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Adaptive behaviour of silicon oxide memristive nanostructures

**D S Korolev, A N Mikhaylov, A I Belov, V A Sergeev, I N Antonov,
O N Gorshkov and D I Tetelbaum**

Lobachevsky University, 23/3 Gagarin prospect, Nizhny Novgorod, 603950, Russia

Abstract. The response to electrical pulses of various parameters has been studied for the CMOS-compatible memristive nanostructures on the basis of silicon oxide demonstrating reproducible resistive switching. It is established that an increase in the amplitude or width of a single programming pulse is followed by the gradual decrease in the device resistivity. By applying periodic pulse sequences of different polarity it is possible to obtain both lower and higher resistance states. This adaptive behavior is analogous to synaptic plasticity and considered as one of the main conditions for the application of memristive devices in neuromorphic systems and synaptic electronics.

1. Introduction

Memristor or a similar memristive device can be defined as a nonlinear resistor with memory and is usually implemented in a simple capacitor-like nanostructure of the ‘metal-insulator-metal’ (MIM) type. The key advantages of memristive devices are simple structure (the change of electric resistance with applied voltage occurs in thin nanometer film of a material placed between two electrodes), small size (down to 10 nm and smaller) and low power consumption. Because of the ability (by analogy with the biological synapse) to continuously change the resistance in dependence on the input electrical signal, the memristive device is considered as a basis of the next-generation synaptic electronics intended to mimic the adaptive behavior of biological systems [1-2]. The realization of adaptive behavior is based on a gradual character of switching between the different resistive states. It has been already shown that such memristive devices can mimic the plasticity of biological synapses, namely, the short-term and long-term facilitation/depression and spike-timing-dependent plasticity (STDP) [3-5]. Together with the already developed CMOS-integrable neuron-like generators, the memristive devices can be used for the development of artificial networks approaching to the capabilities of brain neural systems.

A challenge is to develop such synaptic electronics on the basis of memristive devices, the technology and materials of which are fully compatible with the traditional CMOS technology. The usage of silicon oxide as a dielectric layer in memristive devices fits organically the technology requirements [6-7]. However, the demonstration of ability to mimic the functions of biological synapse needs special investigation of the device response to the parameters of an individual electrical pulse or their periodic sequences analogous to the bioelectrical activity patterns in a living neural system.



In the present work, the dependence of resistance on the amplitude and width of a single switching pulse as well as on the amplitude, polarity and frequency of the repeated identical pulses is studied for the silicon oxide based memristive nanostructures compatible with the conventional microelectronic technology.

2. Experimental

The capacitor-like MIM nanostructure was deposited on the CMOS-compatible TiN (25 nm) / Ti (25 nm) / SiO₂ (500 nm) / Si substrate by magnetron sputtering using the Torr International® MagSputt™ 3G2 and 2G1-1G2-EB4-TH1 vacuum thin-film deposition systems. The SiO_x film (40 nm) was deposited by RF-magnetron sputtering of fused silica in the argon-oxygen gas mixture (50% oxygen content) at the substrate temperature of 300 °C. Top Au electrodes (40 nm) with the adhesive Zr underlayer (3 nm) and area of $1.2 \cdot 10^{-3} \text{ cm}^2$ were deposited through the mask by the method of DC-magnetron sputtering in an argon atmosphere and substrate temperature of 200°C. The electrical characteristics in the continuous and pulse regimes were measured by the Agilent B1500A semiconductor device analyzer. The sign of bias on the device corresponds to the potential of top electrode (Au) relative to the grounded bottom electrode (TiN).

3. Results and discussion

To obtain the memristive behavior, the as-deposited MIM devices were subjected to electroforming by applying a negative voltage in the range of 4-8 V. Typical current-voltage (I - V) hysteresis of a memristive device after electroforming is shown in Figure 1. The device can switch repeatedly between the two states – high resistance state (HRS) and low resistance state (LRS) that differ in resistance by more than one order of magnitude. The observed bipolar resistive switching is originated from the partial oxidation and recovery (RESET and SET processes, respectively) of conducting filaments grown in silicon oxide film during the electroforming [7].

