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A Cu-Metallized InGaP/GaAs Heterojunction Bipolar Transistor with Reliable Pd/Ge/Cu Ohmic Contact for Power Applications

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A Cu-metallized InGaP/GaAs heterojunction bipolar transistor (HBT) using a Pd/Ge/Cu n-type ohmic contact, a Pt/Ti/Pt/Cu p-type ohmic contact, and a Ti/Pt/Cu interconnect has been fabricated for power applications. The 4 × 20 μm² HBT had an output power of 11.25 dBm with a power-added efficiency of 35.1%. After applying current-accelerated stress for 24 h, the current gain remained larger than 125. The device was also annealed at 200 °C for 24 h, and showed a slight decrease in output power from 10.06 to 9.83 dBm. The results demonstrated that reliable Cu metallization can be used for fabricating InGaP/GaAs HBTs for power applications.

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Copper metallization has been extensively used in the silicon industry since IBM announced its success in silicon very large scale integration process.[1–3] Although 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] Cu has lower resistivity, higher thermal conductivity, higher electromigration resistance, and lower cost than Au, which is commonly used in metallization in the GaAs industry.[4,5] Therefore, it has became a good candidate material for the metallization of GaAs devices in recent years. In previous works, back-side surface copper metallization, Cu Schottky structures in GaAs metal semiconductor field-effect transistors (MESFETs), the use of a copper airbridge in low-noise GaAs high-electron-mobility transistors (HEMTs), and copper interconnect using WN_X as the diffusion barrier in InGaP/GaAs heterojunction bipolar transistors (HBTs) have been studied.[6–8] However, there is as yet no report on the power performance of Cu-metallized power HBTs with related reliability data. Thus, a Cu-metallized GaAs power HBT with an alloyed copper ohmic contact was investigated and characterized in this study.

Conventionally, n-type Au/Ge/Ni/Au and p-type Pt/Ti/Pt/Au ohmic contacts and Ti/Au interconnect metal have been widely used in metallization schemes for the fabrication of GaAs-based HBTs. However, the Au/Ge/Ni ohmic contact system has several drawbacks, such as the large spread of contact resistance, poor contact edge definition, and high annealing temperature, which is necessary for the formation of eutectic Au/Ge alloy. In this study, Pd/Ge/Cu was used as the n-type ohmic contact to improve the surface morphology of an n-type alloyed ohmic contact. Furthermore, the conventional p-type ohmic contact Pt/Ti/Pt/Au and Ti/Au interconnect metals have been respectively replaced with Pt/Ti/Pt/Cu and Ti/Pt/Cu with platinum as the diffusion barrier to fabricate Cu-metallized InGaP/GaAs HBTs.[9] The replacement of Au-based metallization schemes with Cu-based metallization schemes will markedly reduce the production cost of HBTs. The fabrication, electrical characteristics, power performance, and reliability test data of a power InGaP/GaAs HBT with a Pd/Ge/Cu ohmic contact will be discussed in this study. In addition, a conventional Au-based metallization HBT will also be fabricated for comparison.

Layer	Material	Type	Doping	Thickness (Å)
Emitter cap	GaAs	n^+	5×10^{18}	2000
Emitter	InGaP	n	3×10^{17}	500
Base	GaAs	p^+	4×10^{19}	800
Collector	GaAs s	n^-	2×10^{16}	7000
Subcollector	GaAs	n^+	5×10^{18}	5000
Substrate GaAs				

Fig. 1. Epitaxial layer structure of the InGaP/GaAs HBT.

