A Gold Free Aluminum Metalized GaAs PHEMT With Copper Based Air Bridges and Backside

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***Abstract*—This paper presents the results of electrical performance studies of the newly developed GaAs pHEMT transistors with Al-based metallization of the ohmic and barrier contacts, and fully copper metallization of interconnects, air bridges, and backside. The transistors exhibited a source-drain saturation current of I_{dss} = 280 mA/mm and a maximum transconductance of g_m = 450 mS/mm at U_{ds} = 1.5 V. The current cut off frequency for transistors with 600 μm total gate width was 80 GHz at U_{ds} = 1.5 V and U_{gs} = −0.35 V, and the power gain limiting frequency was 100 GHz. Output power at 1 dB gain compression with matched input and output load an impedance was P_{1db} = 26 dBm or 670 mW/mm at an efficiency level of about 28% and the transistor gain G = 11 dB. Measurements were performed at U_{ds} = 8 V, I_{ds} = 1/3 of I_{dss} at 12 GHz. The obtained results demonstrate the promise of Al and Cu metallization in the low cost manufacture of microwave transistors and monolithic integrated circuits based on them.**

***Index Terms*—Aluminum, copper, GaAs HEMT, ohmic contacts, T-shape gate.**

I. Introduction

At present, in the production of GaAs microwave monolithic integrated circuits (MMIC), gold is traditionally used for the metallization of ohmic and barrier contacts, interconnects, air bridges and backside metallization of wafers [1]. Precious metals are not used in silicon technology where aluminium [2] was used previously and now copper [3] is being successfully applied for creating interconnects. Compared to gold, copper has higher thermal conductivity and lower resistivity, while both copper and aluminum are characterized by significantly lower costs [4]. Therefore, transition to metallization with the use of these metals in the manufacturing of GaAs MMIC should improve the performance characteristics, and reduce the cost of device manufacture. In addition, the development of industrial technology of Cu and/or Al based GaAs MMIC should facilitate the integration of GaAs and Si technologies and allow heterointegration through the use lines designed for the production of silicon MIC [5].

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The disadvantages of the use of copper in GaAs technology include its high diffusion capacity and chemical activity, and the fact that copper is an acceptor impurity in GaAs and, when dissolved in an *n*-type semiconductor, it reduces the conductivity of the material [6]. Diffusion barriers and passivation coating must be used to prevent diffusion of copper into GaAs, as well as its interaction with oxygen and other reactive media.

Currently, no GaAs MMIC industrial technology exists with Al and/or Cu metallization. This is largely due to the lack of knowledge on the subject. Most of the studies published to date are devoted to the development of technology for the production of separate elements of MMIC by using Cu metallization: ohmic and barrier contacts of transistors [7]–[10], interconnects [11], [12], or backside metallization [13]. Studies [14], [15] address the issues of creating GaAs transistors with fully copper metallization.

Due to the high diffusion activity of copper, its use as a metallization material for the ohmic contacts and the transistor gate is not advisable. Aluminum, which does not have acceptor properties and is currently used successfully in production of pHEMT and mHEMT transistor gates [16], can serve as an alternative to copper. At the same time, the number of papers in which aluminum would be used for metallization of ohmic contact is very limited.

The aim of this work is to develop the low cost fabrication technology of GaAs pHEMT with Al based metallization of ohmic and barrier contacts and fully copper metalized interconnects, air bridges and backside metallization, and to study the electrical characteristics of transistors based on Al and Cu metallization.

II. Experimental

The experiments aimed at creating pHEMT used epitaxial structures AlGaAs/InGaAs/GaAs produced by molecular beam epitaxy. The heterostructure used in the experiments is described in [14].

The bilayer photoresist mask was formed after performing mesa isolation. Metallization of ohmic contacts based on Pd/Ge/Al/Ti was the deposited on the wafer by electron-beam evaporation at a residual pressure of less than $1\cdot10^{-6}$ Torr. Next, the pattern of ohmic contacts was formed by the lift off method. In order to form the ohmic contact, the samples were heat treated in an inert atmosphere at a temperature of $T = 200$–$450\,^{\circ}$C for $t = 1$–20 min.

The T-shaped gate transistor with 150 nm foot length was formed by electron beam lithography as described in [14]. Metallization of the T-shaped gate based on the Ti/Al/Ti compositions was performed by electron-beam evaporation at a residual pressure of less than $1{\cdot}10^{-6}$ Torr. The gate pattern was formed by the lift off method.

