Copper-Airbridged Low-Noise GaAs PHEMT With Ti/WN$_x$/Ti Diffusion Barrier for High-Frequency Applications

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Abstract—A GaAs pseudomorphic HEMT (PHEMT) with Cu-metallized interconnects was successfully developed. Sputtered WN$_x$ was used as the diffusion barrier and Ti was used as the adhesion layer to improve the adhesion between WN$_x$/Cu interface in the thin-metal structure. After copper metallization, the PHEMTs were passivated with silicon nitride to avoid copper oxidation. The Cu-airbridged PHEMT showed the saturation I_{DS} was 250 mA/mm and the g_m was 456 mS/mm. The Ti adhesion layer plays a significant role on the g_m and V_p uniformity of the Cu-metallized PHEMTs. The GaAs PHEMTs with Ti/WN$_x$/Ti/Cu multilayer have better noise figure and associated gain than those of the devices without the Ti adhesion layer. The fabricated Cu-metallized GaAs PHEMT with Ti/WN$_x$/Ti/Cu multilayer has a noise figure of 0.76 dB and an associated gain of 8.8 dB at 16 GHz. The cutoff frequency (f_T) is 70 GHz when biased at $V_{DS} = 1.5$ V. These results show that the Ti/WN$_x$/Ti multilayer can serve as a good diffusion barrier for Cu metallization process of airbridge interconnects on GaAs low-noise PHEMTs.

Index Terms—Airbridge, copper metallization, diffusion barrier, GaAs, noise figure, pseudomorphic HEMT (PHEMT).

I. INTRODUCTION

COPPER metallization process has been widely used and has become very popular in Si-based ultralarge scale integration (ULSI) fabrication in recent years [1]–[4]. Cu is one of the most attractive materials for an interconnect metallization in the ULSI circuits due to its low resistivity, low cost, and excellent resistance against electromigration. However, copper diffuses very fast into Si when it is in contact with Si substrate without any diffusion barrier [5], [6]. In addition, there are very few reports about Cu metallization process for the GaAs-based devices [7], [8]. Traditionally, plated Au is used in the airbridge fabrication for the GaAs devices, such

as MESFETs and HEMTs. However, the use of Au metal in the GaAs device fabrication is not very cost-effective for mass production.

For Cu metallization of GaAs devices, the major challenges are the choice of suitable diffusion barrier material for Cu and the integration of the diffusion barrier with the Cu metallization process. This is because the Cu atoms diffuse very fast into GaAs [9]. Refractory metals and refractory metal nitrides are good candidates for the diffusion barrier materials. This is because of the high-melting point and the low Cu solubility of these materials even at high temperatures. The refractory metal nitrides such as TiN, TaN, and WN$_x$ have been investigated in silicon industry due to their better thermal stability and antidiffusion capability [1]–[4]. There are only a few reports on the Cu metallization of the GaAs devices using Ta and TaN as the diffusion barriers [7], [8]. These transition metal nitrides, which have high-melting points, relatively high thermal stability, chemical inertness, and low electrical resistivity, do not form metallic compounds with Cu at reasonably high temperatures. Along with the choice of the diffusion barrier materials, the adhesion of the diffusion barrier layer must be considered, since the poor adhesion in the Cu metallization structures will lead to significant degradation on the device performance and uniformity.