The measurements of I - V characteristics in a sweeping regime show the dependence of current values and switching voltages on the sweeping amplitude (Figure 1). As can be also seen, the SET transition from HRS to LRS occurring at negative voltages is not abrupt and represented by a gradual stepwise change in resistance. This gradual behavior is potentially important from the viewpoint of multi-bit information storage and can provide the continuous spectrum of final resistive states of memristive nanostructures, the transition between which can be controlled by changing the electrical pulse parameters.

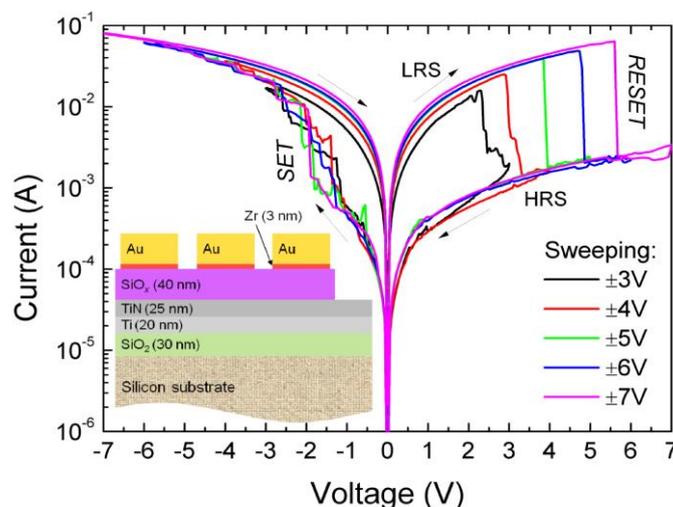


Figure 1. I - V characteristics measured in the cyclic sweeping regime with different sweeping amplitudes. The inset shows schematic cross-section of the Au/Zr/SiO_x/TiN/Ti device.

For the establishment of regularities of adaptive behavior of the same memristive devices, their resistance was measured by applying reading voltage pulses of +0.5 V depending on the parameters (amplitude and width) of programming pulses applied in the SET transition region. The results are shown in Figure 2. An increase in the negative pulse width at a constant amplitude of 7 V leads to the gradual decrease in resistance due to the partial SET transition. After each applied pulse memristive structure was switched back to the HRS by applying a long positive pulse (2 s) with amplitude of 7 V. A similar regularity can be observed in the case of increasing voltage amplitude at a constant pulse width (5 ms) – an increase in the pulse amplitude leads to the decrease in the final LRS resistance. Switching back to HRS in this case occurs by applying long positive voltage pulse (2 s) with the amplitude corresponding to that for the SET transition.

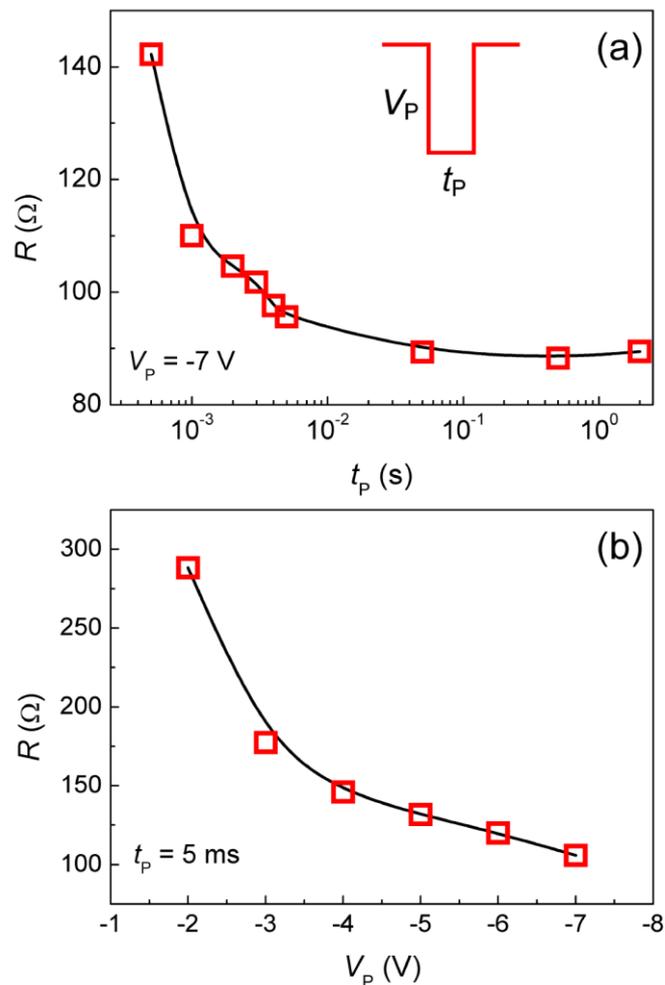


Figure 2. The resistance of memristive device measured at +0.5 V vs. the width (a) and amplitude (b) of a single pulse applied to the device.

