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# A new way to increase the Roff $R_{off}/R_{on}$ Ron memristor parameter on the example of titanium oxide thin-film structure

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A method of increasing the parameter of the Roff$R_{off}/R_{on}$Ron memristor by introducing into its construction an additional electrode of smaller area connected to the lower electrode is proposed. On the example of a memristor based on $TiO_x$ with aluminum electrodes it is shown that this method allows to increase Roff $R_{off}/R_{on}$ Ron not less than three times.

**Keywords:** Memristor, resistive switching, oxygen vacancies, titanium oxide, thin-film structures.

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The construction of computing devices is an area of focus in information technology. Experts believe that the best candidate for next-generation computer memory is resistive random-access memory (RRAM). Studies into the effect of resistive switching of memristor memory elements remain currently relevant, since such elements have great potential for application in digital data processing. In the simplest case, a memristor may be represented by an MIM (metal–insulator–metal) structure with the resistance of the insulator layer varying with the amount of electric charge that has passed through it (the integral of current over time). The first reliable results of examination of the resistive switching effect were obtained in experiments with titanium oxide films [1]. This effect is manifested in them due to the electromigration of oxygen vacancies, which reduces $TiO_2$ to $TiO_{2-x}$ and suppresses the resistance of the memristor active layer. The influence of the memristor electrode material, its shape, and the deposition method of the active layer on the resistive effect has been investigated in subsequent studies [2–6]. Another effective mechanism involves the formation of conductive filaments from atoms of metal electrodes of the memristor structure [7]. One of the main parameters of a memristor is ratio $R_{off}/R_{on}$ of its resistances in high-resistance and low-resistance states in combination with the number of switching cycles and the information storage time.

In the present study, we attempt to improve the $R_{off}/R_{on}$ parameter of an example memristor structure based on $TiO_x$ with a simple engineering solution, which does not affect the method of forming the active layer, by modifying the memristor design with an additional electrode that is positioned in its active region and connected at one end to the bottom electrode.

This was implemented by sequential deposition of layers onto a substrate. The bottom aluminum electrode was formed by thermal evaporation in vacuum at a pressure of $5 \cdot 10^{-5}$ mm Hg. The next layer was deposited by magnetron sputtering of a titanium target in air at a pressure of $6 \cdot 10^{-3}$ mm Hg and had a thickness of 40–100 nm. An aluminum layer (an additional electrode of a smaller area that covered the bottom electrode only partially) with a thickness below 30 nm was deposited after that. A titanium oxide layer with a thickness of 40–100 nm was formed next under the same conditions. At the final stage, the top aluminum electrode was deposited. Figure 1, *a* shows

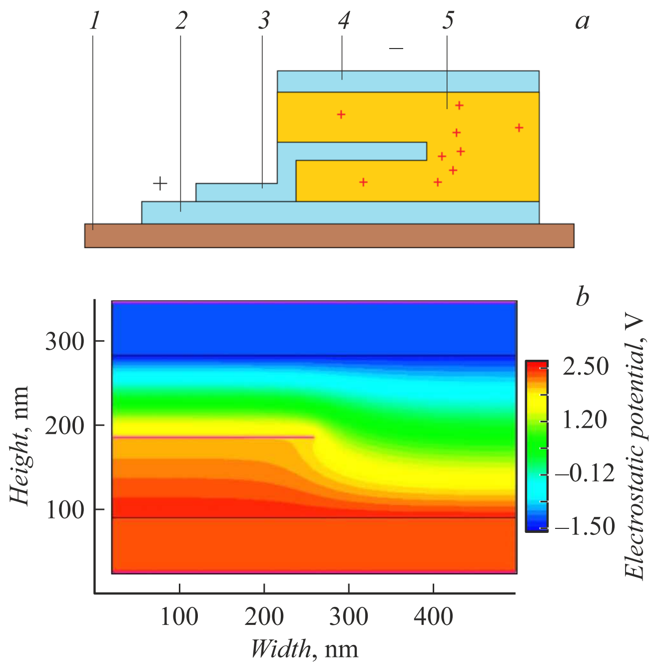


**Figure 1.** *a* — Memristor structure with an additional electrode. *1* — substrate; *2* — bottom electrode; *3* — additional electrode, which does not cover completely the memristor area and is connected to the bottom one; *4* — top electrode; and *5* — oxygen vacancies. *b* — Electric potential distribution with the bottom electrode being at +2 V.

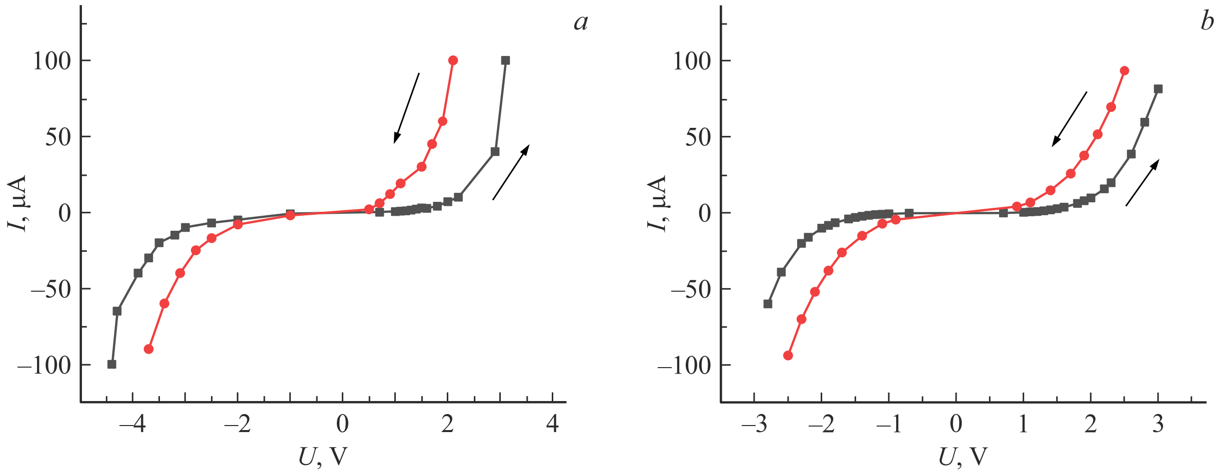


**Figure 2.** Current–voltage curves of the memristor with an additional electrode ($a$) and its prototype fabricated under the same conditions without an additional electrode ($b$).