Generally, the ohmic metal AuGeNiAu and gate metal Ti/Pt/Au are the most widely used structures of the GaAs-based HEMTs. From the phase diagrams of these material systems, there are many possible intermetallic compounds in the Cu–Au binary system. Interdiffusion of Cu and Au in Cu–Au structure was observed at a temperature as low as 150 °C, and very rapid increase in the resistivity was observed at 250 °C [10]. In this paper, the use of WN$_x$ as the Cu diffusion barrier and Ti as the adhesion layer in the Cu-metallized airbridge interconnects was successfully applied to the fabrication of the AlGaAs/InGaAs low-noise pseudomorphic HEMTs (PHEMTs). Tungsten nitride has high-melting point, good thermal, and chemical stability, and is a good diffusion barrier between Si and Cu. In addition, tungsten does not form an intermetallic compound with Cu and Au, as judged from the phase diagram. The metal deposition and etching processes for the Cu metallization are compatible with the conventional Au-metallized GaAs device fabrication process. The thermal stability of Ti/WN$_x$/Ti diffusion barrier on the Cu-airbridged PHEMT was investigated. The
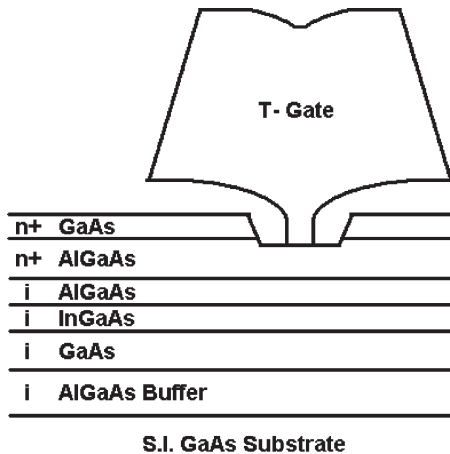
Fig. 1.   Device structure of the AlGaAs/InGaAs low-noise PHEMT.

Fig. 2.   SEM micrograph of the GaAs PHEMT with Cu airbridge using Ti/WN$_x$/Ti/Cu multilayer system.

developed low-noise PHEMTs with Cu airbridges also show comparable electrical performances to those of the conventional Au-airbridged devices.

II. EXPERIMENTAL

In this paper, low-noise Cu-airbridged PHEMTs were used to evaluate the feasibility of using the Cu metallization process for the GaAs device fabrication. The epistructure of the Al-GaAs/InGaAs low-noise PHEMT was grown by molecular beam epitaxy (MBE) on a 3-in (100) oriented semi-insulating GaAs substrate. The structure is shown in Fig. 1. The epilayers of the device, from bottom to top, were composed of a 600-nm AlGaAs buffer, a 15-nm In$_{0.22}$Ga$_{0.78}$As channel, a 2-nm undoped AlGaAs spacer, a 42-nm Si-doped Al$_{0.25}$Ga$_{0.75}$As layer doped to 5×10^{17} cm^{-3}, and a 45-nm Si-doped GaAs capping layer doped to 1×10^{19} cm^{-3}.

The mesa isolation was done using wet chemical etch. The ohmic contacts were formed by evaporating AuGeNiAu and alloyed at 400 °C for 30 s using rapid thermal annealing (RTA). T-shaped Ti/Pt/Au gates were fabricated by electron beam direct writing and liftoff process. A passivation film of silicon nitride was deposited on the device by plasma-enhanced chemical vapor deposition (PECVD). Ti/WN$_x$/Ti multilayer system was used as the thin metals of Cu airbridges. The thickness of the first airbridge photoresist was 2.6 μm. After hard baking of the resist, the Ti/WN$_x$/Ti (30 nm/40 nm/30 nm) multilayer and Cu (100 nm) were subsequently sputtered on the wafer. The copper film was used as the seed layer to conduct electrical currents in the Cu electroplating process. After the second photolithography, copper was electroplated with a thickness of 2.2 μm. In this paper, the Au-airbridged PHEMTs were also fabricated for comparison. The seed layers for electroplating of the Cu and Au airbridges were different. Evaporated Au was used as the seed layer for electroplated Au, whereas the electroplated Cu used sputtered Cu as the seed layer. In this paper, sulfuric acid/Cu sulfate-based solution was used for Cu plating. The current density of the Cu electroplating was 1 A/dm^2 and the plating time was about 10 min. An additional 50-nm-thick SiN$_x$ passivation film was deposited on
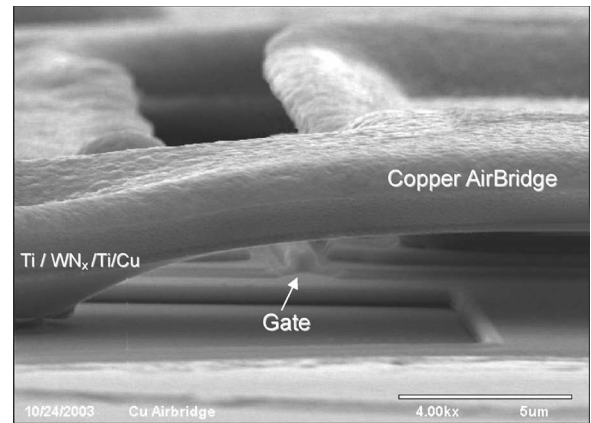
the Cu airbridges by PECVD to avoid the copper oxidation. The scanning electron microscopy (SEM) micrograph of the fabricated low-noise PHEMT with Cu airbridges is shown in Fig. 2.

