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Application of Pd/Ge/Cu alloyed ohmic contact system to n-type GaAs for fully Cu-metallized InGaP/GaAs HBTs

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ABSTRACT

Use of the Pd/Ge/Cu multilayers as the emitter and collector ohmic metal for the fully Cu-metallized InGaP/GaAs heterojunction bipolar transistors is studied. The Pd/Ge/Cu ohmic contact exhibited a very low contact resistance of $5.73 \times 10^{-7}\ \Omega\,cm^2$ at a low annealing temperature (250 °C) and the microstructure evolution of Pd/Ge/Cu ohmic contact was investigated using transmission electron microscopy and energy dispersive spectrometer. We also did some comparisons between the Pd/Ge/Cu, Pd/Ge/Ti/Pt/Cu, and the traditional Au/Ge/Ni/Au ohmic contact structures to n-type GaAs. The common emitter *I–V* curves and Gummel plot of these Cu-metallized HBTs using Pd/Ge/Cu ohmic contact and Cu interconnects showed similar electrical characteristics as those HBTs with conventional Au-metallization. The cutoff frequency (f_T) of 3 × 20-µm-emitter-area devices was about 38 GHz. During both the current-accelerated stress test (110 kA/cm^2 stress for 24 h) and the thermal stability test (annealing at 250 °C for 24 h), the fully Cu-metallized HBT with Pd/Ge/Cu ohmic contact and Cu interconnects showed almost no obvious degradation in electrical characteristics. The results show that the Pd/Ge/Cu ohmic contact in combination with the Cu interconnects can be used on HBT devices to achieve the Au-free fully Cu-metallized InGaP/GaAs HBTs, and the devices exhibit good device performance.

1. Introduction

Copper has been widely used in metallization for the silicon based very-large scale integration (VLSI) because of its lower electrical resistivity, higher electromigration resistance and lower cost [1–3]. However, even though copper metallization has become very popular in the fabrication of Si devices, there are only a few reports on the copper metallization of GaAs devices [4,5]. Comparing to the commonly used Au-metallization for GaAs devices, Cu has lower resistivity, higher thermal conductivity, higher electromigration resistance, and lower cost. In the previous studies, backside copper metallization, Cu Schottky structure in the GaAs metal semiconductor field-effect transistors (MESFETs) [6], the use of copper air-bridges in low-noise GaAs high electron mobility transistors (HEMTs) [7], and the interconnect copper metallization using WN_x as the diffusion barrier for InGaP/GaAs heterojunction bipolar transistors (HBTs) have been reported [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. 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, this ohmic system was not compatible with other Cu metallization scheme. In addition, 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 (the Au–Ge eutectic temperature is 361 °C).

In this paper, we report a low resistance Pd/Ge/Cu ohmic contact system to n-type GaAs with a wide annealing temperature range (220–350 °C). A very low contact resistance of $5.73 \times 10^{-7}\ \Omega\,cm^2$ 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.

The Pd/Ge/Cu ohmic contact was also used as the emitter and collector ohmic metals for a fully Cu-metallized InGaP/GaAs HBTs. The fully Cu-metallized HBTs in this study uses Pt/Ti/Pt/Cu for base ohmic metal, and is passivated with silicon nitride film, and Ti/Pt/Cu for interconnect metal with Pt as the diffusion barrier. The Cu-metallized base metal and interconnect metal used in this study were developed in our previous study [9].

The DC and RF characteristics of the fully Cu-metallized HBTs are also evaluated in this paper. For comparison, the traditional GaAs HBTs using Au based ohmic contacts and interconnects are also fabricated and evaluated. Here, we are reporting the fabrication and electrical performance of the Au-free fully Cu-metallized InGaP/GaAs HBTs with Pd/Ge/Cu as the emitter and collector ohmic contact metal for the first time.