The epitaxial layers of the InGaP/GaAs single-heterojunction bipolar transistor were grown by metal organic chemical vapor deposition (MOCVD) on a 3-in.-diameter semi-insulating (100) GaAs substrate. The layer structure is shown in Fig. 1. The fabrication of Cu metallized power InGaP/GaAs HBTs started from mesa etching. The emitter mesa, base mesa, and isolation mesa were etched step by step. Etching solutions of HCl/H_3PO_4 and $H_3PO_4/H_2O_2/H_2O$ were used to etch InGaP and GaAs, respectively. Then, the emitter and collector ohmic contacts were formed by a standard lift-off process and annealed at 250 °C for 20 min. The emitter and collector ohmic metal was Pd (15 nm)/Ge (150 nm)/Cu (150 nm). For the p-type ohmic contact on the base, a nonalloyed Pt (5 nm)/Ti (20 nm)/Pt (60 nm)/Cu (100 nm) metal was used whose specific contact resistance was $1.08 \times 10^{-6}\ \Omega\,\text{cm}^2$.

After the ohmic process, the devices were passivated with a 100 nm plasma enhanced chemical vapor deposition silicon nitride film. Then, the nitride via was etched by reactive ion etching. After that, a Ti (30 nm)/Pt (60 nm)/Cu (400 nm) metal was sequentially deposited using an electron-gun evaporator as the seed layer for electroplating. Finally, 2 μm copper was electroplated on the seed layer as the interconnect metal. Au-based metallization power InGaP/GaAs HBTs with a Au/Ge/Ni/Au n-type ohmic contact, a Pt/Ti/Pt/Au p-type ohmic contact, and a Ti/Au interconnect were also processed for comparison. The DC characteristics and power performance of the HBTs were then measured using an Agilent E5270 and a load–pull system. Finally, the devices were stressed using a current-

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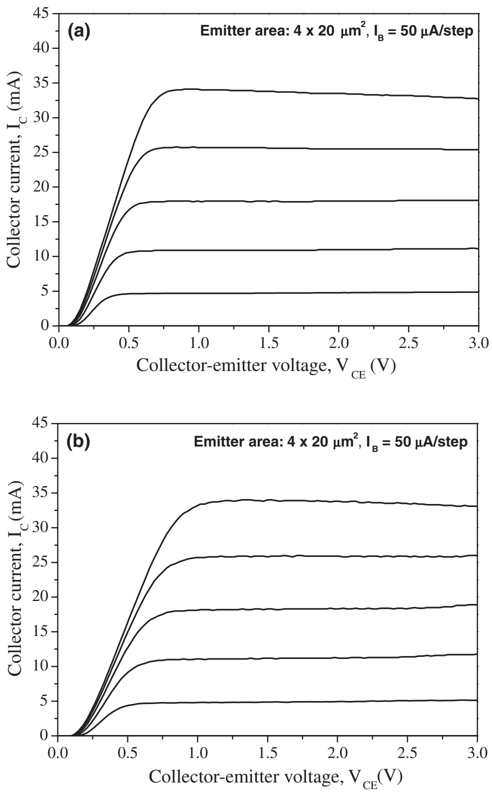

Fig. 2. I_C–V_{CE} curve of power HBTs with (a) Au and (b) Cu metallization (emitter area: 4 x 20 μm^2).

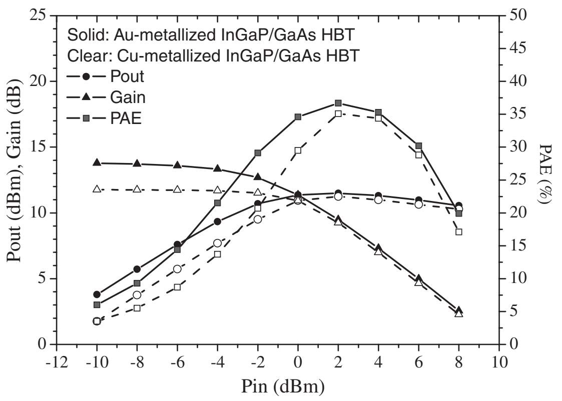

Fig. 3. Power performance of the power HBTs with Cu and Au metallization (emitter area: 4 x 20 μm^2).

