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ZrO_X insertion layer enhanced switching and synaptic performances of TiO_X-based memristive devices

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Abstract. The impact of ZrOx material serving as an electro-thermal modulation layer (ETML) in the TiN/Ti/TiOx/TiN memristive device structure is investigated. Although the introduction of the ETML increases the total thickness of the device resulting in the increase of forming voltage, it helps to generate weak filaments. The formation of weak filaments in analog memristive devices is preferable to ensure stable switching cycles and epoch training. The device made with ETML performs stable endurance for more than 600 cycles with an On/Off ratio of approximately one order of magnitude; moreover, the device exhibits uniform potentiation and depression with low nonlinearity.

Keywords: memristive, data storage, TiO2-based devices, artificial synapses.

1. Introduction

Analog memristive devices show promising potential as the future artificial synapse electronics [1]. The artificial synapses are the main component for making artificial intelligence (AI)-on chip that could bring great benefit in solving complex computations (neuromorphic computing applications) [2]. This technology will revolutionize the traditional Von Neumann computer architecture and realize faster, more efficient, and smarter (having self-adaptive and self-reconfigurable capabilities) electronics where the analog behavior opens the possibility where the memory unit can not only be used as a data storage but also as a processing unit[3]. Nevertheless, sufficient switching and synaptic performances are required to achieve reliable memory and AI chips. Recently, we developed several methods to achieve good memristive devices, such as radiation [4,5], doping[6–8], deposition parameter [9–11], chemical[12–15] and thermal treatments [16,17],

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electrical programming [18,19], 2-dimensional [20]and multistacking structures[21–26]. In this work, we explore the use of the electro-thermal modulation layer (ETML) to enhances the performance of the memristive devices. The ETML technique was introduced by Wu W. et al.[27]to avoid sudden changes in the electric field in HfOx-based memristive cells that can deteriorate the device; the ETML material should have low thermal conductivity and high resistivity. However, the ETML material that works for TiOx-based memristive devices has not been studied yet [28]. We chose ZrOx as the ETML material due to its higher resistivity and lower thermal conductivity than that of the TiOx material [29,30]. This report can provide useful inside in fabricating excellent TiOx-based memristive devices.

2. Methods

A 15 nm thick of TiN bottom electrode was deposited onto Pt/Ti-SiO_2 substrates by atomic layer deposition (ALD). Hereafter, 25 nm thick of TiOx films was deposited using DC sputtering from a Ti target; the deposition was conducted in a mixed Ar/O_2 ambient with the ratio of 2/1, the working pressure of 5 mTorr and sputtering power of 800W. An 11 nm thick of ZrOx was deposited onto the TiOx layer as an ETML layer from a ZrO_2 target under a mixed Ar/O_2 ambient with the ratio of 2/1 and sputtering power of 80W. Multilayer top electrodes having a diameter of 150 μm consisted of 5 nm Ti and 50 nm TiN were deposited using DC sputtering; sputtering power of 600 W and 800 W were used to deposit Ti and TiN, respectively. Note that the condition of the deposition strongly affect the quality of the films [16]; therefore, the conditions of all films were optimized to ensure they have the required properties. Electrical characteristics were studied using Agilent B1500A, and voltage bias was applied on the top electrode while the bottom is ground; current compliance of 10 mA was employed to avoid device breakdown.

3. Result and discussion

Both devices require a forming process to activate the switching characteristics (**Figure 1**). The device made with and without ETML can be switched from pristine state to a low resistance state (LRS, On) by sweeping a positive voltage bias of approximately 3.5 V and 6 V, respectively. The insertion of ETML film increases the total thickness of the switching layer; thus, it requires higher forming voltage to complete the filament formation that grows from bottom to top electrode. Hereafter, a negative voltage of -1.35 V can switch both devices from an LRS to a high resistance state (HRS, Off), called reset. Similarly, a positive voltage sweep switches the devices back to the LRS, called set; the set voltages are less than 1 V. Both devices exhibit analog counter-clockwise switching behavior.