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2. Experimental

The experiments in this study include two parts. The first part is the formation mechanism of the Pd/Ge/Cu ohmic contact system. The substrates used for the ohmic contact resistance measurement in this study were semi-insulating GaAs wafers with a Si-doped GaAs epitaxial layer (2000 Å, 1×10^{18} cm^{-3}). The specific contact resistances of n-GaAs/Pd/Ge/Cu were determined by the transmission line method (TLM). Standard photolithography was used to pattern the substrates for TLM measurements. 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 $\sim 1 \times 10^{-6}$ Torr. After lift-off process, the samples were annealed in a conventional N_2-ambient tube furnace at various temperatures from 150 °C 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. The microstructure evolution of Pd/Ge/Cu/n-GaAs ohmic contact was observed by transmission electron microscopy (TEM) and the compositions of the elements in the microstructure were analyzed by energy dispersive spectrometer (EDX).

The second part of this paper is the Au-free fully Cu-Metallized InGaP/GaAs HBTs fabrication using Pd/Ge/Cu as the emitter and collector ohmic metals. The epitaxial layers of the InGaP/GaAs single heterojunction bipolar transistors (SHBTs) were grown by molecular beam epitaxy (MOCVD) on semi-insulating (100) GaAs substrate. The layer structure consists of (from bottom to top) a n^+-GaAs subcollector (500 nm, 4×10^{18} cm^{-3}), a n^--GaAs collector (700 nm, 2×10^{16} cm^{-3}), a p^+-GaAs base (83 nm, 3×10^{19} cm^{-3}), an n-InGaP emitter (50 nm, 3×10^{17} cm^{-3}), and an n^+-GaAs cap (200 nm, 3×10^{18} cm^{-3}). The HBT devices were fabricated using a standard triple mesa process. The InGaP and GaAs layers were etched by HCl/H_3PO_4 and $H_3PO_4/H_2O_2/H_2O$ solutions, respectively. Pd/Ge/Cu, Pt/Ti/Pt/Cu, and Pd/Ge/Cu ohmic metal systems were used for the emitter, base, and collector ohmic contacts, respectively. The passivation of the device was realized with PECVD silicon nitride. After opening the via on the nitride film, Ti/Pt/Cu interconnect metal were sequentially deposited by electron-beam evaporator. The bulk of the resist and metal were then removed by a wet solvent lift-off process, followed by a high pressure DI water rinse to remove the residues. The HBTs with conventional Au-metallization were also prepared for comparison. The structure of the InGaP/GaAs HBTs in this study is shown in Fig. 1.

After all process, the DC current–voltage (I–V) characteristics of the HBT devices were measured by HP4142B. The collector to emitter voltage (V_{CE}) was biased from 0 to 3 V for the 3×20 µm^2 and 4×20-µm^2-emitter-area HBT devices. Both the Cu-metallized InGaP/GaAs HBT with Pd/Ge/Cu ohmic contact and the traditional Au-metallized HBT were stressed using current-accelerated test and high-temperature thermal annealing test for reliability evaluation and comparison. The high current test was performed at a high emitter current density of 110 kA/cm^2 at collector-emitter voltage of 1.5 V for 24 h. The thermal annealing test was carried out by annealing at 250 °C for 24 h in nitrogen ambient.

The RF performance of the HBT devices was characterized by on-wafer-S-parameter measurements using HP8510C network analyzer. The S-parameters were measured in frequencies ranging from 1 to 40 GHz. The h_{21} as a function of frequency were measured under collector-emitter voltage (V_{CE}) of 2 V, 2.5 V, and 3 V. The base current was 0.06, 0.08, 0.1, 0.12, and 0.14 mA. The f_T was extrapolated with a −20 dB/decade slope.

3. Results and discussion

The results of the specific contact resistance (ρ_c in Ω cm^2) of the Pd/Ge/Cu ohmic contact extracted from the transmission line measurements (TLM) as a function of annealing temperature after annealing in a traditional tube furnace at different temperatures for 20 min are shown in Fig. 2. 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. The lowest specific contact resistance was 5.73×10^{-7} Ω cm^2 after the sample Pd (15 nm)/Ge (150 nm)/Cu (150 nm) was annealed at 250 °C for 20 min. Fig. 2 also shows the contact resistance of the Pd/Ge/Cu samples with different Pd or Ge 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 value of the ohmic contact resistance. 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 than GaAs for Ga, thus causing Ga atoms to out-diffuse 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 had a specific contact resistance of 6.5×10^{-7} Ω 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 doesn't 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 lower contact resistance [10]. As Fig. 2 shows, the thickness of Ge layer also has a significant effect on the ohmic contact resistance. The Pd/Ge/Cu sample with 150 nm and 200 nm Ge layer have 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 TEM images and the EDX profiles of the Pd/Ge/Cu ohmic metal structure after 250 °C annealing are shown in Fig. 3a and 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 in GaAs [11]. The EDX profiles in Fig. 3c also show that there was no Cu atom diffusion into the GaAs substrate near the Pd/GaAs interface after 250 °C annealing. On the other hand, the $PdGa_xAs_y$ compound started to appear at the GaAs surface after 250 °C annealing as shown in Fig. 3d. So the final structure of the Pd/Ge/Cu ohmic contact system is $Cu_3Ge/PdGa_xAs_y$/Ge-doped GaAs/GaAs.

