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LOW RESISTANCE OHMIC CONTACTS TO N+-GAAS WITH REFRACTORY METAL SIDEWALL DIFFUSION BARRIER

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ABSTRACT

Modern device concepts strongly depend on reliable and well-controlled electrical contacts through which one has to communicate with the interior of the device from the outside world. In particular, micron and submicron size III-V devices can be fully exploited only with adequate ohmic contacts. In addition to a wide variety of device and circuit applications, good quality ohmic contacts are required for investigating the physical and electrical properties of bulk materials and related III-V heterostructures. Consequently, much attention has been recently devoted to the development of new techniques for improving the properties of ohmic contacts to III-V materials, such us gallium arsenide (GaAs).

This paper presents a comparative analysis of the parameters of non-alloyed Pd/Ge/Ta/Cu and alloyed Ge/Au/Ni/Ta/Au ohmic contacts to n^+*-GaAs, both with planar as well planar and sidewall diffusion barriers based on Ta films formed by magnetron sputtering. It has been found that use of sidewall diffusion barriers reduces the value of specific contact resistance of ohmic contacts of both types and improves the thermal stability of the edge morphology of the contact pad in the case of alloyed Ge/Au/Ni/Ta/Au ohmic contacts. The effects observed for the samples with effective diffusion barrier are explained by limiting diffusion, as well as limiting the interaction of Au or Cu atoms with underlying metallization layers and with gallium arsenide, taking place along the sidewall surfaces of the ohmic contact.*

Key words: GaAs, ohmic contact, sidewall diffusion barrier, copper, gold.

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1. INTRODUCTION

Frequency, noise, amplification, reliability and other characteristics of GaAs microwave monolithic integrated circuits (MMIC) are largely determined by the parameters of transistors, and, in particular, by the resistance and thermal stability of the ohmic contacts to the source and drain regions, as well as by the surface and edge morphology of the contact pads [1]–[4]. Therefore, one of the ways to improve the characteristics of transistors and MMIC on their basis is to improve the parameters of ohmic contacts. The problem of obtaining improved ohmic contact is becoming increasingly important due to the transition to transistor components of nanometer size [5].

The current fabrication process of HEMT based GaAs microwave MMIC widely uses ohmic contacts based on a multilayer Ge/Au/Ni composition, obtained by vacuum evaporation [6]. This contact is characterized by low values of specific contact resistance, but exhibits fairly high sheet resistance.

Non-alloyed ohmic contact based on Pd/Ge films [7], formed during heat treatment by solid-state diffusion of Ge atoms into GaAs, has a fairly low specific contact resistance, but is also characterized by high sheet resistance. In comparison with the Ge/Au/Ni ohmic contact, it has better thermal stability of electrical parameters and smoother contact pad surface morphology.

To reduce the sheet resistance of Ge/Au/Ni and Pd/Ge ohmic contacts, an additional layer of highly conducting metal, such as film Au or Cu is deposited on their surface [8, 9, 10]. In this case, the minimum value of the specific contact resistance may increase after thermal treatment due to the diffusion of Au and Cu into GaAs. To limit the Au and Cu diffusion into GaAs, the composition of the metallization of contacts is supplemented by a planar diffusion barrier layer formed of films of refractory metals or their compounds [8]. However, the use of a planar barrier in the ohmic contact metallization does not preclude diffusion processes occurring along its sidewalls, resulting in the interaction of the top layers of the metallization with the GaAs, impairing the specific contact resistance and the edge morphology of the contact pads [11]–[13].

Studies [14, 15] first showed that the simultaneous use in the Ge/Au/Ni/Ti/Au ohmic contact of Ti planar and sidewall diffusion barriers, formed by electron-beam evaporation in a vacuum, reduces the value of the specific contact resistance and improves the thermal stability of the edge morphology of the contact pad.

It can be assumed that the use of planar and sidewall diffusion barriers in Pd/Ge/Cu contact must also improve its performance. For this purpose, a film of refractory metals (e.g. Ta) and their compounds (e.g. TaN), formed by magnetron sputtering, can be used as an effective diffusion barrier.