It is found that the devices made with ETML perform better endurance performance; the device shows excellent stability with an On/Off ratio of approximately one order of magnitude for more than 600 cycles (**Figure 2**). On the other hand, the device made without the ETML exhibits severe switching instability. One of the generally accepted switching mechanism in memristive devices is filamentary-based mechanism [31]. Henceforth, the TiN/Ti top electrode and HfOx have high thermal conductivity and induces the formation of strong or large filaments at the top electrode/switching layer interface region; consequently, it is challenging to rupture the filaments during the reset process. The ZrOx serves as the ETML, that modulates the thermal conduction in the cell and induce weak filaments formation. Thus, the device can be easily turned Off (reset). This result suggests that the TiN/Ti/ZrOx/TiOx/TiN device structure can be useful for data storage applications.

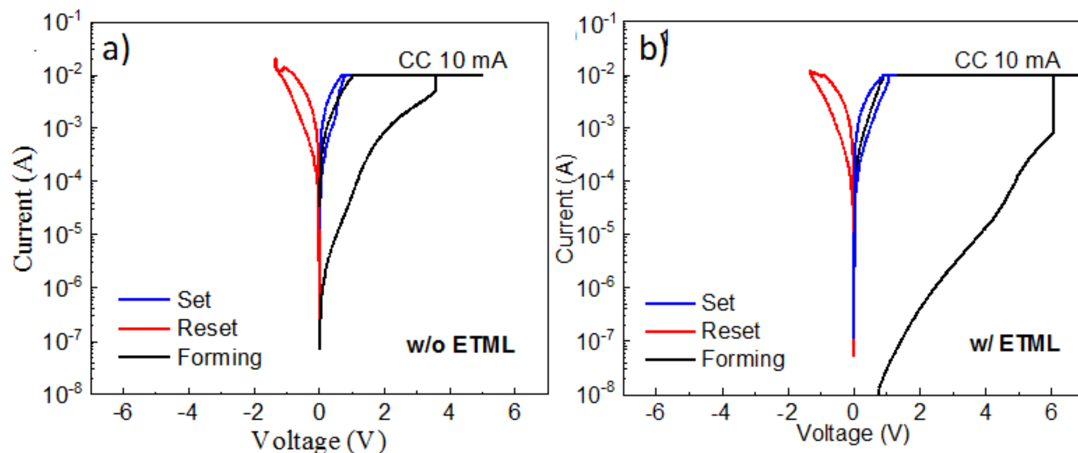

Figure 1. Typical I-V curves of devices made: a) without ZrO2 ETML and b) with ZrO_2 ETML

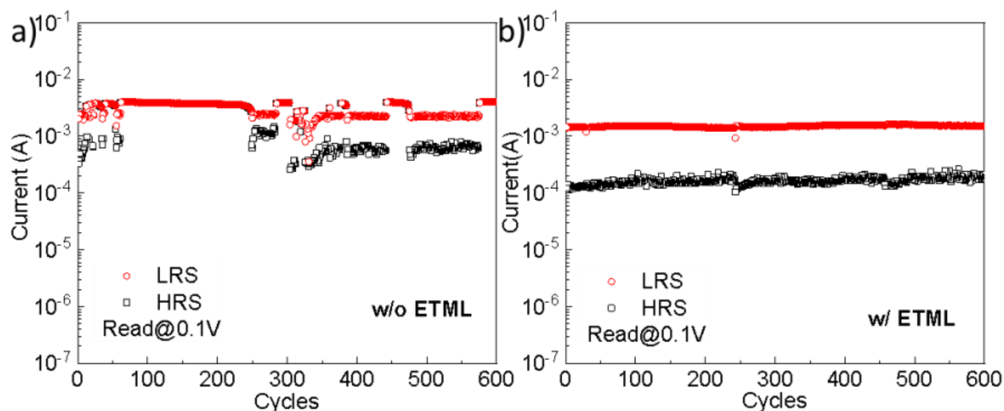

Figure 2. Endurance performance of devices made: a) without ZrO_2 ETML and b) with ZrO_2 ETML