III. THERMAL STABILITY OF THE DIFFUSION BARRIER

Auger electron spectroscopy (AES) was used to analyze the depth profiles of the Ti/WN$_x$/Ti/Cu multilayer system. The AES results for the Ti/WN$_x$/Ti/Cu multilayer system before and after thermal annealing are shown in Fig. 3. It indicates that there is no interatomic diffusion between Cu and Au after annealing at 400 °C for 30 min. When the annealing temperature was increased to 500 °C, Cu and Au started to diffuse through the diffusion barrier layer. Fig. 4 shows the X-ray diffraction (XRD) patterns of the Ti/WN$_x$/Ti diffusion barrier between Au and Cu layers before and after annealing. As can be seen, the Ti/WN$_x$/Ti multilayer system was very stable after annealing at 300 °C and 400 °C and showed no interdiffusion between Cu and Au after the annealing. It proves that the Ti/WN$_x$/Ti diffusion barrier was very effective in preventing Cu from diffusing into the Au layer even up to 400 °C annealing. However, additional peaks identified as Cu$_3$Au$_2$ and Cu–Au in Fig. 4 were observed after annealing at 500 °C. The Au was from the underlying Au-based contact metals, i.e., AuGeNiAu ohmic and Ti/Pt/Au gate. This was consistent with the AES depth profile analysis shown in Fig. 3(c), indicating the interdiffusion of Au and Cu across the Ti/WN$_x$/Ti had occurred at 500 °C. The diffusion of the Au was from both ohmic and Schottky contacts (i.e., AuGeNiAu ohmic and Ti/Pt/Au gate metals). The top layers of the ohmic and gate metals are all Au metal. The transverse electromagnetic (TEM) cross section micrographs of the Ti/WN$_x$/Ti diffusion barrier structure before and after 400 °C annealing are shown in Fig. 5(a) and (b), respectively. In Fig. 5(b), the interface of the WN$_x$ layer was very sharp and no reaction between Ti, Au, Cu, and WN$_x$ layers was observed. The TEM results are consistent with the above AES and XRD results. It shows that the Ti/WN$_x$/Ti multilayer system is a very effective diffusion barrier structure between Cu and Au and is stable up to 400 °C annealing for 30 min.