The purpose of this paper is a comparative study of the influence of planar, as well as planar and sidewall Ta diffusion barriers formed by magnetron sputtering on the electrical and morphological characteristics of non-alloyed Pd/Ge/Ta/Cu and alloyed Ge/Au/Ni/Ta/Au ohmic contacts to n^+-GaAs.

2. EXPERIMENTAL

GaAs/AlGaAs/InGaAs heterostructures, obtained by molecular beam epitaxy, were used in experiments. The ohmic contacts were formed on the n^+-layer of GaAs with an electron density of $n = 5\times10^{18}$ cm^{-3}.

At the initial stage, insulation was produced on the wafer by mesa etching. Then, a bilayer photoresistive mask was formed on the wafer surface, in which windows were cut at the sites of future ohmic contacts. The wafer was next divided into 4 parts, which formed 4 groups of samples. In order to remove native oxides of GaAs, the samples were treated before metalizing with an aqueous solution of HCl (1:10) for 3 minutes followed by rinsing in deionized water and drying in a flow of dry nitrogen. Using electron beam evaporation in a vacuum at a residual pressure of less than 7×10^{-7} mbar, thin films of Pd, Ge and Ta were deposited on the surface of the samples I and II, while Ge, Au, Ni and Ta thin films were deposited on the surface of the samples III and IV. Ta film served as the planar diffusion barrier.

Additional Ta film deposition was then performed on the surface of the samples from all four groups. For samples of groups I and III, the deposition was carried out by electron beam evaporation, and the samples of groups II and IV - by magnetron sputtering. The use of magnetron sputtering provided for the formation of a thin sidewall diffusion barrier film on the sidewall of the ohmic contact (Fig. 1, pos. 7). During deposition of the Ta film by electron beam evaporation, no sidewall diffusion barrier was formed; only the thickness of the planar barrier has increased.

The magnetron sputtering process of the Ta target was carried out in DC mode. Discharge current density was j = 14 mA/cm^2, the argon flow was 20 sccm, and the distance from the magnetron target to the sample was 30 cm.

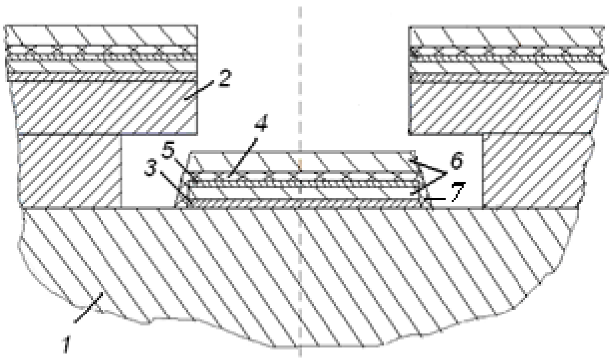

Figure 1 Schematic diagram of the GaAs/AlGaAs/InGaAs wafer with a double-layer resistive mask, 1 – wafer, 2 – photoresist mask, 3 – Ge film, 4 – Ta planar diffusion barrier, 5 – Ni film, 6 – Au film; 7 – Ta sidewall diffusion barrier.

Next, using electron beam evaporation in a vacuum at a residual pressure of less than 9×10^{-7} Torr, the Cu film (samples of groups I and II) or Au film (sample groups III and IV) was deposited. After removal of the photoresist mask, in order to form the ohmic contact, samples of all groups were divided into parts and subjected to thermal annealing in the temperature range T = 300–500 °C for t = 3 minutes.

The sample’s surface was studied by optical and scanning electron microscopy. The metallization thickness of the ohmic contacts was monitored by profilometry with an accuracy of 0.1 nm. Specific contact resistance ρ was measured using the transmission line method on 10 test samples and averaged [20]. Measurement error did not exceed 10-15%.

3. RESULTS

Fig. 2 shows the specific contact resistance of Pd/Ge/Ta/Cu ohmic contacts, ρ as a function of the annealing temperature for samples with planar (sample group I), as well as planar and sidewall (sample group II) diffusion barriers.

Both curves exhibit identical trends across the range of annealing temperatures, but the ohmic contacts with Ta planar and sidewall diffusion barriers show 2 times lower minimum values of specific contact resistance.