Analog switching behavior is beneficial for making artificial synapse electronics for neuromorphic computing applications. As both devices exhibit analog behavior (see **Figure 1**), we evaluated the synaptic characteristics of the devices by employing identical pulses having a width of 25 μs and amplitude of 0.8 V and -0.93 V for potentiation and depression, respectively, while the pulse read at the amplitude of 0.2 V and width of 0.1 ms. A single epoch training consists of 60 pulses of potentiation and 60 pulses of depression. The conductance of the devices made without ETML raises quickly during potentiation results in a very high dynamic range; however, the depression cannot reach the original conduction value.Consequently, the device exhibits epochs instability with a poor linearity (**Figure 3a *and* Figure 3b**).

Meanwhile, the device made with ETML exhibits stable epoch training and excellent linearity (nonlinearity was calculated to be 2.08 and 1.84 for potentiation and depression, respectively) (**Figure 3c and 3d**). We suggest that the strong filaments in the device made without ETML compete with each other during the epoch training which the most massive filament become stronger, and the weakest will be diminished after several epochs; henceforth, the depression is unable to decrease the conductance down to the value where the potentiation was started. However, the insertion of the ETML induces the formation of weak filaments, and these filaments can contribute equally during potentiation and depression and, thus, the device can achieve stable epoch training.

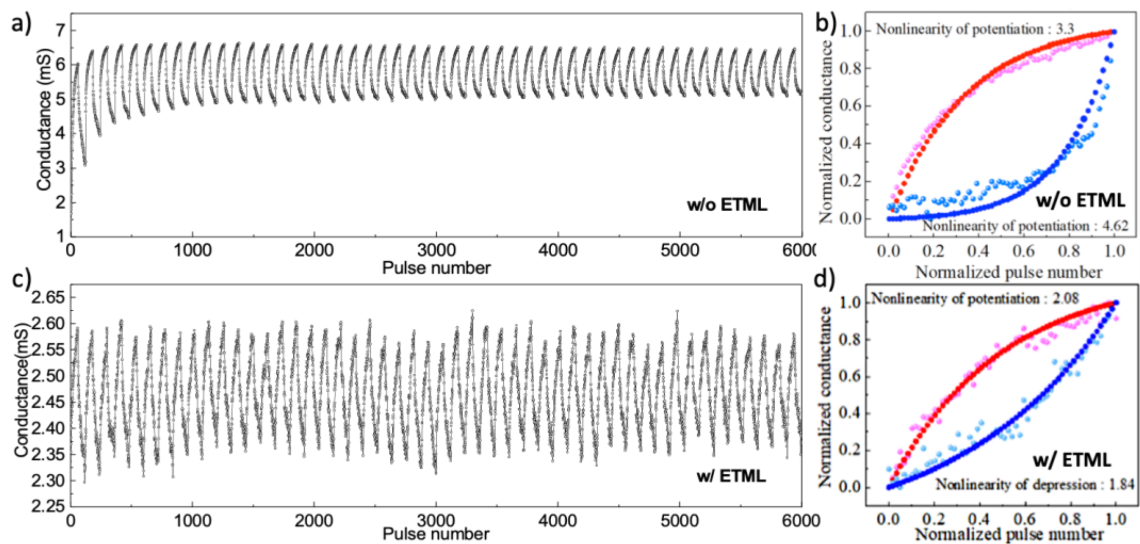

Figure 3. Potentiation and depression characteristics of devices made (a,b) without ZrO_X ETML and (c,d) with ZrO_X ETML.

4. Conclusion

The employment of ZrOx as an ETML in the TiN/Ti/TiOx/TiN device structure can significantly enhance the switching and synaptic performances. The device made without the ETML tends to have strong filaments, which make it difficult to achieve a successful reset or depression. The insertion of ZrOx in the device structure induces the formation of weak filaments due to the low thermal conductivity of the ZrOx material and, thus, improves the endurance and epoch training.

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