The response of memristive device to the voltage pulse amplitude and width can be explained as related to the physical-chemical processes occurring under the recovery of conductive filament in an oxide film [7]. During the application of a low-voltage pulse, the filament recovers only partially, and the degree of the filament ripening depends on the pulse amplitude. The dependence of resistance on the pulse width goes into saturation in the case of long-time pulses. This may be due to the fact that the reduction (SET) process has some finite duration at a fixed voltage.

The fabricated memristive devices were also investigated by applying the sequences of identical voltage pulses with fixed width and amplitude (see typical current response in Figure 3). The ability of device to change the resistance is found to depend on the polarity and frequency of a periodic signal. The observed response of memristive devices is functionally similar to the facilitation and depression properties of a biological synapse.

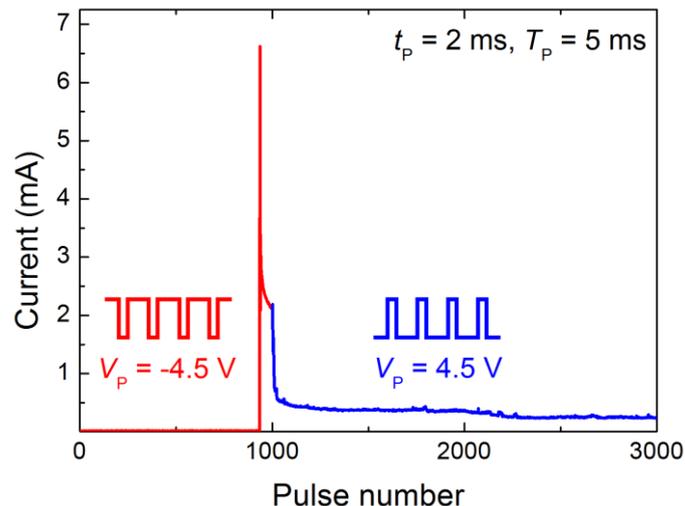


Figure 3. The dependence of current through the memristive device on the number of repeated identical pulses of different polarity.

Further experiments will be focused on the experimental realization of plasticity phenomena using the FitzHugh-Nagumo neuron-like spike generators and modelling the artificial neuronal network based on memristive devices.

4. Conclusions

In summary, the measured dependencies of resistance of SiO₂-based memristive devices on the amplitude and duration of applied voltage pulses show that a continuous spectrum of resistive states is realized and the device resistance depends on the parameters of periodic pulse sequences. The studied memristive devices on the basis of CMOS-integrable materials and technology reveal the synaptic (adaptive) behavior and can be implemented in the development of new-generation artificial neural networks and neuroprocessors.

Acknowledgments

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References

- [1] Kuzum D, Yu S and Philip Wong H-S 2013 *Nanotechnology* **24** 382001
- [2] Thomas A 2013 *Journal of Physics D: Applied Physics* **46** 93001
- [3] Choi S-J, Kim G-B, Lee K, Kim K-H, Yang W-Y, Cho S, Bae H-J, Seo D-S, Kim S-I and Lee K-J 2011 *Applied Physics A* **102** 1019–25
- [4] Tsuruoka T, Hasegawa T, Terabe K and Aono M 2012 *Nanotechnology* **23** 435705
- [5] Ohno T, Hasegawa T, Tsuruoka T, Terabe K, Gimzewski J K and Aono M 2011 *Nature Materials* **10** 591
- [6] Mehonic A, Cuffe S, Wojdak M, Hudziak S, Jambois O, Labbé C, Garrido B, Rizk R and Kenyon A J 2012 *Journal of Applied Physics* **111** 74507
- [7] Mikhaylov A N, Belov A I, Guseinov D V, Korolev D S, Antonov I N, Efimovych D V, Tikhov S V, Kasatkin A P, Gorshkov O N, Tetelbaum D I, Gryaznov E G and Yatmanov A P 2015 *Mat. Sci. Eng. B* **194** 48