Fig. 4. XRD patterns of the Ti/WN$_x$/Ti/Cu multilayer system after annealing at different temperatures for 30 min.
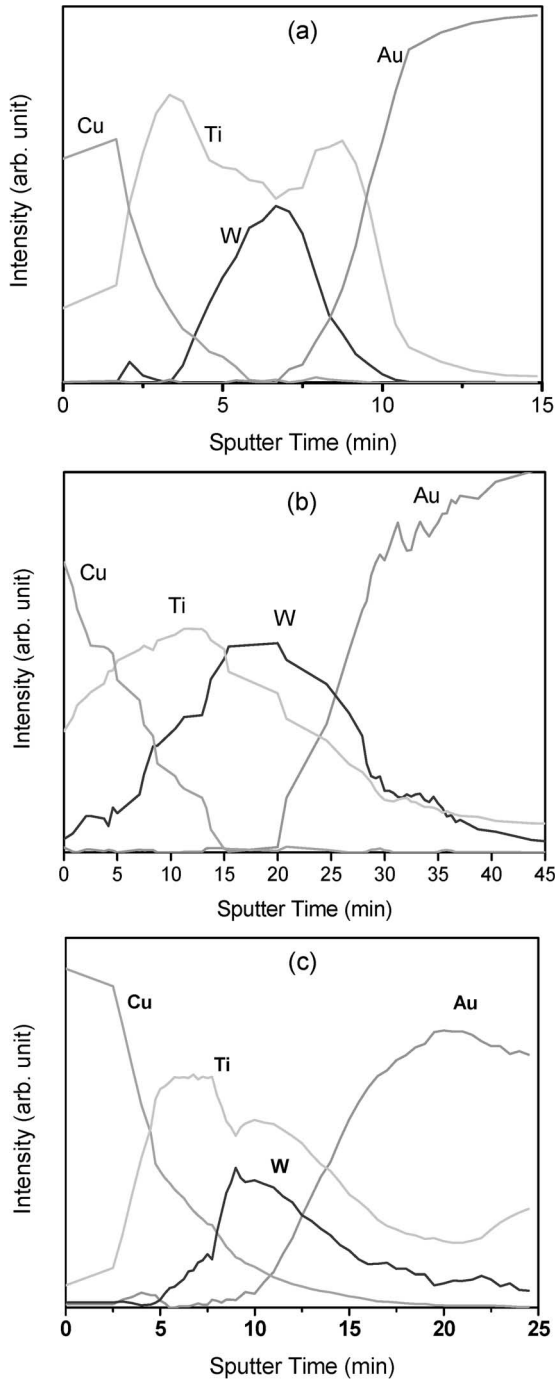

Fig. 3. AES depth profiles of the Ti/WN$_x$/Ti/Cu multilayer system (a) as deposited, (b) after 400 °C annealing for 30 min, and (c) after 500 °C annealing for 30 min.

Fig. 5. TEM cross section of Ti/WN$_x$/Ti/Cu multilayer system (a) as deposited and (b) after 400 °C annealing for 30 min.

