Effect of current limitation on the adaptive behavior of memristive nanostructures

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Abstract. Adaptive behavior of resistive state in response to electrical stimulation has been studied for the silicon oxide based memristive nanostructures subjected to electroforming in the conditions of current compliance. The limitation of current and temperature during electroforming affects the parameters of growing conductive filaments and reduction-oxidation reactions resulting in a higher dynamic range of gradual resistance change important for neuromorphic applications.

1. Introduction

The rapid development of information technologies and electronics is associated with innovations in the information storage devices and neuromorphic (biosimilar) systems based on memristive nanomaterials [1]. Memristive effect is often implemented in a thin-film nanostructure of the metal-oxide-metal type as a reproducible resistance change between the low-resistance and high-resistance states under application of electric stress [2, 3]. The resistance change is analogous with the change in transmissive efficacy of synaptic junction and considered as one of the main conditions for the application of memristive devices in neuromorphic systems.

The ability of memristive nanostructures to continuously change the resistance in dependence on input electrical signal is equivalent to the adaptive behavior (plasticity) of synapse as a key mechanism underlying the phenomena of learning and memory in neural networks. The realization of adaptive behavior of metal-oxide memristive nanostructures [4] is based on a continuous spectrum of resistive states related to the different configurations of conductive silicon filaments grown in oxide film during electroforming (EF) and on a gradual character of switching between the different resistive states. The range and sensitivity of a resistive state to electrical stimulation should depend on the kinetics of microscopic reduction-oxidation phenomena driven by electric field and temperature. Effect of current compliance (CC) applied during EF on the character and parameters of resistive switching (RS) was investigated in several works for different compositions of materials in a memristive nanostructure [5, 6]. For the HfO$_2$-based memristive nanostructures [7], it was established that the character of RS (gradual or abrupt) in the processes of increase (SET) or decrease (RESET) of conductivity also depends on the use of CC. Obviously, such peculiarities of a memristive device must depend on specific materials used in its thin-film structure. To the best of our knowledge, for the CMOS-compatible SiO$_2$-based nanostructures [8], the detailed study of CC effect on the adaptive behaviour of resistive state has not been reported yet.
In the present work, the adaptive change of resistance in a wide range is studied for the silicon oxide based memristive nanostructures in dependence on the application of CC during EF and RS.

2. Experimental

The capacitor-like metal-oxide-metal nanostructure was deposited on the CMOS-compatible TiN (25 nm) / Ti (25 nm) / SiO$_2$ (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$_2$ film (40 nm) was deposited by RF-magnetron sputtering of fused silica in the argon-oxygen gas mixture (30% oxygen content) at the substrate temperature of 300 °C. The top Au electrodes (40 nm) with area of 1.2·10$^{-3}$ cm$^2$ were deposited through the mask by the method of DC-magnetron sputtering in an argon atmosphere and substrate temperature of 300°C. The electrical characteristics in 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). The EF was performed during the first current-voltage sweep at the negative bias with or without application of CC.

3. Results and discussion

Typical curves of EF realized in the range of 2-6 V of negative bias and subsequent RS hysteresis of the valence-change type [8] are shown in Figure 1 for the fabricated SiO$_2$-based memristive nanostructure.

If no CC is used during EF, the “strong” silicon filaments are grown in oxide film, and the structure can be switched between the low-resistance state (LRS) and high-resistance state (HRS) in the so-called high-current mode. The corresponding RS hysteresis is shown by the red current-voltage curves in Figure 1 and characterized by the gradual or abrupt stepwise current changes in the SET (HRS to LRS) and RESET (LRS to HRS) transitions, which are poorly reproducible from cycle to cycle.

If the CC at 100 μA is applied during EF, the SET transition becomes abrupt but is followed by a monotonous RESET process to the “deeper” HRS state with the lower threshold voltage. This gradual RESET transition is reproducible and is much more appropriate for the demonstration of adaptive behavior compared to the SET transition in the high-current RS mode studied in our previous work [9]. It should be noted that the observed deep HRS state cannot be achieved in the high-current RS mode, even if CC is applied during the preceding SET transition (e.g. CC at 1 mA shown in Figure 1).

![Figure 1](image-url)
The averaged dependence of resistance on the amplitude of positive (RESET) programming pulse (5 ms) is shown in Figure 2a for the memristive nanostructure subjected to EF in the conditions of CC at 100 μA. The resistance was measured at a reading voltage of +0.5 V after each RESET pulse, which was also followed by the negative pulse (−6 V) used to set the structure back to LRS.

In contrast to adaptive behavior measured in the SET region (Figure 2b – see detailed discussion in [9]), the adaptive behavior related to the gradual and deeper RESET transition is characterized by the almost linear dependence on the voltage amplitude in the range of 0-5 V and the much higher dynamic range of resistance change from $10^2$ to $10^5$ Ω important for the application as a programmable weight in artificial neural networks.

![Figure 2a](image-a.png) ![Figure 2b](image-b.png)

**Figure 2.** The resistance of memristive nanostructure vs. the RESET pulse amplitude (a) compared to the analogous dependence of resistance on the SET pulse amplitude [9] (b).

The observed effect of CC applied during EF can be interpreted from the viewpoint of previously proposed RS model [3, 8] based on the processes of formation and partial oxidation of a silicon filament accompanied by the migration of interstitial O$^2$ ions produced during the breaking of Si-O-Si bonds. Without CC, the high current value through the forming filament provides the strong Joule heating in a local area adjacent to filament. As a result, the thermal diffusion moves oxygen far away from the filament. When current is limited by the CC value, the temperature around the filament at the stage of EF is smaller, and the distance of oxygen removal from the filament is lower too. In this case, the RESET process associated with the filament oxidation near the electrode begins at lower voltages and leads to a more expressed oxidation, which cause the decrease in RESET voltage and increase in HRS resistance. The RESET process becomes gradual because the oxidation takes place in a broad range of voltages, whereas the “high-current” RESET transition is realized only in a narrow voltage range and has an abrupt character.

The obtained dependence of resistance of memristive device on the amplitude of voltage pulse (Figure 3) provides the following technique of programming the resistance (weight) of a memristor for the application in neural networks. The desired value of resistance is set by the application of programming pulse with the amplitude in the range of 1-5 V. To set the next value (in any direction of resistance change), the initializing pulse of opposite polarity with the amplitude of 5-8 V (which turns the device into initial resistance state) is applied before the programming pulse. The amplitude of a voltage pulse, which does not change the resistance, should be lower than ±1 V.

The histograms of resistive states obtained by multiple (100 times) programming of each value (programming pulses: 1 V; 2 V; 3 V; 4 V) in the RESET mode for a memristive device subjected to EF with CC are shown at Figure 3. By using Gaussian fitting of the resistance distributions for different programming voltages, it is obtained that the variation (standard deviation) of resistance increases with increasing the resistance of memristive device, but in relative units (relative to the mean value) it remains approximately constant and does not exceed 30%. It is evident that the observed
variation of memristive states is caused by the stochastic nature of RS process [3] and should be taken into account in the design of artificial neural networks based on memristive devices.

**Figure 3.** The histograms of resistive states of memristive device programmed by the application of different RESET voltage pulses.

4. Conclusions
In summary, the limitation of current during electroforming process allows controlling the parameters of adaptive behavior of SiO₂-based memristive nanostructures. Programming the resistive state in a wide range with the 30% accuracy is demonstrated in the region of gradual transition from low-resistance to high-resistance state of memristive device. The developed memristive devices on the basis of CMOS-integrable materials and technology can be used in the design and hardware implementation of artificial neural networks and neuroprocessors.

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