A 150–200 nm layer of Si_xN_y was deposited on the wafer in order to passivate the surface of the transistors. Dielectric deposition was carried out by deposition from the gaseous phase in ICP plasma. The windows in the Si_xN_y film were then opened by reactive ion etching.

To create the interconnections, a bilayer resistive mask was formed on the surface of the wafer, onto which the metallization of the first level of interconnects based on Mo/Cu/Mo was deposited by the electron beam evaporation method. The Mo films were used as diffusion barriers for Cu.

The air bridges were formed by electroplating of a copper film from aqueous solution of $CuSO_4 + H_2SO_4$. To start, the first resistive mask was formed on the substrate. After developing, in order to smooth the profile of the resist, the substrate was heat treated at $T = 120\,°C$ for $t = 15$ min. The conductive sublayer based on Ti/Cu was then deposited by two-layer metallization using electron beam evaporation. A 3 μm Cu film was deposited after forming the second resistive mask. Then, in sequence, the second resistive mask was removed from the wafer surface, the Cu and Ti films were selectively etched, and the first resistive mask was removed.

Final passivation was conducted in two stages. In the first stage, a layer of Si_xN_y was deposited on the wafer surface; in the second, a 5 μm thick layer of photosensitive BCB was applied by centrifuging. After opening the windows in the BCB film, the wafer was heat treated. Then, following the pattern in the BCB film, windows were opened to the contact pads in the Si_xN_y film.

The wafer was next glued to a sapphire carrier and thinned from the back side to a thickness of 100 μm. The via holes were etched by reactive ion etching in ICP plasma. After removal of the resistive mask, layers of W/Cu were formed by magnetron sputtering on the backside surface of the wafer. Then, a 3 μm thick Cu film was formed by electrochemical deposition.

In the final stage, the wafer was removed from the sapphire carrier and its surface was cleaned of the resist and glue.

The external appearance and surface morphology of the transistor elements were investigated by electron microscopy. DC parameters of the produced transistors were measured by HP4156A Semiconductor Parameter Analyzer, and the microwave signal parameters by the ZVA-40 Vector Analyzer. The output power of the transistors was measured with the Load Pull method with use of Focus Microwave tuners on the Cascade Microtech probe station.

III. Results

A. *Aluminium Metalized Ohmic Contacts to n^+-GaAs*

Fig. 1 shows the specific contact resistance ρ of the ohmic contacts based on Pd/Ge/Al/Ti as a function of the annealing temperature in an inert atmosphere.

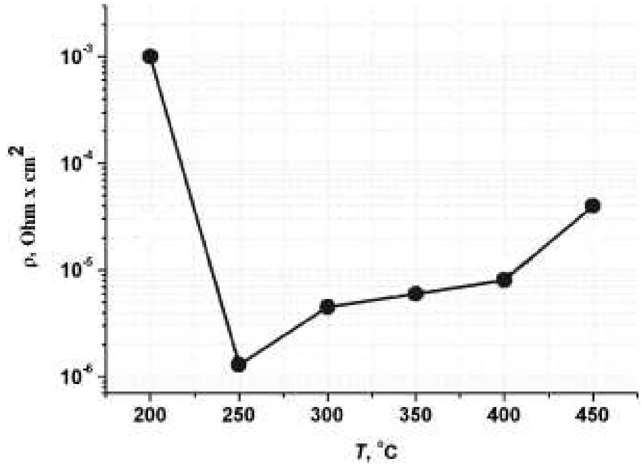

Fig. 1. Specific contact resistance ρ of the ohmic contacts based on Pd/Ge/Al/Ti to n^+-GaAs ($n = 5{\cdot}10^{18}$ cm^{-3}) as a function of the annealing temperature in an inert atmosphere.

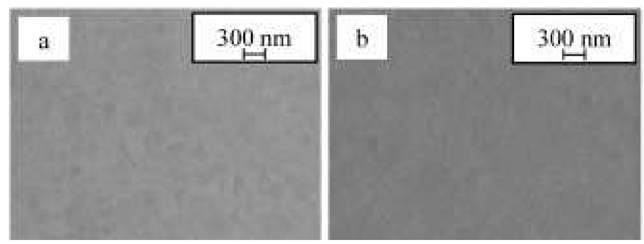

Fig. 2. SEM images of Pd/Ge/Al/Ti ohmic contact surface after thermal annealing at 250 °C (*a*) and 450 °C (*b*) in an inert environment.

