ISSN 1063-7850, Technical Physics Letters, 2017, Vol. 43, No. 11, pp. 1043–1046. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © A.Yu. Pavlov, V.Yu. Pavlov, D.N. Slapovskiy, 2017, published in Pis'ma v Zhurnal Tekhnicheskoi Fiziki, 2017, Vol. 43, No. 22, pp. 96–103.

The Thermal Stability of Nonalloyed Ohmic Contacts to AlGaN/GaN Heterostructures

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Received June 14, 2017

Abstract—Degradation of nonalloyed ohmic contacts with heavily doped GaN epitaxially grown to the heterostructures with two-dimensional electron gas has been investigated. The change in the relative contact resistivity at temperatures of up to 600°C for the Ti/Pd/Au, Cr/Au, and Cr/Pd/Au metallization compositions has been studied. It is demonstrated that the Cr/Pd/Au metallization composition, the resistivity of which decreases at working temperatures of 400°C, is the most resistant to the effect of temperature. It is shown for the first time that the largest contribution to the increase in the contact resistivity to two-dimensional electron gas upon heating above 400°C is made by the resistivity of the Cr/Pd/Au–n^+-GaN metal–dielectric structure, while, at temperatures of 400°C and higher, the resistance between heavily doped GaN and two-dimensional electron gas decreases.

DOI: 10.1134/S1063785017110281

The AlGaN/GaN heterostructures have gradually filled the place of GaAs-based heterostructure elements in microwave semiconductor electronics, since the AlGaN/GaN material has a wider band gap and high majority carrier density, which ensure operation of AlGaN/GaN-based devices at higher temperatures with a higher output power. In Russia, the basic possibility of designing a Russian element base formed on nitride structures with an operation band of up to 100 GHz has been demonstrated [1, 2]. These microwave monolithic chips are fabricated using nonalloyed ohmic contacts, which evoked increased interest due to the necessity for broadening the chip operating range. The nonalloyed ohmic contacts allow retaining smooth relief and straight boundaries of the ohmic contacts of a field-effect transistor in the circuit, since they are fabricated without high-temperature treatment after contact metallization deposition. This makes it possible to form electron-beam lithography marks in one layer with the contact metallization, which provides better positioning between the field-effect transistor ohmic contacts, which are sometimes several micrometers from each other. In this case, the resistivity of nonalloyed ohmic contacts is several times lower than that of alloyed ohmic contacts, which is an additional advantage of their use [3].

The use of nonalloyed techniques for forming ohmic contacts to the AlGaN/GaN heterostructures needs additional investigations to determine the change in their characteristics under the action of external factors, e.g., temperature. During fabrication and operation of devices, the metal–semiconductor contact heats up and can change its properties. In the technique of manufacturing alloyed contacts, the ohmic contacts are subjected to high-temperature treatment and have a higher thermal stability than do nonalloyed contacts. In the nonalloyed techniques, the Ti/Au and Cr/Au compositions are used as contact metallization materials without thermal treatment. To prevent migration of gold through the Ti (Cr) contact layer in a semiconductor upon heating, the ohmic contact composition has the platinum of a palladium layer added to it, which provides better thermal stability of nonalloyed ohmic contacts at temperatures of up to 350–400°C. The use of traditional Ti/Al/Ti/Au alloyed metallization composition as a contact to heavily doped GaN after deposition provides the low contact resistivity, but upon heating this composition to 300–400°C the metal–semiconductor contact behaves as non-ohmic and has a nonlinear *I*–*V* characteristic [4, 5]. Since fabrication of microwave monolithic chips includes operations with a process temperature of 300–350°C, the use of traditional Ti/Al/Ti/Au alloyed metallization composition without alloying is meaningless.

In view of the aforesaid, the problem to be solved is to establish the temperature range of using nonalloyed ohmic contacts with different compositions to epitaxially grown heavily doped GaN under metallization of the ohmic contact selectively deposited through a preformed dielectric mask during fabrication and operation of microwave monolithic chips. It is necessary to find the degradation of nonalloyed ohmic contacts to the AlGaN/GaN heterostruc-

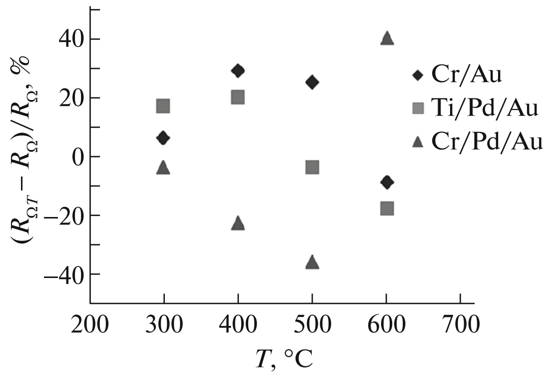

Fig. 1. Temperature dependence of the change in the contact resistivity measured after heating relative to the initial value R_{Ω}.

tures at temperatures of up to 400°C and higher by evaluating the change in resistivity of the ohmic contact to two-dimensional electron gas (2DEG) of a heterostructure.

