from the four-point probe method was due mostly to the metal layers and not by the highly doped n-GaAs layer, the bulk resistance and the sheet resistance of the semiconductor without metal layers were also measured by the four-point probe measurement; the

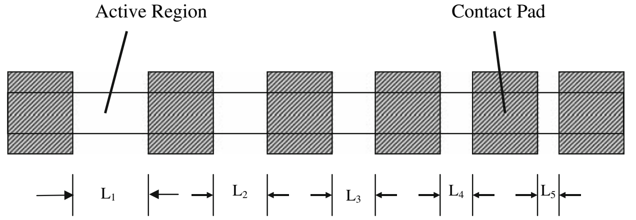

Fig. 1. Transmission-line method (TLM) patterns, where L_1, L_2, L_3, L_4, and L_5 are 36 μm, 20 μm, 10 μm, 5 μm, and 3 μm, respectively.

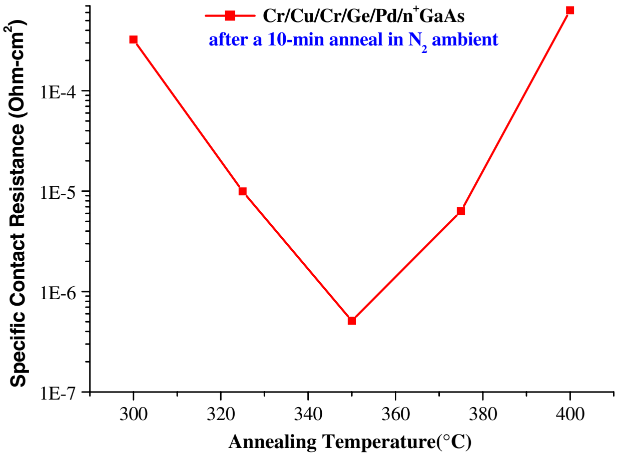

Fig. 2. Specific contact resistivity as a function of annealing temperature after a 10-min anneal for the Cr/Cu/Cr/Ge/Pd/n$^+$-GaAs ohmic structure.

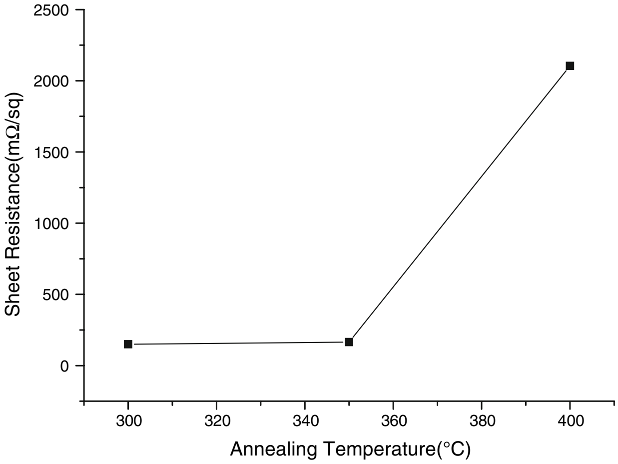

Fig. 3. Metal sheet resistance of the Cr/Cu/Cr/Ge/Pd/n$^+$-GaAs ohmic structure after annealing at 300°C, 350°C, and 400°C for 30 min.

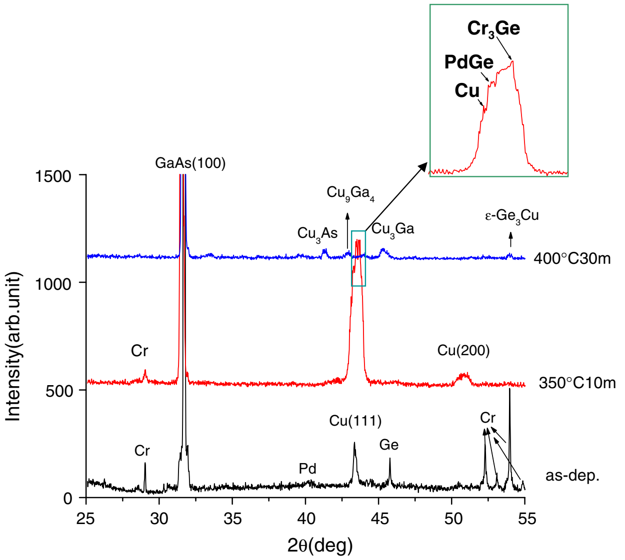

Fig. 4. XRD results of the Cr/Cu/Cr/Ge/Pd/n$^+$-GaAs ohmic structure, as deposited and after annealing at various temperatures.