Fig. 1 shows that the variation in the value of specific contact resistance of the Pd/Ge/Al/Ti ohmic contacts as a function of the annealing temperature in the range of $T = 200$–$450\,°C$ is represented by a characteristic curve with a minimum. The contact reaches a minimum value of contact resistance $\rho = 1.3{\cdot}10^{-6}$ Ohm·cm^2 after heat treatment at $T = 250\,°C$. Further increase in heat treatment temperature leads to a monotonic increase in the value of ρ. The reached minimal value of the specific contact resistance is an optimal for high electron mobility transistor performance. But the optimization of Pd, Ge and Al films thickness ratio may be reduce the value of ρ.

Fig. 2 shows the microscopic images of the Pd/Ge/Al/Ti ohmic contact surface after thermal annealing at $T = 250$ (*a*) and 450°C (*b*) in an inert environment. Pd/Ge/Al/Ti-based contact shows smooth surface morphology throughout the range of annealing temperatures.

Results of these experiments demonstrate the promise of using Pd/Ge/Al/Ti-based ohmic contacts in the GaAs transistor fabrication technology.

B. *Fabrication of GaAs pHEMT with Copper Based Air Bridges and Backside Metallization*

Fig. 3 shows a microscopic image of the cross section of a GaAs pHEMT transistor with Pd/Ge/Al/Ti ohmic contacts and 150 nm Ti/Al/Ti based T-shape gate.

Fig. 4 shows the microscopic images of the transistor after the formation of Cu air bridges.

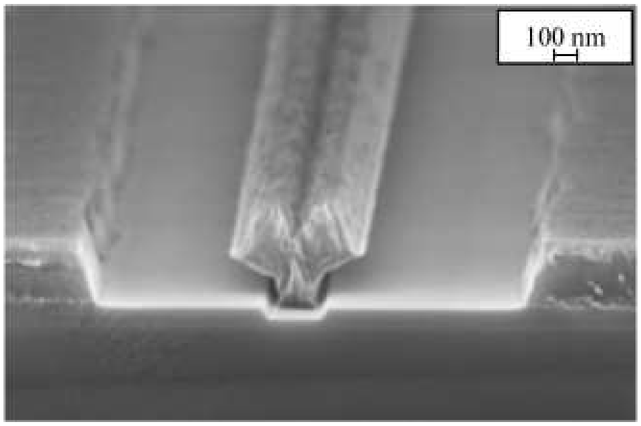

Fig. 3. Cross section SEM image of a transistor with Pd/Ge/Al/Ti ohmic contacts and 150 nm Ti/Al/Ti based T-gate.

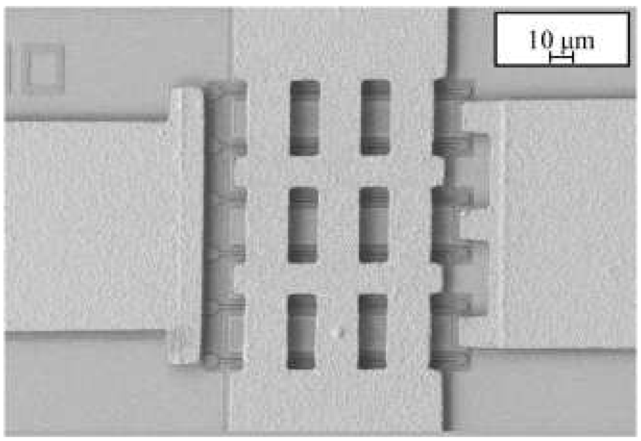

Fig. 4. SEM image of the transistor with Cu air bridges.

The air bridges have smooth surface morphology and the resistivity of the deposited Cu film was 1.8 μ Ohm·cm.

Fig. 5 shows the microscopic images of the test transistor after opening the windows in the BCB/Si_xN_y windows to the contact areas (*a*) and cross-sectional SEM view of the transistor (*b*).

Window to the contact pads of the transistor have straight edges (Fig. 5, *a*). The BCB film has smooth morphology, indicating good planarization of the surface (Fig. 5, *b*).

Fig. 6 shows a cross section microscopic image of a via hole after the formation of the copper backside metallization of the wafer.

It can be seen that the Cu film covers the surface of the wafer and the hole with a uniform layer and has smooth morphology. The measured electrical resistance of the via hole metallization was less than 0.05 Ohms.

C. Copper Metalized GaAs pHEMT Performance

Fig. 7 and 8 show the DC and RF performance of GaAs pHEMT transistors fabricated using Al-metalized ohmic and barrier contacts and Cu based air bridges and backside. The summary width of the transistor gates of the tested transistors was 600 μm.