We also did some comparisons between the Pd/Ge/Cu, Pd/Ge/Ti/Pt/Cu, and the traditional Au/Ge/Ni/Au ohmic contact structures to n-type GaAs, and the results were shown in Figs. 4–6.

Fig. 4 shows the comparison of the sheet resistance (R_s in Ω/sq) as a function of annealing temperature for the Pd/Ge/Cu, Pd/Ge/Ti/Pt/Cu, and Au/Ge/Ni/Au ohmic contact structures to n-type GaAs. The sheet resistance of the Au/Ge/Ni/Au structure drastically increased after 350 °C annealing, and the Pd/Ge/Ti/Pt/Cu structures

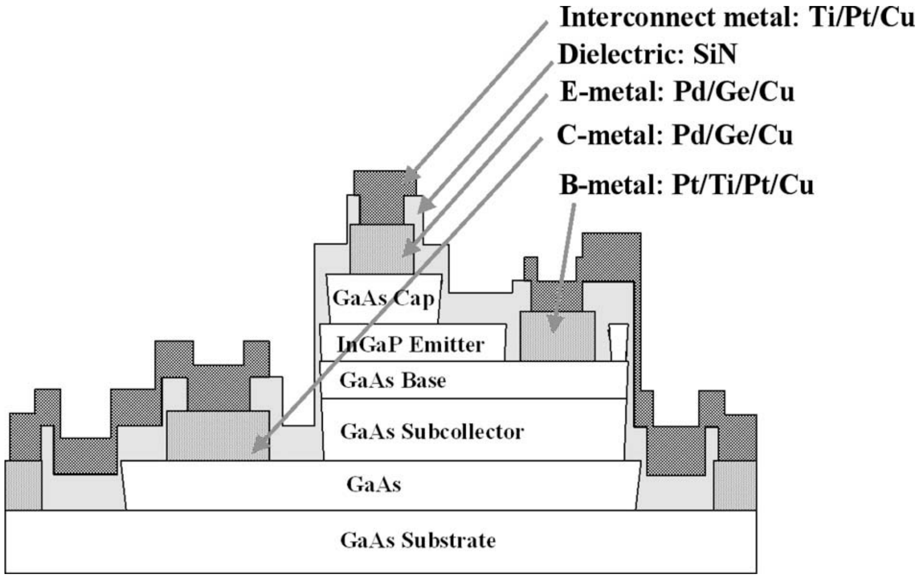

Fig. 1. Cross-section of the fully Cu-metallized InGaP/GaAs HBT with Pd/Ge/Cu as the emitter and collector ohmic contacts.

slightly increased after 450 °C annealing which was due to the atomic diffusion and inter-atomic reactions between these layers. From this figure, we can see that the Pd/Ge/Cu ohmic contact to n-type GaAs is stable up to 450 °C annealing.

The sheet resistance (R_s in Ω/sq) as a function of annealing time for the Pd/Ge/Cu, Pd/Ge/Ti/Pt/Cu, and Au/Ge/Ni/Au ohmic contact structures to n-type GaAs at 350 °C and 450 °C were shown in Figs. 5 and 6, respectively. As Fig. 5 shows, all the ohmic contact structures were stable up to 72 h annealing at 350 °C. However, we can see from Fig. 6, the sheet resistance of the Au/Ge/Ni/Au structure drastically increased after 24 h annealing at 450 °C, and the Pd/Ge/Cu and the Pd/Ge/Ti/Pt/Cu structures were stable up to 72 h annealing at 450 °C.