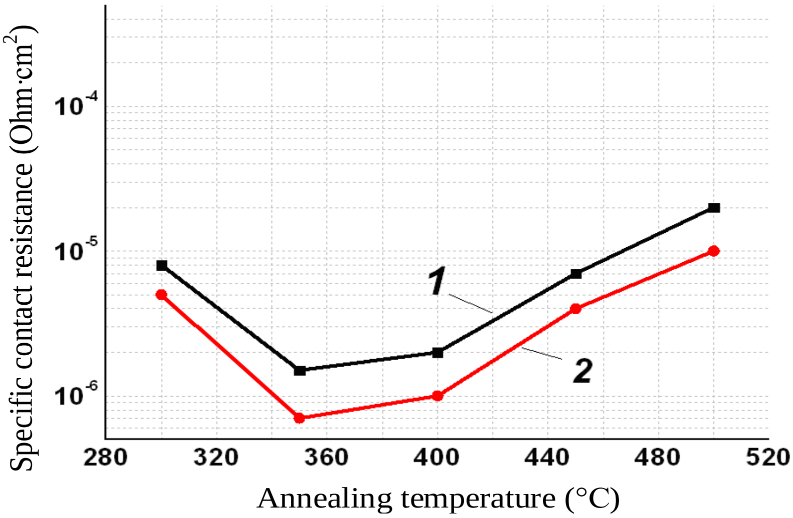

Figure 2 Specific contact resistance of Pd/Ge/Ta/Cu ohmic contact as a function of the heat treatment temperature; 1 – samples with Ta planar diffusion barrier; 2 – samples with Ta planar and sidewall diffusion barriers.

Fig. 3 shows specific contact resistance, ρ of the alloyed Ge/Au/Ni/Ta/Au ohmic contact as a function of the annealing temperature for samples with planar (sample group III), and planar and sidewall (sample group IV) diffusion barriers.

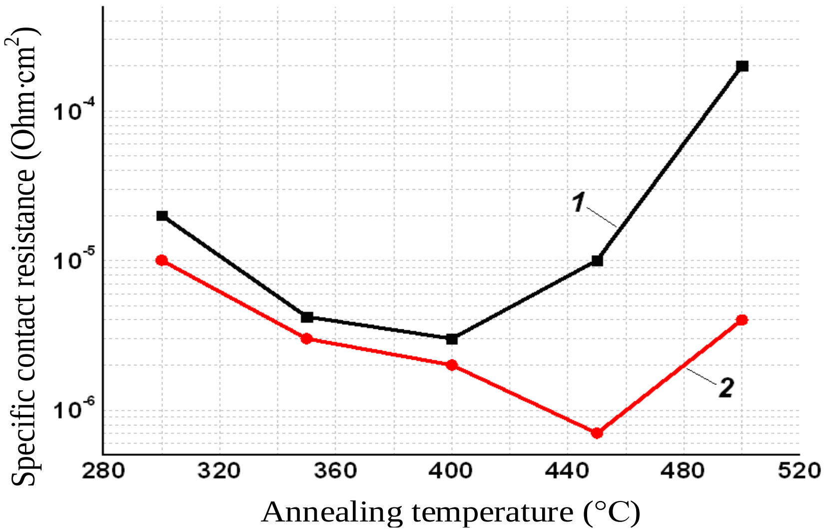

Figure 3 Specific contact resistance of Ge/Au/Ni/Ta/Au ohmic contact as a function of the temperature of the heat treatment; 1 – samples with Ta planar diffusion barrier; 2 – samples with Ta planar and sidewall diffusion barriers.

The temperature functions in Fig. 3 are exhibited as curves with a minimum, well known from the published literature [6]. With increasing annealing temperature, the interdiffusion processes strengthen between the layers of metallization and GaAs, which leads to a monotonic decrease of the specific contact resistance, until it reaches a minimum value. Further increase in temperature leads to an increase in contact resistance, caused by the formation of high-resistance intermetallic phases. The minimum value of the specific contact resistance equal to ρ_{min} = 3×10^{-6} Ohm cm^2 for Ge/Au/Ni/Ta/Au ohmic contact without sidewall barrier is observed at T = 400°C (sample group III). For ohmic contacts with planar and sidewall diffusion barriers (sample group IV), minimum contact resistance is achieved at higher temperatures T = 450°C and comprises ρ_{min} = 7×10^{-7} Ohm x cm^2.