IV. ELECTRICAL CHARACTERISTICS OF THE Cu-METALLIZED AIRBRIDGE PHEMTs

Electrical characteristics of both Cu- and Au-airbridged low-noise PHEMTs were measured and compared to evaluate the device performances after Cu metallization process. In the Fig. 6, the dc characteristics of the Cu-airbridged PHEMTs using Ti/WN$_x$/Ti multilayer showed saturation drain–current (I_{DS}) of 250 mA/mm when biased at $V_{DS} = 1.5$ V. In order to compare the dc characteristics of the Cu- and Au-airbridged PHEMTs, transconductance (g_m) versus gate bias voltage
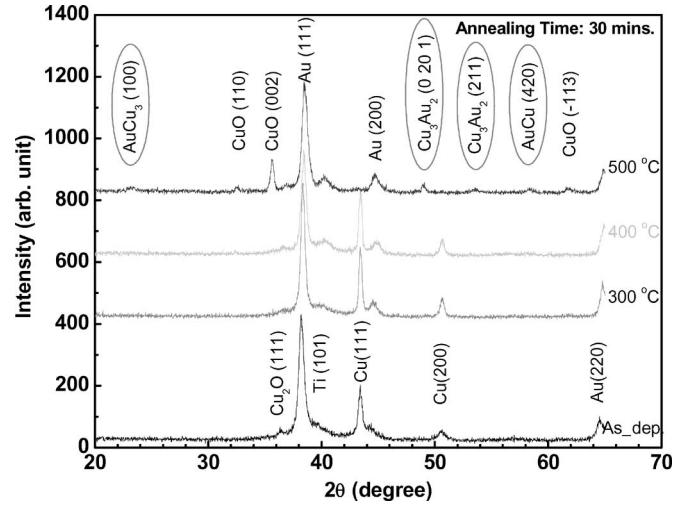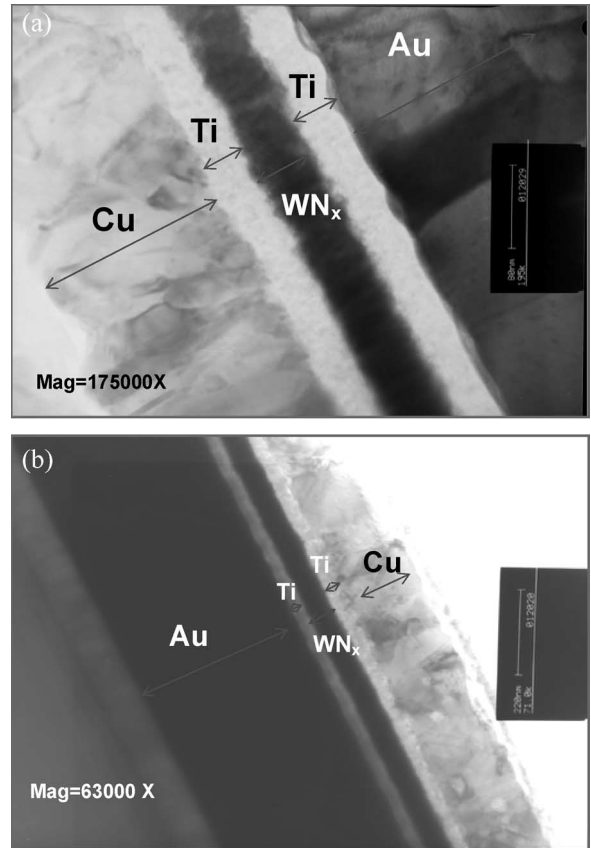
(V_{GS}) curves of these two devices are shown in Fig. 7. The maximum g_m of the Cu-airbridged PHEMT with Ti/WN$_x$/Ti diffusion barrier was 476 mS/mm. The g_m, I_{DS}, and pinchoff voltage (V_p) of the Au- and Cu-airbridged PHEMTs were similar due to the Schottky contacts were with the same structure that was Ti/Pt/Au on AlGaAs.

There were two structures of thin-metal stacks, Ti/WN$_x$/Ti and WN$_x$ (without Ti layer), for Cu-airbridged process that were studied to improve the performance and the uniformity
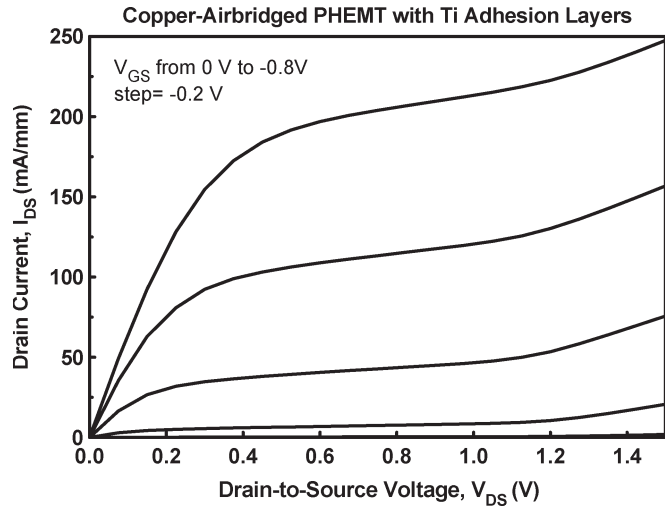
Fig. 6. Current–voltage curves of the low-noise Cu-airbridged PHEMTs with Ti/WN$_x$/Ti/Cu as the thin-metal system.
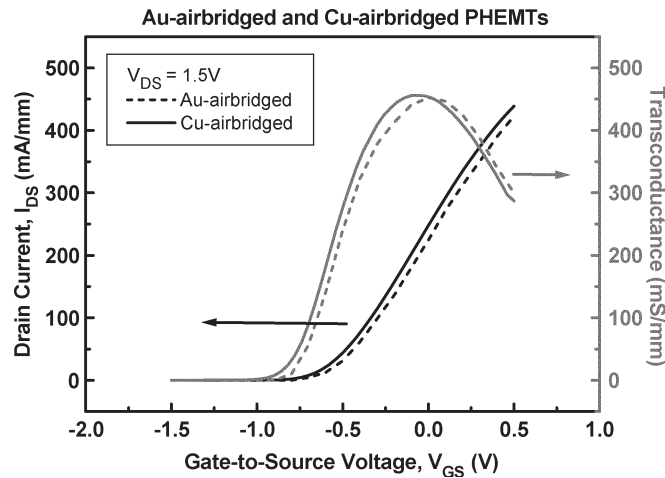