The Pd/Ge/Cu ohmic contact was applied to the fully Cu-metallized InGaP/GaAs HBTs as the emitter and collector ohmic metals.

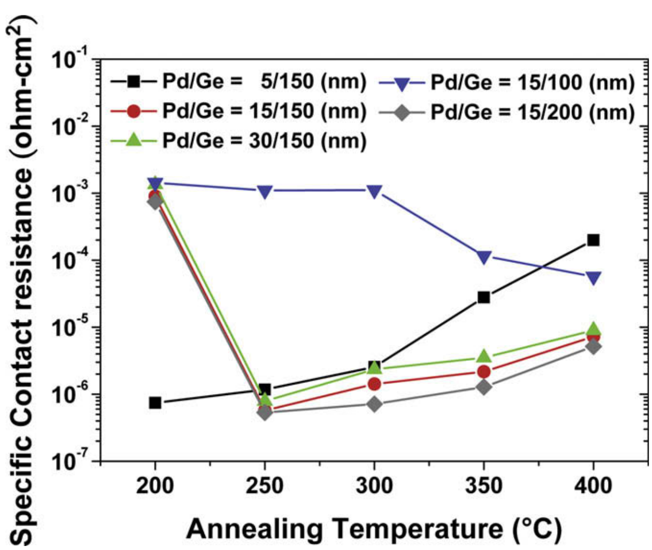

Fig. 2. Specific contact resistance (ρ_c in $\Omega\,cm^2$) as a function of annealing temperature for the Pd/Ge/Cu (150 nm) ohmic contact structure to n-type GaAs with different Pd or Ge thicknesses.

In this fully Cu-metllized HBT, Pt/Ti/Pt/Cu was used for the base metal, SiN_x was used for passivation, and Ti/Pt/Cu was used for interconnect metal with Pt as the diffusion barrier. InGaP/GaAs HBTs with traditional n-type ohmic metal (Au/Ge/Ni/Au), and p-type ohmic metal (Pt/Ti/Pt/Au), and interconnect metal (Ti/Au) were also processed on half of the same wafer for the device performance comparison. Fig. 7 shows the typical common emitter characteristics of HBTs with emitter-area of $4 \times 20\ \mu m^2$. It can be seen from Fig. 7 that these two kinds of HBTs show similar knee voltage and offset voltage. We did not observe significant increase in the knee voltage or decay in the collector current. The common emitter current gain was around 130 for both cases. Gummel plots of the HBTs with the traditional Au-metallized and the Au-free fully Cu-metallized were also compared as shown in Fig. 8 and it can be seen that the two HBTs showed similar behaviors. These results indicate that the InGaP/GaAs HBT with Pd/Ge/Cu ohmic contact has comparable performance with the device with Au-metallized ohmic contact.

To test the reliability of the fully Cu-metallized HBTs using Pd/Ge/Cu as the n-type ohmic metal, the devices with 4×20-μm^2-emitter-area were subjected to current-accelerated stress test with high current density of 110 kA/cm^2. It is much higher than 25 kA/cm^2 required for the normal device operation and the purpose is to shorten the stress time so that the stress tests could be performed at wafer level without using any package and the results could be obtained in a few hours [13]. Fig. 9 plots the current gain (β) of the fully Cu-metallized HBTs with Pd/Ge/Cu ohmic contact after stressed at the high current density of 110 kA/cm^2 with V_{CE} of 2.5 V for a period of 24 h. The measurements were made at an ambient room temperature of T_A = 25 °C. It can be seen from the data that the current gain of the device showed no significant change with time. The change in the ratio of the final/initial current gain was less than 4% for the device and was still higher than 115 after the current-accelerated stress test for 24 h.