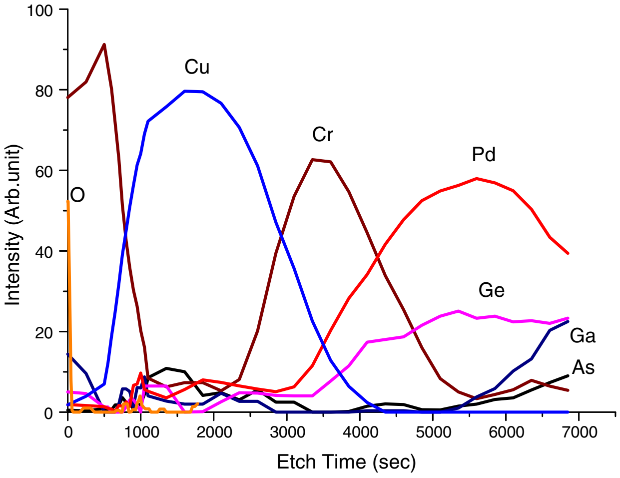

Fig. 5. AES depth profiles of the Cr/Cu/Cr/Ge/Pd/n$^+$-GaAs ohmic structure after annealing at 350°C for 10 min.

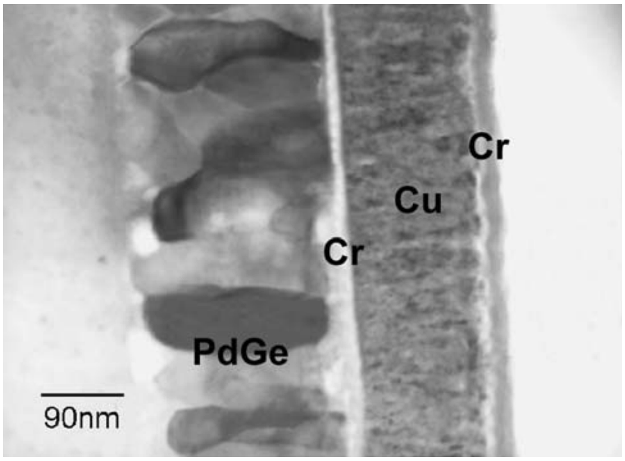

Fig. 6. Cross-sectional TEM micrograph of the Cr/Cu/Cr/Ge/Pd/n$^+$-GaAs ohmic structure after annealing at 350°C for 10 min.

resulting data were 4.14 kΩ and 287.7 Ω/square, respectively. The lowest metal sheet resistance after metallization and annealing at 350°C was 230 mΩ/square. By comparing the sheet resistances, we can see that the semiconductor sheet resistance is much higher than the metal sheet resistance. Since the resistance of the metal layer and the resistance of the semiconductor layer are in parallel with each other, the sheet resistance we measured is mostly contributed by the metal layers. This indicates that there is only negligible parallel conduction in the semiconductor layer. XRD was used to identify the interfacial reactions between the ohmic metals and n$^+$-GaAs. Figure 4 shows the XRD patterns of the Cr/Cu/Cr/Ge/Pd/n$^+$-GaAs, as deposited and after annealing at 350°C and 400°C. From a careful inspection of the peak at about 43 deg after annealing at 350°C reveals Cr$_3$Ge, PdGe, and Cu (111) peaks. This further indicates that Pd reacts with Ge to form large PdGe grains and reveals the reaction of Cr with Ge to form Cr$_3$Ge. The metal-like behavior of Cr$_3$Ge with higher Cr concentration could reduce the contact resistance of the proposed structure. The XRD data show no extra copper compound formed after annealing up to 350°C, suggesting that the contact was quite stable up to 350°C. This is consistent with the results of TLM measurements. When the annealing temperature was increased to 400°C, the interdiffusion of the ohmic metals and the substrate material occurred. Extra compounds such as Cu$_3$Ga, Cu$_3$As, Cu$_9$Ga$_4$ and ε-Ge$_3$Cu formed after 400°C annealing as indicated in the XRD data. This result indicates that the multilayer structure was destroyed as a result of the strong reaction of Cu with Ga to form Cu$_9$Ga$_4$ and Cu$_3$Ga, the reaction of Cu with As to form Cu$_3$As, and the reaction of Ge with Cu to form Ge$_3$Cu after the failure of the Cr diffusion layer due to massive diffusion of the elements. It is apparent that the Cr diffusion barrier failed to prevent the Cu atoms from penetrating into the Pd/Ge layers, and the Cu atoms diffused through Cr barrier and reacted with the Pd/Ge metals and GaAs at this temperature. This is consistent with the drastic increase of the metal sheet resistance after annealing at 400°C as shown in Fig. 3. Additional evidence showing the stability of the contact after 350°C annealing can be seen from the AES depth profiles shown in Fig. 5. As can be seen from this figure, the Auger depth profiles clearly indicate that the Cr layer was very stable and there was no Cu diffusion into the Pd/Ge layers after 350°C annealing. To further investigate the reactions at the interfaces after thermal annealing at 350°C, cross-sectional TEM analysis was performed on the annealed samples. Figure 6 shows the cross-sectional TEM micrograph of this ohmic contact after 10 min, 350°C annealing. In Fig. 6, the TEM image shows that the PdGe grains formed after