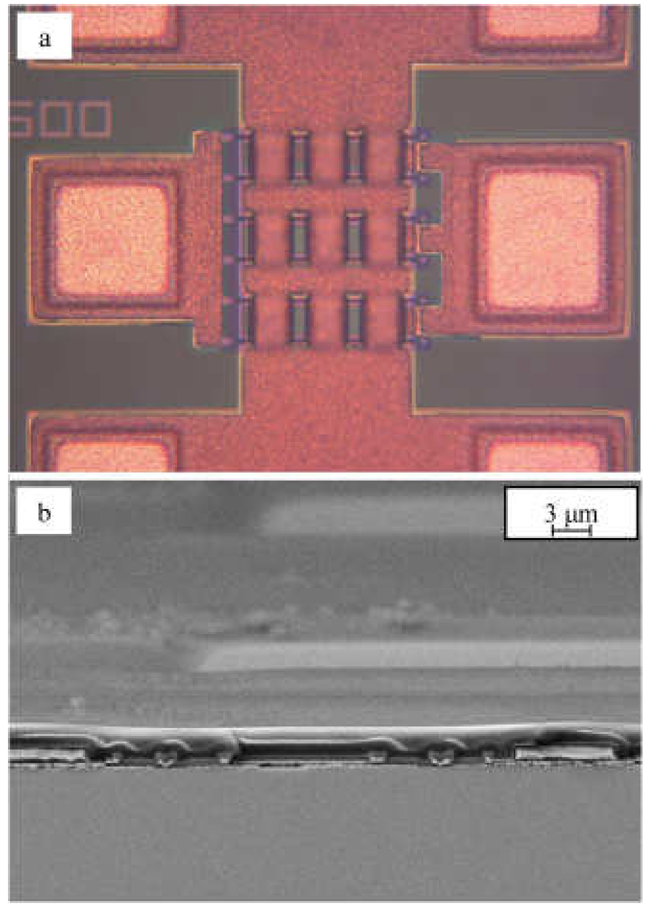

Fig. 5. Optical microscopy image of the transistor with open windows in the BCB/Si_xN_y to the source, drain and gate areas (a) and cross section SEM image of the transistor (b).

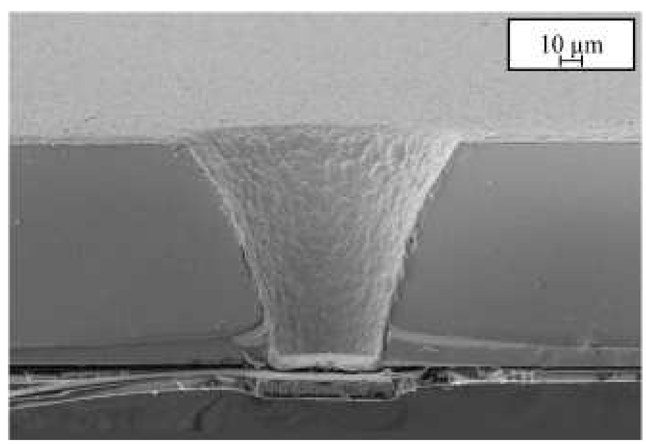

Fig. 6. Cross section SEM image of a copper metalized via hole.

The transistors have a drain-source saturation current $I_{dss} = 280$ m*A*/mm, maximum transconductance $g_m = 450$ mSm/mm at $U_{ds} = 1.5$ V (Fig. 7).

The current cut off frequency was 80 GHz at $Uds = 1.5$ V and $U_{gs} = -0.35$ V, the power gain limiting frequency was 100 GHz (Fig. 8).

Fig. 9 shows the relationships of the transistor's output power and gain with matched input and the output load a

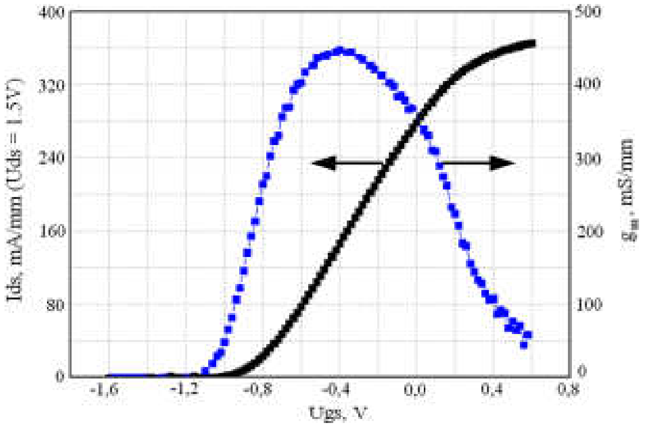

Fig. 7. Transfer characteristics of GaAs pHEMT with Al-metalized ohmic and barrier contacts and Cu based air bridges and backside.