To study the thermal stability of the fully Cu-metallized HBT with Pd/Ge/Cu ohmic contact, the 4×20-μm-emitter-area HBT devices were annealed at 250 °C for 24 h and tested for the electrical performance. Fig. 10 shows the common emitter I–V curves of the fully Cu-metallized HBT before and after the annealing and there is no obvious change in the offset voltage, knee voltage, and satura-

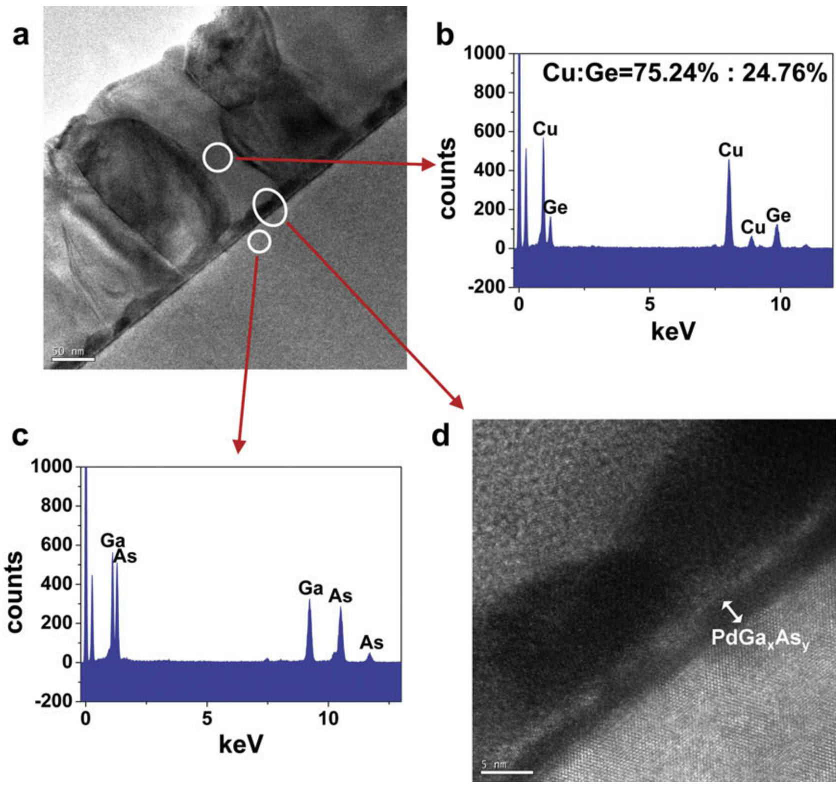

Fig. 3. (a) The TEM image of the Pd (150 Å)/Ge (1500 Å)/Cu (1500 Å) ohmic contact, (b) the EDX profiles of the Cu_3Ge compound grain, (c) the EDX profiles of the GaAs substrate near the Pd/GaAs interface, and (d) the TEM image of the interface between Pd layer and GaAs substrate after annealing at 250 °C for 20 min.

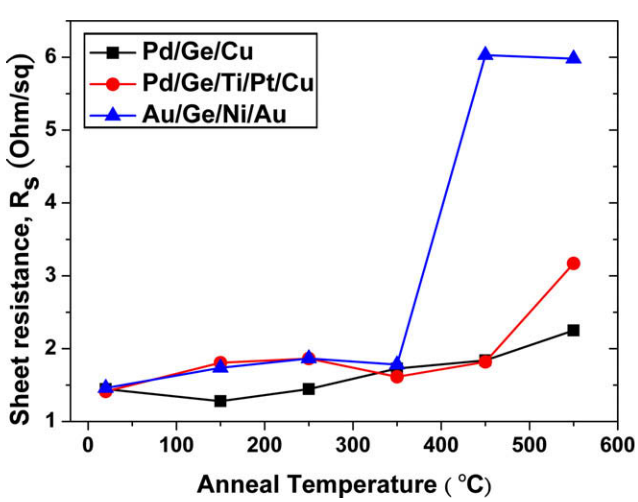

Fig. 4. Sheet resistance (R_s in Ω/sq) as a function of annealing temperature for the Pd/Ge/Cu, Pd/Ge/Ti/Pt/Cu, and Au/Ge/Ni/Au ohmic contact structures to n-type GaAs.