Fig. 7. Transconductance (g_m) versus gate bias voltage (V_{GS}) of the (a) Au-airbridged PHEMTs and the (b) Cu-airbridged PHEMTs with Ti/WN$_x$/Ti multilayer.
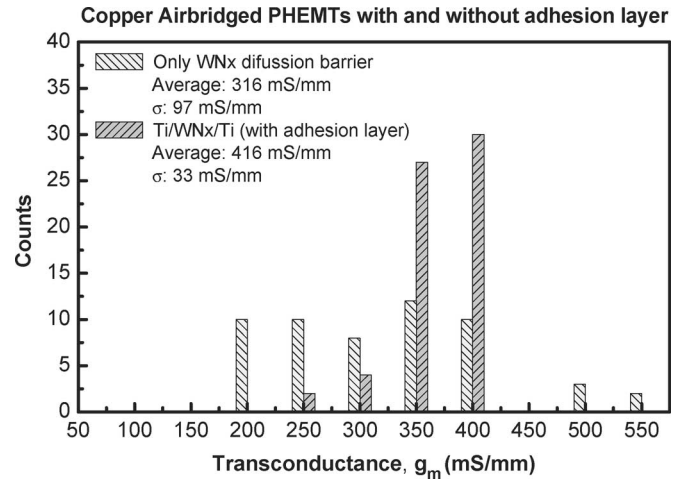

Fig. 8. Histograms of the transconductance (g_m) of the Cu-airbridged PHEMTs with and without adhesion layer.
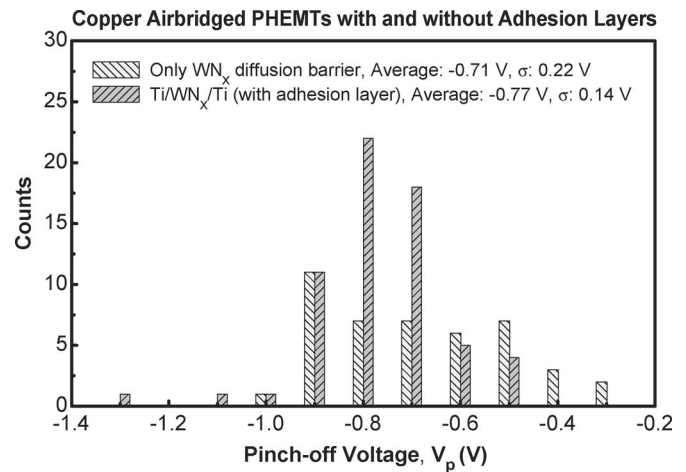
Fig. 9. Histograms of the pinchoff voltage (V_p) of the Cu-airbridged PHEMTs with and without adhesion layer.