The effect of decreasing specific contact resistance, observed for Pd/Ge/Ta/Cu and Ge/Au/Ni/Ta/Au ohmic contacts with sidewall barrier as compared to contacts without sidewall barrier correlates well with the results obtained by [14] – [16], where use of Ti-based planar and sidewall diffusion barrier films on the alloyed Ge/Au/Ni/Ti/Au ohmic contact to *n*-*i*-GaAs (n = 2×10^{17} cm^{-3}) resulted in a 50-fold reduction in the minimum specific contact resistance values. Apparently, both in the case of non-alloyed Pd/Ge/Ta/Cu and in the case of alloyed Ge/Au/Ni/Ta/Au contacts, a reduction in specific contact resistance can be linked to the action of the Ta sidewall diffusion barrier.

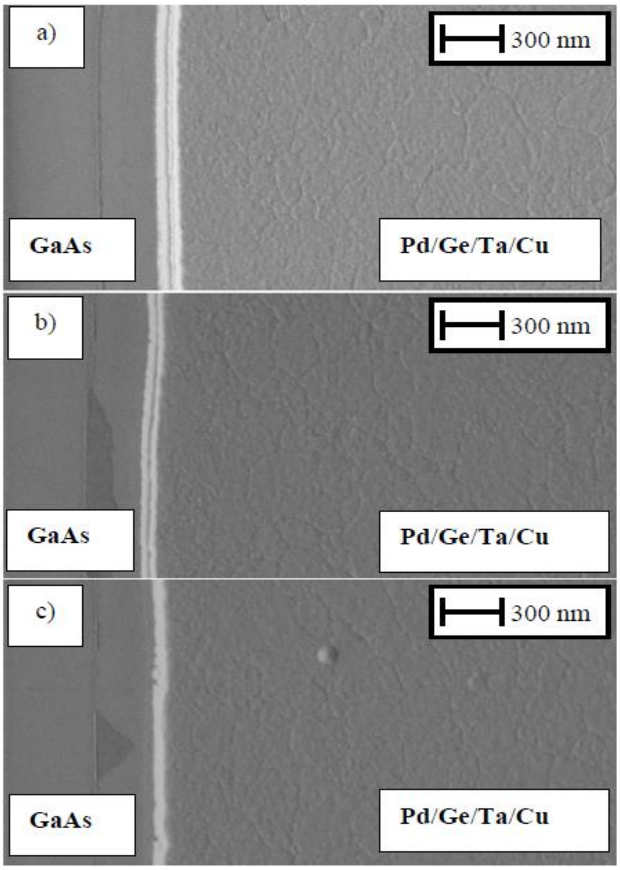

Figure 4 Microscopic images of the Pd/Ge/Ta/Cu ohmic contact surface before (a) and after heat treatment at T = 500 °C with a planar (b), as well as planar and sidewall (c) Ta diffusion barriers.

Fig. 4 and 5 show surface micrographs of Pd/Ge/Ta/Cu and Ge/Au/Ni/Ta/Au ohmic contacts with planar as well as planar and sidewall diffusion barriers before and after annealing at a temperature T = 500 °C.

Data on Fig. 4 shows that for the Pd/Ge/Ta/Cu ohmic contact, annealing at the maximum temperature used in the experiments, did not lead to significant changes in the edge and surface morphology of the contact pad; this held true for the samples with planar and the samples with planar and sidewall diffusion barriers. Apparently, this is due to the fact that this type of contact is formed without forming a liquid phase.