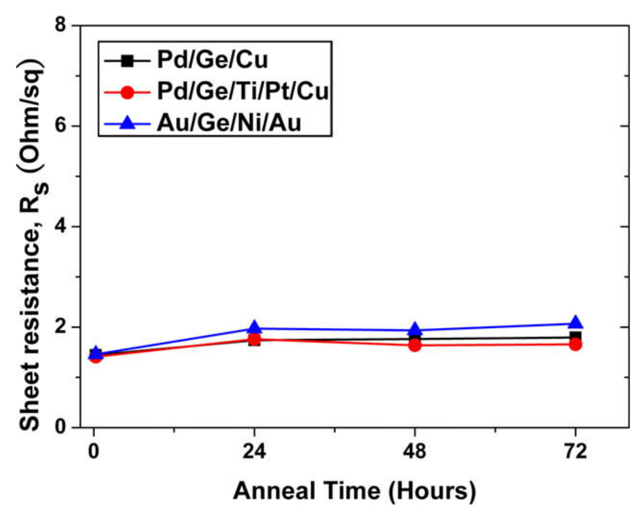

Fig. 5. Sheet resistance (R_s in Ω/sq) as a function of annealing time at 350 °C for the Pd/Ge/Cu, Pd/Ge/Ti/Pt/Cu, and Au/Ge/Ni/Au ohmic contact structures to n-type GaAs.

tion current as the figure shows. Fig. 11 plots the current gain (β) as a function of aging time at 250 °C for the 4 × 20-μm-emitter-area fully Cu-metallized HBT with Pd/Ge/Cu ohmic contact. The results suggest that there was no ohmic degradation, copper oxidation, and copper diffusion in the fully Cu-metallized HBT with Pd/Ge/Cu ohmic contact after the annealing test.

The microwave performance of the fully Cu-metallized HBT with Pd/Ge/Cu ohmic contact was characterized by on-wafer *S* parameter measurement using a network analyzer. Fig. 12 shows the h_{21} curve of the 3 × 20-μm-emitter-area HBT device at the V_{CE} = 2.5 V and I_B = 0.14 mA as a function of frequency. The cutoff frequency was about 38 GHz. The microwave performance of the fully Cu-metallized HBT using Pd/Ge/Cu ohmic contact is comparable to the performance of the Au-metallized HBT in our previous study [9].

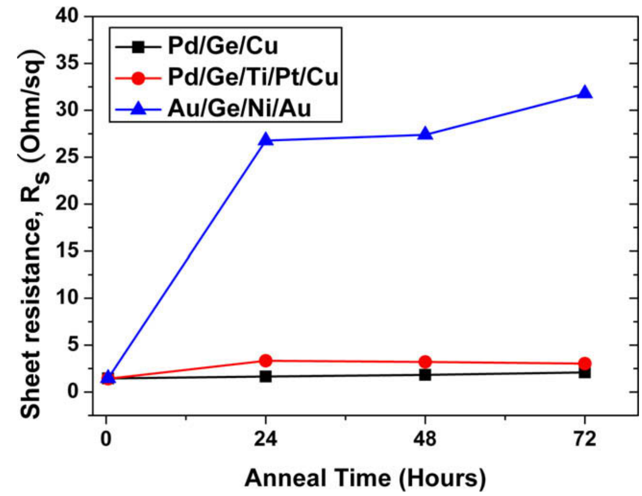

Fig. 6. Sheet resistance (R_s in Ω/sq) as a function of annealing time at 450 °C for the Pd/Ge/Cu, Pd/Ge/Ti/Pt/Cu, and Au/Ge/Ni/Au ohmic contact structures to n-type GaAs.

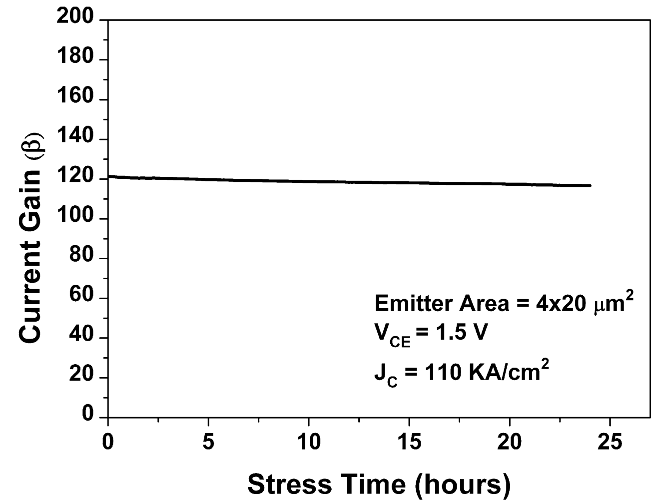

Fig. 9. The current gain (β) as a function of stress time at constant I_B for the 4×20-μm^2-emitter-area fully Cu-metallized HBT with Pd/Ge/Cu ohmic contact.