of the Cu-airbridged PHEMTs. Histograms of the transconductance (g_m) and the pinchoff voltage (V_p) of the devices are shown in Figs. 8 and 9, respectively. Two half wafers from the same full 3-in wafer were processed, one half with the Ti adhesion layer and the other half without the Ti adhesion layer. The statistical data were collected from these two half wafers using semiautomatic probe system (SUSS PA200, KarlSuss) and wafer map software. A single die was probed from every 30-devices unit regularly arrayed on the wafer. More than 60 samples were measured across each half 3-in wafer. In Fig. 8, the average transconductance of the Cu-airbridged PHEMTs with Ti/WN$_x$/Ti adhesion layer was 416 mS/mm, which was higher than that of the devices without Ti layer. The standard deviation of g_m of the Cu-airbridged PHEMTs with Ti adhesion layer was 33 mS/mm, which was much smaller than that of the PHEMT without adhesion layer. The distribution of the pinchoff voltages for the Cu-airbridges and Au-airbridged PHEMTs are shown in Fig. 9. The pinchoff voltage of the Cu-airbridged devices with adhesion layer was distributed around $V_g = -0.7$ to -0.8 V, and the standard deviation of the devices

was 0.14 V, which was smaller than that without adhesion layer (0.22 V). According to the results of Figs. 8 and 9, higher yield and better uniformity of the Cu-airbridged PHEMTs was achieved by adding the Ti adhesion layers to the Au/WN$_x$ and WN$_x$/Cu interfaces. The overall yield for the half piece with Ti adhesion layer was 86.5%, and the half piece without Ti adhesion layer was 67.7%. The Ti layer can improve the interfacial adhesion and avoid the metal peeling after thermal treatment.

The noise figure and gain performances of the Au-airbridged low-noise PHEMTs are shown in Fig. 10. The noise figure is 0.74 dB and the associated gain is 9.2 dB at 16 GHz. Fig. 11 also shows the noise and gain performances of the Cu-metallized PHEMTs fabricated with and without the Ti adhesion layer. The noise figure of the device without Ti adhesion layer is 1.4 dB and the associated gain is 7.0 dB measured at 16 GHz. After adding Ti adhesion layers in the thin-metal structure, the noise figure and associated gain were improved by 0.76 and 8.8 dB, respectively. The performance of the Cu-metallized PHEMTs is improved by adding Ti adhesion layers. From the above results, the noise figure and the gain
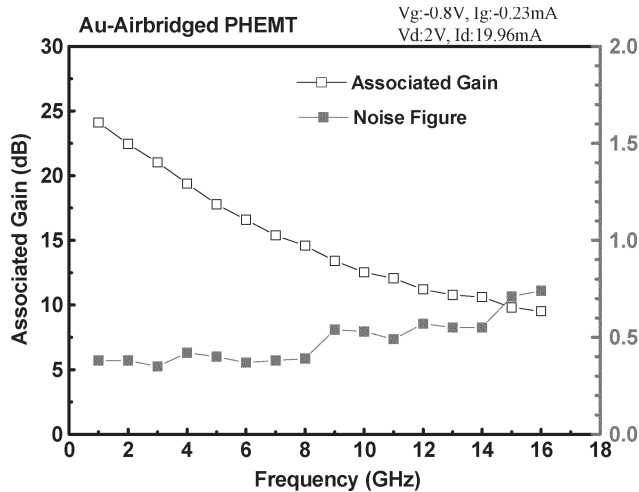
Fig. 10. Noise figure and gain performances of the Au-metallized low-noise PHEMT.
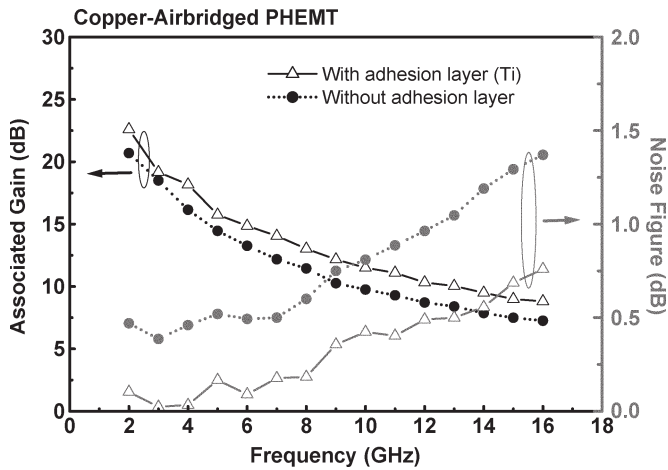