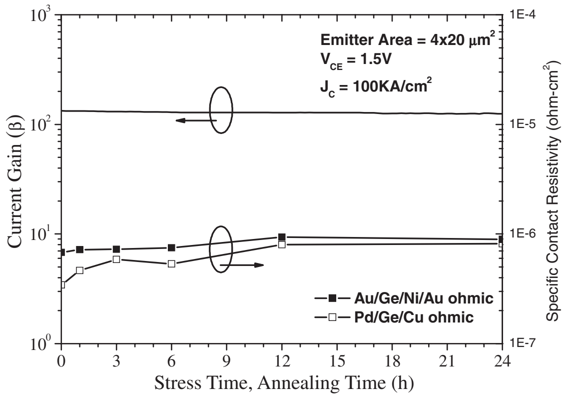

Fig. 4. Specific contact resistance of Pd/Ge/Cu as a function of annealing time, and current gain (β) as a function of stress time at constant I_B for Cu-metallized power HBT with Pd/Ge/Cu ohmic contact.

accelerated test and a high-temperature thermal annealing test for reliability evaluation.

Figures 2(a) and 2(b) respectively show the common emitter characteristics of the Cu-metallized and conventional Au-metallized power HBTs with an emitter area of 4×20 μm^2. It can be seen that these two devices have the same offset voltage of 100 mV and the same saturation collector current of 42.5 kA cm^{-2}. Also, the common emitter current gain for both devices was 130. This implies that the characteristics of the InGaP/GaAs HBTs using the Pd/Ge/Cu ohmic contact are reasonably good.

The power performance of the HBTs was measured at 2 GHz using a load–pull system, and the results are shown in Fig. 3. When the Au-metallized InGaP/GaAs HBT was tuned for maximum power-added efficiency (PAE) matching, the output power (P_{out}) was 11.49 dBm and the maximum PAE was 36.7% under DC bias conditions of $V_{CE} = 2$ V and $I_C = 12$ mA. Under the same DC bias conditions, the Cu-metallized InGaP/GaAs HBT had an output power of 11.25 dBm and a maximum PAE of 35.1%, but a lower linear gain was observed owing to the higher knee voltage shown in the I_C–V_{CE} curves in Fig. 2(b).

Before the device reliability test, the thermal stability of the alloyed Pd/Ge/Cu ohmic contact was also studied. The alloyed Pd/Ge/Cu on n-GaAs with transmission line method (TLM) patterns was annealed at 250 °C for 24 h and monitored for any changes in contact resistance with time. As shown in Fig. 4, the lowest specific contact resistance after the formation of the alloyed ohmic contact was 5.7×10^{-7} Ω cm^2. After 12 h of annealing, the contact resistance remained as low as 8×10^{-7} Ω cm^2, but slightly increased to 9×10^{-7} Ω cm^2 after another 12 h of annealing. It is thus indicated that the Pd/Ge/Cu ohmic contact with n-type GaAs has good thermal stability.

For the reliability test, the Cu-metallized 4×20 μm^2 InGaP/GaAs HBT was subjected to a current-accelerated stress test with a high current density of 100 kA cm^{-2}, which is much higher than the normal operation current of 25 kA cm^{-2}. The purpose of using high current density is to shorten the stress time.[10] The stress test was performed at the wafer level without using packages. Figure 4 shows a plot of the current gain (β) of the Cu-metallized HBTs with a Pd/Ge/Cu ohmic contact after subjection to stress at $V_{CE} = 1.5$ V for 24 h. The measurements were conducted at an ambient room temperature of 25 °C. The current gain of the device showed no significant change with time. The change in the ratio of the final current gain to the initial current gain was less than 6%, and the current gain remained higher than 125 after 24 h of the current-accelerated stress test.