To study the thermal stability of nonalloyed ohmic contacts to the AlGaN/GaN heterostructures with different ohmic-contact metallization compositions, we examined structures grown on sapphire substrates by chemical-vapor deposition using organometallic compounds without a protective layer with an open barrier. To determine the effect of temperature on the ohmic contact resistivity, we formed test elements on the heterostructures, which implemented the linear transmission-line method (LTLM) and represented a set of contact pads with a width of 20 μm and distances that were multiples of 2 between each other: the gaps between contact pads were 2, 4, 8, and 16 μm. Fabrication of the test elements included the following sequence of operations [6]. First, instrumental isolation is formed on the AlGaN/GaN heterostructures and heterostructure active layers are removed in a chlorine-containing medium through a photoresist mask to a depth of about 70 nm. Then, a dielectric mask is formed, which has open windows in the places of contact of the metal composition to a semiconductor; before growing heavily doped GaN, the heterostructure is etched in the chlorine-containing plasma to the 2DEG level or lower through this mask [7]. Heavily doped GaN is selectively grown by ammonia molecular-beam epitaxy on the heterostructure with the formed mask; thus, a heavily doped semiconductor is formed in the places of future ohmic contact. The dielectric mask is removed by wet chemical etching in a hydrofluoric-acid-based solution. Contact metallization of a desired composition is deposited without heating on the heterostructure with the heavily doped GaN areas through a bilayer photoresist mask by thermal (resistive) vacuum deposition.

To compare thermal stability of nonalloyed ohmic contacts to the AlGaN/GaN heterostructures with growing heavily doped GaN, we investigated the Ti/Pd/Au, Cr/Au, and Cr/Pd/Au metallization compositions. Titanium and chromium were chosen as contact metallization layers to a semiconductor, palladium was added as a diffusion barrier, and gold worked as a chemically inactive upper contact layer to the ohmic-contact metallization.

Samples with test structures and metallizations of different compositions were simultaneously annealed in an STE RTA79 rapid-thermal-annealing facility from 300 to 600°C with a step of 100°C for 15 min in inert nitrogen atmosphere. Before and after annealing, the contact resistivity of ohmic contacts for each sample was estimated to determine its change relative to the initial value. Since the samples were fabricated on different plates and taken from different plate parts, we determined the relative change in the contact resistivity for each sample. For each heating, we used a sample that was not heated earlier. The results are presented in Fig. 1 in the form of the temperature dependence of the change in the contact resistivity relative to its initial value. It can be seen that the resistivities of ohmic contacts with the Cr/Au and Ti/Pd/Au metallization compositions increase upon heating to 400°C relative to the resistivity measured at room temperature, while the resistivities of ohmic contacts with the Cr/Pd/Au metallization remain nearly invariable. However, upon heating above 400°C, we observe the opposite situation: the resistivities decrease for all the metallization compositions.

In the LTLM measurements of contact resistivity, the total measured resistance R_{Ω} to the heterostructure channel includes Cr/Pd/Au–n^{+}-GaN metal–semiconductor resistance R_c, resistance R_{GaN} of the epitaxially grown heavily doped GaN semiconductor, and resistance R_{2DEG} between heavily doped GaN and 2-DEG (see a schematic in Fig. 2). To estimate the contribution of each resistance to the resulting contact resistivity of the nonalloyed ohmic contact to the AlGaN/GaN heterostructure, we additionally introduced in the test sample unit the analogous LTLM test to heavily doped GaN (R_c) epitaxially grown on the heterostructure buffer layer and the heavily doped semiconductor resistivity test ($R_{\mathrm{GaN}} = 100\ \Omega/\square$). Thus, subtraction of the measured contact resistivity to heavily doped GaN from the total measured contact resistivity to the AlGaN/GaN heterostructure yields the contact resistivity to 2DEG of the heterostructure ($R_{\mathrm{2DEG}} \approx R_{\Omega} - R_c$ [Ω mm]). Using these tests, we can estimate the change in each resistance upon temperature impact on the nonalloyed ohmic contact and see which of the included resistances degrades most upon