Fig. 11. Noise figure and gain performances of the Cu-metallized low-noise PHEMT with and without Ti adhesion layer.

performances of the Cu-airbridged PHEMTs are comparable to those of the Au-airbridged PHEMTs after the insertion of the Ti adhesion layers in the Cu airbridge fabrication.

The current gain curves of the low-noise Au-airbridged and Cu-airbridged PHEMTs with and without the Ti adhesion layers are shown in Fig. 12. The three kinds of devices show similar performances. The cutoff frequency (f_T) of the devices is all about 70 GHz. These results show that the Cu-airbridged PHEMTs with Ti adhesion layers in the thin-metal structure have comparable RF performance to conventional Au-airbridged PHEMTs.

V. CONCLUSION

The Cu airbridge interconnect process has been successfully applied to the fabrication of GaAs low-noise PHEMTs. WN_x was used as the diffusion barrier and Ti was used as the adhesion layer to improve the adhesion between WN_x/Cu interfaces in the thin-metal structure. From the results of AES depth profiles, TEM analysis, and XRD patterns, $Ti/WN_x/Ti$ multilayer system can sustain even after thermal annealing at 400 °C for 30 min. The GaAs PHEMTs fabricated with
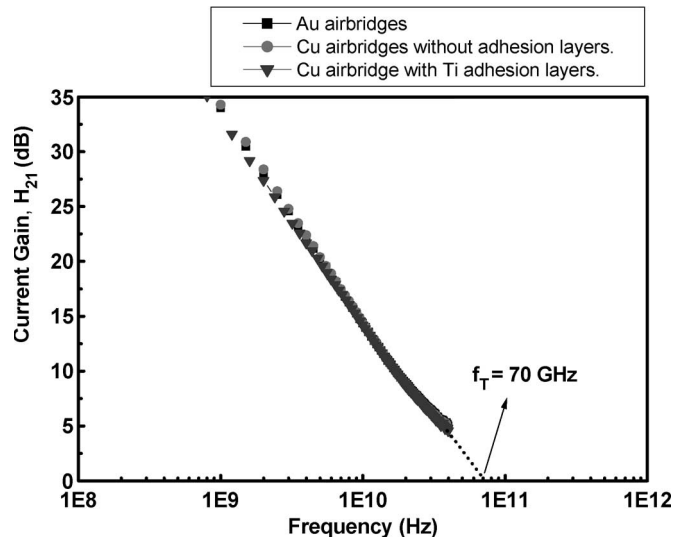

Fig. 12. Cutoff frequency of the GaAs low-noise PHEMTs with Au and Cu airbridges.

$Ti/WN_x/Ti$ multilayer have higher g_m and V_p uniformity than those of the GaAs PHEMTs with only WN_x layer. This is due to the improved adhesion of WN_x diffusion barrier layer by the insertion of the Ti layers. The noise figure and the associated gain of Cu-metallized PHEMTs were improved by 0.76 and 8.8 dB at 16 GHz, respectively, after using $Ti/WN_x/Ti$ multilayer system. The f_T of the Cu- and Au-airbridged low-noise PHEMTs are about 70 GHz. The Cu-metallized low-noise GaAs PHEMTs have comparable electrical performances to those of the conventional Au-metallized devices. As a result, the $Ti/WN_x/Ti$ multilayer can serve as a good diffusion barrier for Cu metallization process for airbridge interconnects on the low-noise GaAs PHEMTs.

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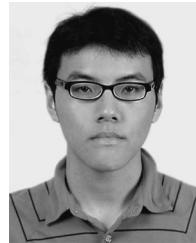
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