Investigation of resistive switching effect in nanocrystalline TiO$_2$ thin film for neuromorphic system manufacturing

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Abstract. Effect of resistive switching in TiO$_2$ thin film was investigated. It was shown, resistive switching from high resistance state (HRS) to low resistance state (LRS) has occurred at 3.2±0.2 V, and from LRS to HRS at -2.8±0.5 V. Endurance test shown that HRS decreased from 42.31±5.26 kΩ to 26.45±1.15 kΩ, LRS increased from 2.25±1.15 kΩ to 3.45±1.18 kΩ. HRS/LRS coefficient has decreased from 18.8 to 7.6. Time-stability of TiO$_2$ surface charge was investigated. It was shown, that voltage decreased from 320±21 to 22±5 mV during 90 minutes and square side increased from 3.43±0.12 to 4.12±0.14 µm during 90 minutes. The results can be useful for neuromorphic systems manufacturing based on nanocrystalline TiO$_2$ films.

1. Introduction
The Von Neumann architecture was the main architecture of computer systems for almost fifty years. The main concept of Von Neumann architecture (physical separation of processor and memory) could not more resolve high speed increase problems. One of the possible solutions to this problem is the transition from Von Neumann computing systems to neuro-inspired neuromorphic systems (NS), which is a set of parallel-connected low-power computing elements - neurons and synapses [1-3]. Such computers will be able to surpass Von Neumann computers in many tasks related to unstructured data classification and pattern recognition, as well as low-power consumption and high speed. One of the main ways of technical implementation of this architecture is a memristor - fourth passive component of electronics, based on a change in electrical resistance between high resistance state (HRS) and low resistance state (LRS) of transition metal oxides thin films (effect of resistive switching). One of the promising oxides for NS manufacturing is titanium dioxide (TiO$_2$), which exhibits the effect of resistive switching with increased speed and low-power consumption [4-9]. TiO$_2$ is compatible with traditional semiconductor technology and widely used in electronic elements development [10-15]. Nanocrystalline TiO$_2$ thin films formed by pulsed laser deposition have unique properties and can be used to fabricate NS [15-23]. To fabricate TiO$_2$ based NS elements, it is necessary to carry out investigations of resistive switching effect in TiO$_2$ thin films.
2. Experiment details

TiO₂ film was grown by pulsed laser deposition. Sapphire substrate Al₂O₃ with a crystallographic orientation (0001) as a wafer was used. As the bottom electrode titanium nitride (TiN) with thickness 30.3±5.1 nm was used. Deposition performed under the following conditions: wafer temperature: 400°C, target–wafer distance: 50 mm, O₂ pressure: 1 mTorr, pulse energy: 300 mJ. To provide electrical contact to the bottom TiN electrode, the TiO₂ film were deposited through a special mask pattern. So, on a mask-protected surface area of the TiN films TiO₂ was not deposited.

An AFM-images of the TiO₂ film surface were obtained in semi-contact mode (figure 1) using nanolaboratory Ntegra (NT-MDT, Russia) [14]. The AFM-image processing was performed using Image Analysis software.

Electrical measurements were carried out using semiconductor characterization system Keithley 4200-SCS (Keithley, USA) with W probes. Current-voltage (IV) characteristics of the TiN film was obtained to confirm Ohmic behavior. During the study of resistive switching, TiN layer was grounded. Current-voltage curves were obtained from –5 to +5 V sweep for 10 cycles at the same point (figure 2 a). To prevent thermal breakdown of the nanocomposite film, 1 mA compliance current was set during electric measurements. According to the results obtained, HRS/LRS dependence on cycle number was built (endurance test) (figure 2 b).

Time-stability of resistive switching on TiO₂ surface was implemented using nanolaboratory Ntegra in two stages. On the first stage, square area with 3 µm sides was scanned in contact mode at 5 V (figure 3 a). On the second stage, charged area was scanned in Kelvin mode from 0 to 90 minutes with a 15 minute step (figure 3 b, c).

3. Results and discussion

Figure 1 shows experimental investigations of TiO₂ film morphology. It is shown that TiO₂ film surface has 0.38±0.24 nm roughness (figure 1b). The TiO₂ film thickness was measured by TiO₂/TiN boundary scanning and was equalled to 27.3±4.1 nm.

Figure 2 shows electric measurements of TiN/TiO₂/W structure. Resistive switching from high resistance state (HRS) to low resistance state (LRS) has occurred at 3.2±0.2 V, and from LRS to HRS at -2.8±0.5 V (figure 2 a). Endurance test shown that HRS decreased from 42.31±5.26 kΩ to 26.45±6.14 kΩ, LRS increased from 2.25±1.15 kΩ to 3.45±1.18 kΩ (figure 4 b). It was shown, that HRS/LRS coefficient decreased from 18.8 to 7.6 at –5 to +5 voltage sweep during endurance test. Read voltage was 2.4 V.
Figure 2. Resistive switching in TiN/TiO$_2$/W structure:
a) – current-voltage characteristic; b) – endurance test

The HRS/LRS decrease may be due to the increase in the additional concentration of oxygen vacancies in TiO$_2$ film volume during resistance switching process. It leads to decrease in the length of the destroyed section of the nanosized conduction channel and, consequently, to increase of current through film in HRS state. LRS increase can be explained by decrease in area of nanosized conduction channel built around TiO$_2$/W interface in each resistance switching cycle [15].

Investigation of time-stability of resistive switching shown, that TiO$_2$ surface charge persists during 90 minutes. According to the results obtained, time dependence of voltage and time dependence of charge area size (figure 4) were built.

Figure 3. TiO$_2$ film surface charge: a) – AFM-image of charging area (inside white square); b) – Kelvin mode; c) – cross-section profile along line on (b)

Figure 4. Investigation of TiO$_2$ film surface charge structure stability:
a) – time dependence of voltage; b) – time dependence of structure size
It was shown that voltage decreased from 320±21 to 22±5 mV in 90 minutes (figure 4 a) and structure size increased from 3.43±0.12 to 4.12±0.14 μm in 90 minutes (figure 4 b). The results can be useful for RRAM and neuromorphic systems manufacturing based on TiO₂ thin films.

4. Acknowledgements

This work was supported by RFBR (№ 19-29-03041 мк project), by Grant of the President of the Russian Federation №. MK-2721.2018.8, and by RFBR according to the research project № 18-37-00299. The results were obtained using the equipment of the Research and Education Center and Center for Collective Use "Nanotechnologies" of Southern Federal University.

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