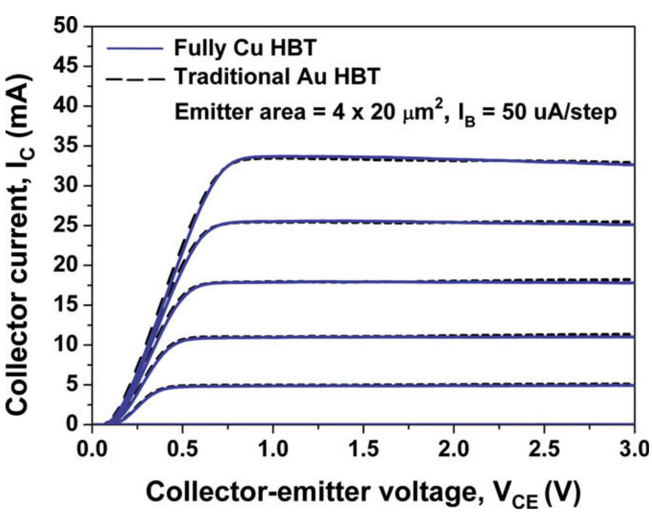

Fig. 7. Comparison of the typical I_C–V_{CE} characteristics for the emitter-area ($4 \times 20\ \mu m^2$) HBTs with Cu and with Au-metallizations.

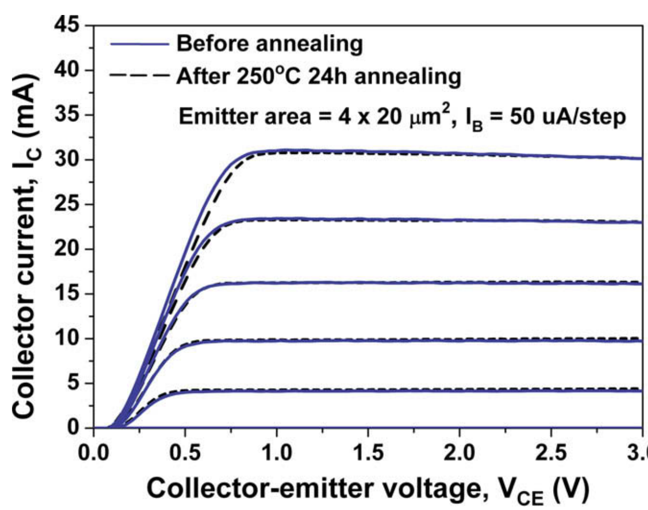

Fig. 10. Common emitter I–V curves measured before and after annealing at 250 °C for 24 h for the 4×20-μm^2-emitter-area fully Cu-metallized HBT with Pd/Ge/Cu ohmic contact.

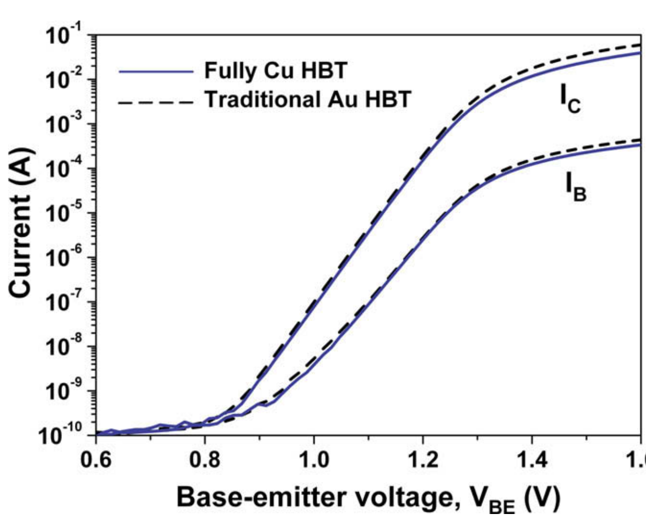

Fig. 8. Comparison of Gummel plots for the emitter-area ($4 \times 20\ \mu m^2$) HBTs with Cu and with Au-metallizations.