The Cu- and Au-metallized power HBT devices were also annealed at 200 °C for 24 h to investigate their thermal stability. Figures 5(a) and 5(b) show the common emitter *I*–*V* curves of the Cu- and Au-metallized power HBTs before and after annealing at 200 °C for 24 h, respectively. Only a small increase of the knee voltage was observed. The power performance of the Cu-metallized HBTs was meas-

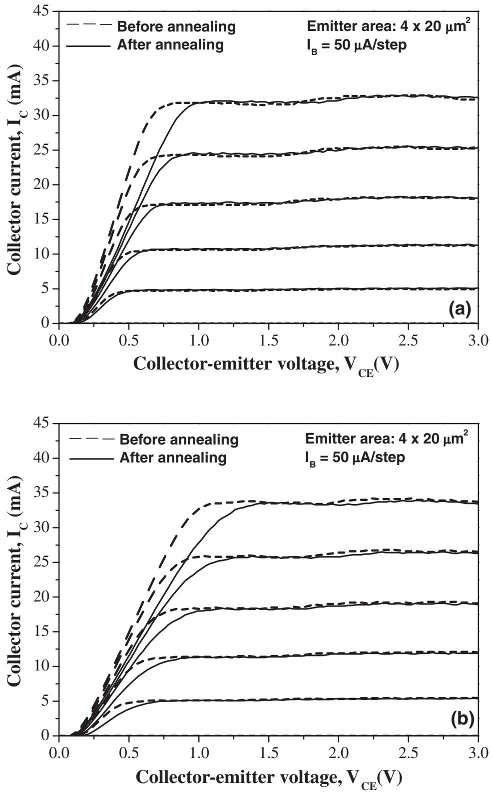

Fig. 5. Common emitter *I*–*V* curves of 4 x 20 µm^2 power HBT with (a) Au and (b) Cu metallization measured before and after annealing at 200 °C for 24 h.

ured after annealing at 200 °C for 24 h. The output power decayed from 10.06 to 9.83 dBm, and the maximum PAE decreased from 35.6 to 35.5%, as shown in Fig. 6. The small increase in Pd/Ge/Cu ohmic contact resistance after 24 h of annealing may be one of the reasons for the degradation of the power performance of HBT devices at high frequencies.

In this study, a Cu-metallized InGaP/GaAs HBT using a Pd/Ge/Cu ohmic contact with n-type GaAs, a Pt/Ti/Pt ohmic contact with p-type GaAs, and a Ti/Pt/Cu interconnect has been successfully fabricated. The contact resistance of the Pd/Ge/Cu ohmic contact was 5.7×10^{-7} $\Omega\,\mathrm{cm}^2$ and remained lower than 9.0×10^{-7} $\Omega\,\mathrm{cm}^2$ after 24 h of annealing at 250 °C.

The 4 × 20-µm^2-emitter-area Cu-metallized HBT using the Pd/Ge/Cu ohmic contact had a saturation collector current of 42.5 kA cm^{-2} and a common emitter current gain of 130. After a current-accelerated stress test with a current density of 100 kA cm^{-2} for 24 h, the current gain remained higher than 125. The Cu-metallized HBT also had an output power of 11.25 dBm and a PAE of 35.1% at 2 GHz. After thermal annealing at 200 °C for 24 h, the output power slightly decreased from 10.06 to 9.83 dBm with a PAE of 35.5%. The results showed that novel Cu metallization scheme can be used for InGaP/GaAs power HBTs with good device performance and reliability.

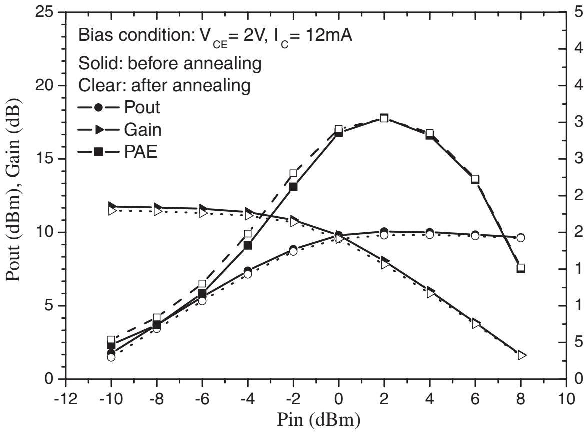

Fig. 6. Power performances of 4 x 20 µm^2 Cu-metallized power HBT before and after annealing at 200 °C for 24 h.

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