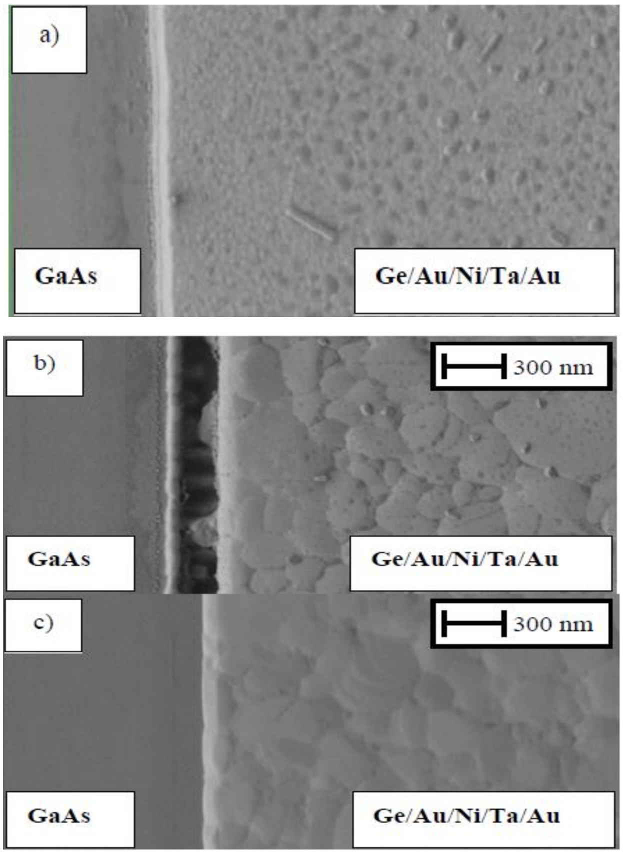

Figure 5 Microscopic images of the Ge/Au/Ni/Ta/Au ohmic contact surface before (*a*) and after heat treatment at T = 500 ^{o}C with a planar (*b*), as well as planar and sidewall (*c*) Ta diffusion barriers.

A different picture is observed in the case of alloyed Ge/Au/Ni/Ta/Au ohmic contact (Fig. 5). After annealing of the sample with a planar diffusion barrier, a broad dark band shows along the edge of the pad, the emergence of which is associated with the interaction between the upper, thick Au film with the underlying layers. This effect was not observed for the sample with planar and sidewall barriers. This indicates a higher thermal stability of edge morphology of the ohmic contacts of that type. The observed effect may be due to the suppression of diffusion and interaction of Au atoms with the underlying metallization, as well as with GaAs along the contact sidewalls in case of a sample with sidewall diffusion barrier.

Fig. 6 and 7 show cross-sectional pictures of Pd/Ge/Ta/Cu and Ge/Au/Ni/Ta/Au ohmic contacts with planar, as well as planar and sidewall diffusion barriers after annealing at a temperature T = 500 ^{o}C, confirming the above trends and their underlying mechanisms.

After thermal annealing at T = 500 ^{o}C, Pd/Ge/Ta/Cu ohmic contact, both with sidewall and without sidewall diffusion barrier, shows no interaction between the upper Cu layer and the underlying metallization layers, as well as GaAs.

In the case of Ge/Au/Ni/Ta/Au ohmic contact without sidewall barrier, after annealing at T = 500^{o}C, near the edge of the contact pad on the surface of GaAs the appearance of a fairly thick film of conductive material is observed (Fig. 7, *a*). Its appearance seems to be associated with active diffusion of the top layer of Au along the sidewalls of the pad, taking place during annealing. Diffusion is stimulated by the mechanism of contact formation involving liquid phase, resulting in the upper Au film more actively interacting with both the underlying layers of metallization and with the GaAs.

Concurrent use of planar and sidewall diffusion barriers can solve this problem and can also increase the thermal stability of the edge morphology of the contact pad. The data in Fig. 7, *b* confirms that, in this case, no diffusion on Au is observed along the sidewall of the contact pad.

