Atomic force microscopy of titanium oxide nanostructures with forming-free resistive switching

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Abstract. The paper presents the results of study of the resistive switching effect in titanium oxide nanostructures obtained by local anodic oxidation. It was shown that the resulting structures exhibited a forming-free resistive switching effect. Analysis of the current-time characteristics made it possible to obtain a resistance ratio in the HRS and LRS states of about 70. The formed LRS regions persisted for 75 days.

1. Introduction
Modern computer technology based on standard microelectronics elements and methods of their formation has approached its technological limit and cannot be improved further [1-6]. This is because, firstly, the classical lithography methods approached their fundamental limitations, and, secondly, further microelectronics components miniaturization will lead to characteristics degradation due to the stray capacitance appearance, the breakdown voltages reduction, and the leakage currents appearance. Thus, an increase in the productivity and speed of modern electronics is associated with the development and investigation of perspective elemental base and nanolithography methods for formation of nanostructures [7-14]. One of the promising methods is the local anodic oxidation nanolithography, which allows preforming the oxide nanostructures precision formation with a thickness less than 5 nm. It can be used to form memristor structures that can switch between high (HRS) and (LRS) low resistance states [15-26]. The advantages of this method include obtaining non-uniform oxide phases of stoichiometric composition in the volume of titanium oxide nanostructures, which allows obtaining a forming-free memristor effect. To obtain such a result by other methods, it is necessary either to deposit sequential oxide layers with different compositions, or to carry out an additional annealing of memristor structures. Nevertheless, the issue of obtaining memristor structures based on titanium oxide is poorly studied in the literature. Therefore, for introducing into production, it is necessary to study the resistive switching patterns of memristor structures based on titanium oxide obtained by local anodic oxidation.

2. Experiment
Experimental studies were carried out on a 20 nm thick titanium film, obtained by magnetron sputtering on a dielectric SiO₂ substrate. A local anodic surface oxidation was preliminarily performed using a Solver P47 Pro scanning probe microscope. A titanium oxide nanostructure with lateral dimensions of 4×4 μm² and a thickness of 4.8 nm was formed (Fig. 1). Then, its current-voltage characteristics were measured, which showed that the obtained structure exhibited a memristor effect and switched between HRS and LRS (Fig. 2).
To study the current-time characteristics, a voltage pulses series with an amplitude of ± 1.5 V and a duration of 100 ms were applied to the applied structure.

Then, the duration of information storage in memristor structures was studied. For this, an oxide nanostructure with a lateral size of 5×5 μm² was formed in a similar way on the surface of such a structure using current SPM lithography by applying voltage pulses of -6 V to form LRS regions. Then, when applying voltage pulses of 1.5 V using the current AFM method, phase contrast AFM images of the formed regions were obtained 1 minute and 75 days after formation.

3. Results and discussion
Current-time characteristics analysis (Fig. 2) showed that in the initial state, upon application of positive voltage pulses, the current through the memristor structure was about 4.6 pA, which corresponded to the HRS state. When negative voltage pulses were applied, the current through the structure was of the order of 0.3 nA, which corresponds to the LRS state. The results obtained correspond to a memristor effect based on modulation of the width of potential barrier at the metal/oxide interface. The resistance

Figure 2. Titanium oxide nanostructure current-voltage characteristics.
ratio in the HRS and LRS was about 70. Then, the duration of information storage was studied. By the current AFM method, it was shown that as a result of current lithography, LRS regions were formed on the titanium oxide nanostructure surface (Fig. 3a). Repeated scanning of the structure after 75 days showed the presence of these areas (Fig. 3b).

4. Conclusion
It was shown that the local anodic oxidation method allowed forming oxide nanoscale titanium structures exhibiting a forming-free resistive switching effect. Such structures switched between the HRS and LRS states; the resistance ratio in the HRS and LRS states was about 70. The LRS regions formed by current lithography were preserved for a long time.

The obtained results can be used in the development of technological processes for manufacturing the elemental base of RRAM based on oxide nanosized titanium structures using probe nanotechnology.

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