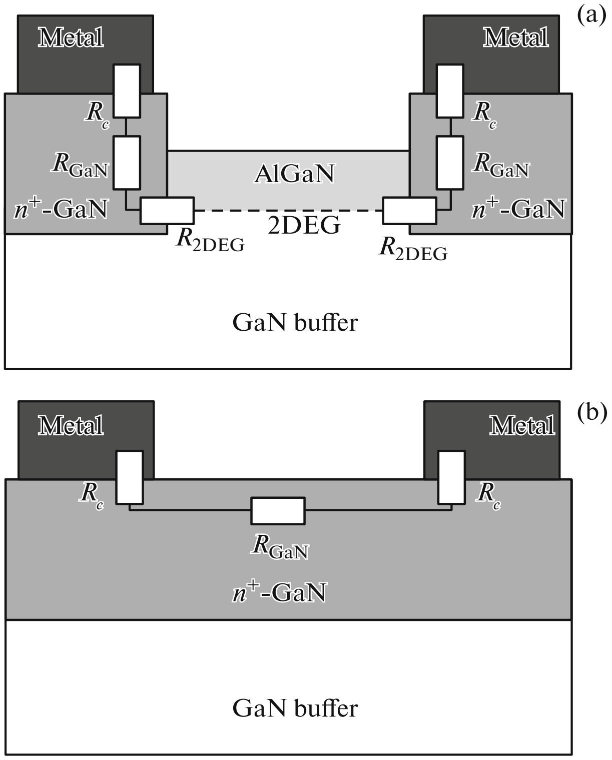

Fig. 2. Schematic cross section of a test element for determining the contact resistivity to (a) the AlGaN/GaN heterostructure and (b) heavily doped GaN. R_c is the metal–heavily doped GaN resistance, R_{GaN} is the heavily doped GaN resistance, and R_{2DEG} is the resistance between heavily doped GaN and 2DEG.

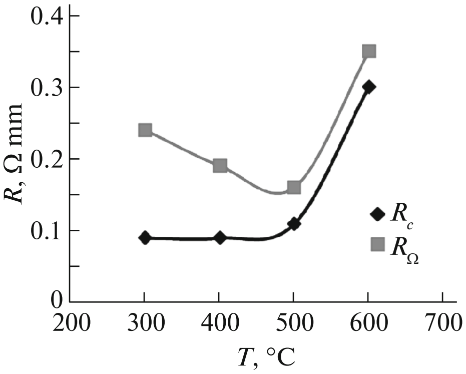

Fig. 3. Temperature dependence of contact resistivity R_c to heavily doped GaN and contact resistivity R_Ω to the AlGaN/GaN heterostructure.

heating. To thermally influence these tests, we used the Cr/Pd/Au contact metallization. The samples with tests were heated at temperatures of 300, 400, 500, and 600°C for 15 min in the nitrogen atmosphere analogously to the first experiment. After each heating, contact resistances R_Ω and R_c were measured. The experiment showed that, upon heating of the nonalloyed ohmic contacts with epitaxially grown GaN, contact resistance R_c of the Cr/Pd/Au-n^+–GaN metal–semiconductor resistance increases, which is consistent with experimental data reported in the foreign literature [4, 5] and is explained by migration of gold to the metal–semiconductor interface upon heating with the subsequent diffusion of gold in GaN. In this case, the measured resistivity on the ohmic contact test to the heterostructure with 2DEG decreased, which is indicative of a decrease in the resistance between heavily doped GaN and 2DEG, since the metal–semiconductor resistance on the same sample under the same conditions increased. The resistance between heavily doped GaN and 2DEG was about 0.15 Ω mm upon annealing at a temperature of 300°C and 0.05 Ω mm upon annealing at temperatures above 500°C. When the resistance between heavily doped GaN and 2DEG is high, it can be minimized by preliminary heating of the heterostructure with formed heavily doped GaN before forming the contact metallization of nonalloyed ohmic contacts. According to data reported in the foreign literature, the theoretical limit of resistance to 2DEG for GaN HEMT is lower than 0.02 Ω mm [8].

Thus, the results of thermal action on nonalloyed ohmic contacts with heavily doped GaN epitaxially grown to the AlGaN/GaN heterostructures showed that the best thermal stability is characteristic of the Cr/Pd/Au metallization composition, which can be used without changing the contact resistance at temperatures of up to 400°C, i.e., the maximum temperature of the microwave-chip fabrication process. For all the investigated metallization compositions, we noted an initial increase in the contact resistivity; above 400–500°C, however, it slightly decreased relative to the initial value. In addition, it was established that heating of the ohmic contact to the heterostructure with 2DEG with the Cr/Pd/Au metallization composition above 400°C leads to degradation of the metal–semiconductor-contact resistance against a background of increased total contact resistance due to migration of gold toward the semiconductor through the Pd diffusion barrier. The effect of decreasing contact resistance to 2DEG at temperatures above 400°C was unpredictable, since in the foreign literature degradation of nonalloyed ohmic contacts formed directly on heavily doped GaN was mainly investigated.

Acknowledgments. This study was supported by the Ministry of Education and Science of the Russian Federation, subsidy agreement no. 14.607.21.0124, unique project identifier RFMEFI60715X0124.

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Translated by E. Bondareva