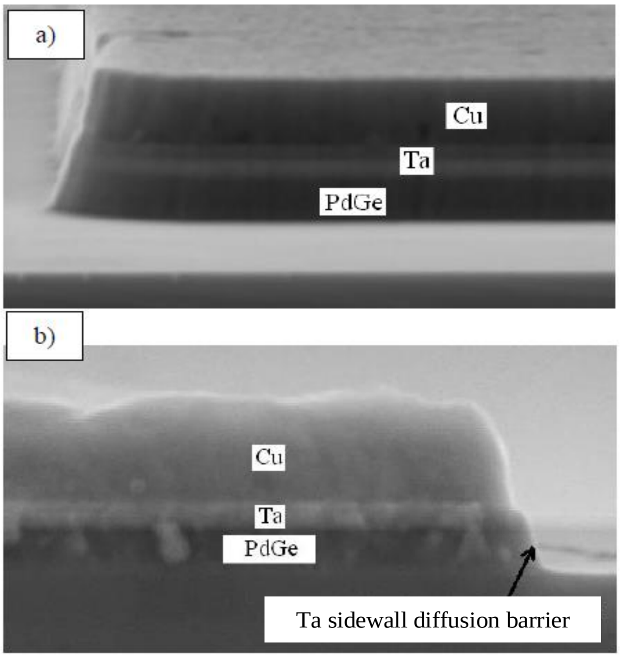

Figure 6 Microscopic cross-sectional images of Pd/Ge/Ta/Cu ohmic contact after thermal treatment at T = 500 °C with planar (*a*), as well as planar and sidewall (*b*) Ta diffusion barriers.

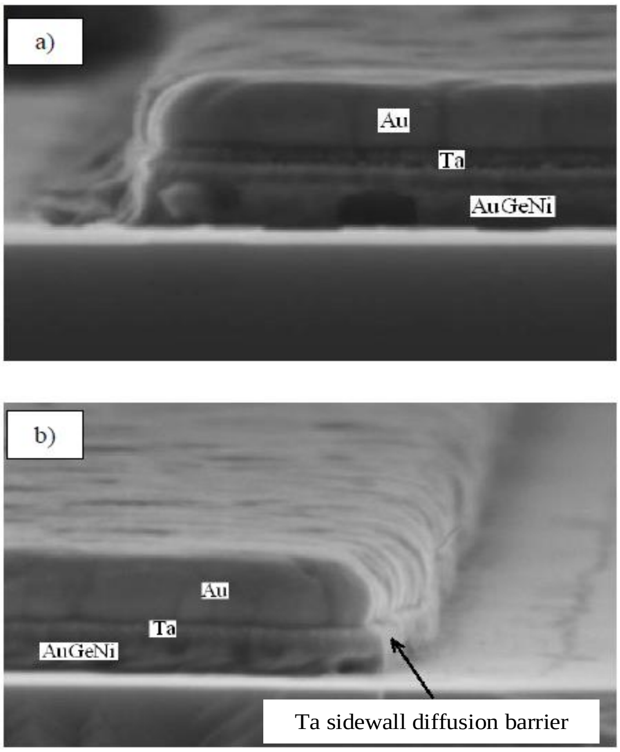

Figure 7 Microscopic cross-sectional images of Ge/Au/Ni/Ta/Au ohmic contact after thermal treatment at T = 500 °C with planar (*a*), as well as planar and sidewall (*b*) Ta diffusion barriers.

It should be noted that the obtained results correlate well with the data obtained by [17] – [19], which showed that, for the alloyed Ge/Au/Ni/Ti/Au ohmic contact, but with a Ti barrier deposited by electron beam evaporation, the introduction of sidewall barrier in the ohmic contact metallization prevents the interaction of the top Au layer with the underlying layers and increases the thermal stability of the contact pad edge morphology.

4. CONCLUSIONS

This study presents a comparative analysis of the parameters of non-alloyed Pd/Ge/Ta/Cu and alloyed Ge/Au/Ni/Ta/Au ohmic contacts to n^+-GaAs, with planar as well as planar and sidewall Ta diffusion barriers formed by magnetron sputtering. It has been established that concurrent use of planar and sidewall diffusion barriers reduces the value of specific contact resistance of ohmic contacts of both types by a factor of 2 and 4, respectively, and improves the thermal stability of the edge morphology of the contact pads of alloyed Ge/Au/Ni/Ta/Au ohmic contacts. The observed effects are explained by limiting the diffusion of Au and Cu atoms through the sidewall surface of the contact pad, caused by the presence of the sidewall diffusion barrier and, as a consequence, the absence of interaction between the upper layer of metal with the underlying layers and with the GaAs.

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