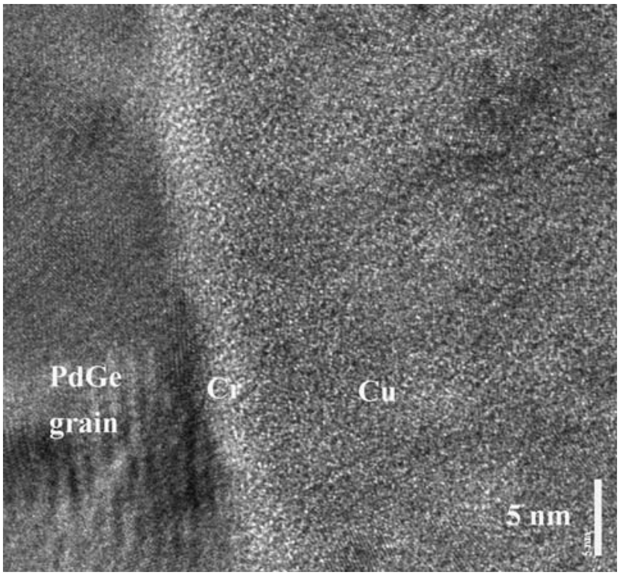

Fig. 7. High-resolution TEM micrograph of the Cu/Cr/Ge/Pd ohmic contact structure after annealing at 350°C for 10 min.

350°C annealing. Radulescu et al. suggested that the PdGe phase dominated in the Pd:Ge reaction after 322°C annealing. At the low contact resistance, ohmic contact formation was mainly due to the PdGe phase formed.[13] Figure 6 also shows no evidence of intermixing between Cu and Cr, indicating that Cr is a reliable diffusion barrier for Cu. Figure 7 shows the high-resolution TEM micrograph of the Cu/Cr/Ge/Pd contact structure after 350°C annealing. This result shows that the interfaces between the contact metals were quite sharp, indicating again that the Cr is an effective diffusion barrier between Cu and underlying metals. Judging from the data of XRD, AES, and TEM described above, it can be concluded that Cr is a reliable diffusion barrier for Cu ohmic contacts on n^+-GaAs, and that Cu/Cr/Ge/Pd is an effective low contact resistance ohmic contact to n^+-GaAs.

CONCLUSIONS

A Cu/Cr/Ge/Pd ohmic contact was proposed and characterized. The Cu/Cr/Ge/Pd ohmic contact structure achieved a lowest contact resistance of $(5.1 \pm 0.6) \times 10^{-7}\ \Omega\ \text{cm}^2$ after annealing at 350°C. At this temperature, the reaction of Cr with Ge to form the intermetallic Cr_3Ge compound could reduce the contact resistance. However, the contact structures deteriorated after annealing at 400°C due to the interfacial reactions between Cu and the underlying films. The metal sheet resistance, XRD, AES, and TEM analysis data also proved that Cr is a reliable diffusion barrier for the Cu-based ohmic contacts to n^+-GaAs for annealing up to 350°C and failed to be an effective diffusion barrier after annealing at 400°C. The experimental results in this study suggest that Cu/Cr/Ge/Pd is an effective copper-based ohmic contact structure and can be used for future copper metallization of GaAs-based electronic devices.

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