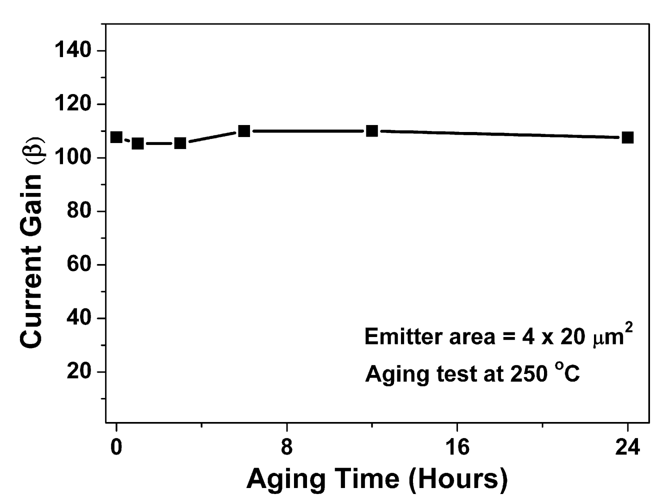

Fig. 11. The current gain (β) as a function of aging time at 250 °C for the 4×20-μm^2-emitter-area fully Cu-metallized HBT with Pd/Ge/Cu ohmic contact.

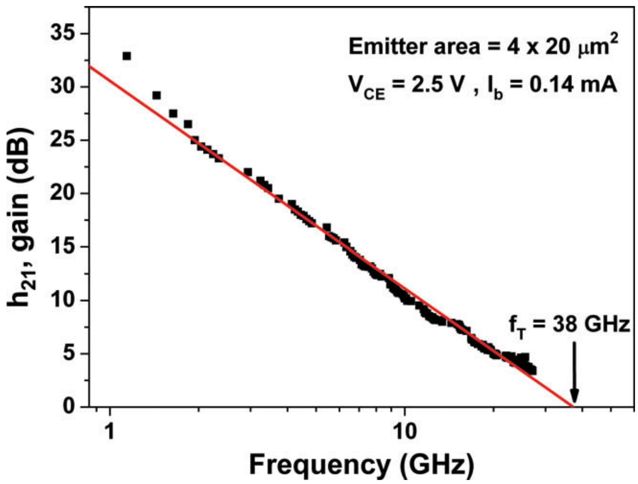

Fig. 12. Current gain h_{21} vs frequency curve for the 3×20-μm-emitter-area fully Cu-metallized HBT.

4. Conclusion

The Au-free fully Cu-metallized InGaP/GaAs HBTs using Pd/Ge/Cu alloyed ohmic contact system as the emitter and collector ohmic contacts have been fabricated for the first time in this study. The optimized Pd (150 Å)/Ge (1500 Å)/Cu (1500 Å) metal structure exhibits a low contact resistance of $5.73 \times 10^{-7}\ \Omega\,cm^2$ to n-type GaAs after annealing at 250 °C for 20 min. From the TEM and EDX studies, the microstructure evolution and the mechanism for the Pd/Ge/Cu alloyed ohmic contact formation were identified. After applying the Pd/Ge/Cu ohmic contact to the HBT, the common emitter *I–V* curves and the Gummel plot of the copper metallized HBT showed similar electrical characteristics as those of the conventional Au-metallized HBT. During both the current-accelerated stress test (110 kA/cm^2 stress for 24 h) and the thermal stability test (annealing at 250 °C for 24 h), the fully Cu-metallized HBT with Pd/Ge/Cu alloyed ohmic contact showed no obvious degradation in the electrical characteristics. The cutoff frequency (f_T) of the 3×20-μm-emitter-area Cu-metallized HBT was about 38 GHz at V_{CE} = 2.5 V and I_B = 0.14 mA. The results in this study show that the Pd/Ge/Cu alloyed ohmic contact can be applied to the InGaP/GaAs HBTs to achieve an Au-free fully Cu-metallized HBTs with excellent electrical characteristics.

Acknowledgements

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