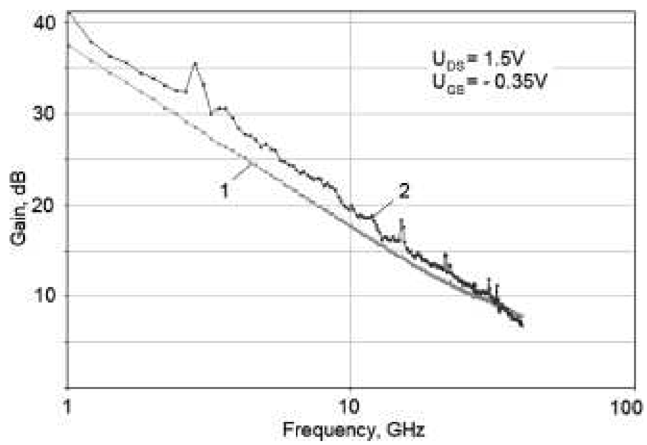

Fig. 8. Measured current gain (1) and masons gain (2) of pHEMT as a function of frequency.

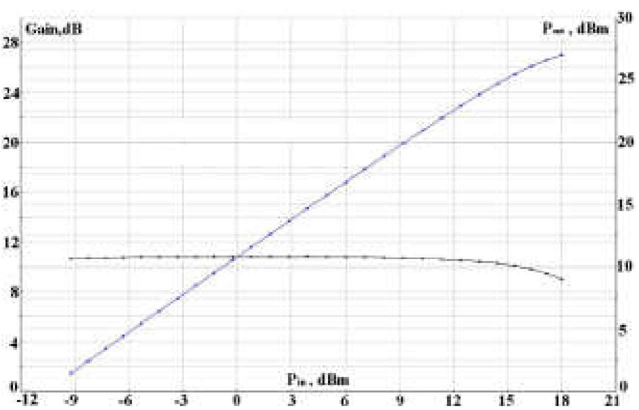

Fig. 9. PHEMT output power and gain factor with matched input and output load a impedance.

impedance. The measurements were carried out at $U_{\mathrm{ds}} = 8$ V, $I_{ds} = 1/3\ I_{\mathrm{dss}}$ at a frequency of 12 GHz. Output power at 1 dB gain compression was $P_{\mathrm{1db}} = 26$ dBm or 670 mW/mm at an efficiency level of about 28% and gain $G = 11$ dB.

It should be noted that the parameters of the newly-developed transistor were similar to those of transistors with conventional Au metallization of the ohmic and barrier contacts, interconnects, air bridges and backside. The obtained results demonstrate the promise of Al and Cu metallization in the manufacture of microwave transistors and MMICs.

IV. Conclusion

In this study, technology has been developed and GaAs pHEMT were fabricated based on Al and Cu metallization. The newly-developed transistors exhibited a source-drain saturation current of $I_{dss} = 280$ mA/mm and a maximum transconductance of $g_m = 450$ mS/mm at $U_{ds} = 1.5$ V; current cut off frequency for transistors with 600 μm total gate width was 80 GHz at $Uds = 1.5$ V and $U_{gs} = -0.35$ V; the power gain limiting frequency was 100 GHz. Output power at 1 dB gain compression was $P_{\mathrm{1db}} = 26$ dBm or 670 mW/mm at an efficiency level of about 28% and the transistor gain $G = 11$ dB. Measurements were performed at $U_{ds} = 8$ V, $I_{ds} = 1/3\ I_{\mathrm{dss}}$ at a frequency of 12 GHz.

The fabricaed transistors had the similar DC and RF performance to the conventional gold based devices but have the lower cost of device manufactore.

The obtained results demonstrate the promise of Al and Cu metallization in the manufacture of microwave pHEMT and monolithic integrated circuits on their basis. The reliability of fabricated copper metalized devices will be investigated in the future work.

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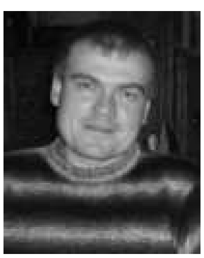

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