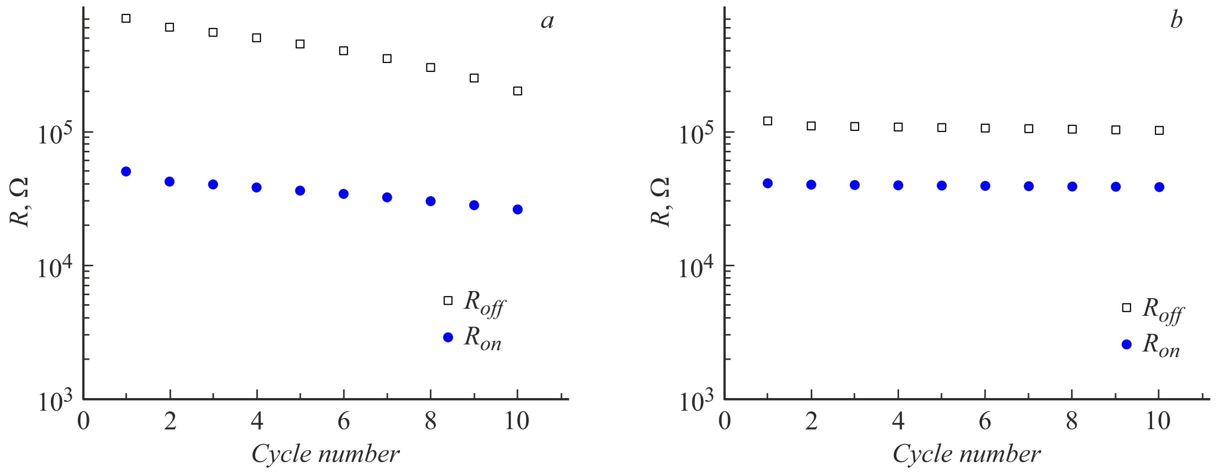


**Figure 3.** Resistances in high-resistance ($R_{off}$) and low-resistance ($R_{on}$) states for the positive ($a$) and negative ($b$) branches of the current–voltage curve in several switching cycles.

the schematic structure of the memristor with an additional electrode.

One may gain a certain understanding of the concept discussed in the present study by modeling the distribution of electric potential in a TCAD (computer-aided design) system with account for the specifics of the proposed memristor design. When a positive potential is applied to the bottom electrode (2 V in the example presented in Fig. 1), the electric field gets deformed in such a way that a region with a potential gradient forms at the edge of the additional electrode. Owing to this, oxygen vacancies drift from the dielectric layer located between the additional electrode and the bottom one (Fig. 1, $b$). This results in accumulation of oxygen vacancies at the edge of the additional electrode, which reduce $TiO_2$ to $TiO_{2-x}$. This region will be characterized by reduced electrical resistance, and the layer between the similarly charged bottom and additional electrodes, which are connected to each other, will act as a source of oxygen vacancies.

The performance of the memristor was tested by measuring the current–voltage curve at a constant voltage (Fig. 2) and determining the switching stability within ten cycles (Fig. 3).

When a positive potential is applied to the bottom electrode of the structures under study and a negative potential is applied to the top electrode, the memristor remains in a high-resistance state until the voltage reaches a level of approximately 3 V. At this point, the current starts to increase rapidly (i.e., the memristor switches to a low-resistance state). When the voltage decreases (the branch of the current–voltage curve indicated by circles in Fig. 2), the structure will maintain a low electrical resistance down to the switching voltage in the negative branch. In other words, at a voltage up to $\sim 2$ V, when the electric field strength does not introduce significant changes into the structure, parameter $R_{off}/R_{on} \sim 15$ for the positive branch of the current–voltage curve; in the negative region, $R_{off}/R_{on} \sim 3$ at a reading voltage of $\sim 3$ V. The structures demonstrate an acceptable stability in both cases. The fact that the memristor effect in the negative branch of the current–voltage curve is weaker is attributable to the lack of accumulation of positively charged oxygen vacancies in the case of application of a negative potential to the additional and bottom electrodes, since the drift of these vacancies is then divided into two flows directed toward the bottom electrode and the region between the bottom and additional electrodes. Comparing the examined memristors with titanium oxide-based ones fabricated in the same way but without an additional electrode (Fig. 2, $b$), one finds that the resistive memory window in the positive branch of the current–voltage curve is expanded by a factor of at least 3, since parameter $R_{off}/R_{on} \sim 5$ with less abrupt switching at a reading voltage of 2 V.

Thus, the discussed engineering solution allows one to increase the ratio between resistive states of a memristor without adjusting the procedure of formation of its active layer. However, it should be noted that this solution is applicable only to memristor structures where resistive switching is associated with the process of electromigration of oxygen vacancies.

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### Conflict of interest

The authors declare that they have no conflict of interest.

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