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A Physically Based Model to describe Resistive Switching in different RRAM technologies

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***Abstract*— A model for filamentary conduction in RRAMs based on Metal-Insulator-Metal (MIM) structures has been developed. The model describes RRAM resistive switching processes by calculating the formation and rupture of conductive filaments (CFs) in the dielectric. The resistance of the electrodes, of the CF and the hopping current in the gap between the CF tip and the electrode, are taken into consideration. The thermal description of the CF is included by solving the heat equation. The model has been employed to reproduce I-V curves of different RRAM technologies making use of the correct model parameters in each case. Therefore, it is suitable to be implemented in circuit simulators to analyze circuits based on RRAMs under different operation regimes.**

Keywords—Compact model, device modeling, non-volatile memory, resistive RAM, Resistive swictching memory, RRAM .

I. INTRODUCTION

Resistive random-access memories (RRAMs) are built as stacks made of two electrodes, top and bottom, and a dielectric in between; for this technology, both MIM and MIS structures are employed. Several metal oxides have been used as dielectrics, among them: HfO_2, TiO_2, NiO, ZnO, Al_2O_3, SiO_2, ZrO_2 [1-5]. For RRAMs based on these dielectrics, resistive switching (RS) operation has been reported. RS shows up when a device switches between a high resistive state (HRS) to a low resistive state (LRS). This process is named SET and the inverse RESET. It should be noted that in devices with the same Transition Metal Oxide (TMO) as dielectric, the electrical behavior of the RRAMs can be different depending on the materials employed for fabricating the top electrode (TE) and bottom electrode (BE). For example, with a stack such us $Pt/HfO_2/Pt$ [3], the device could undergo both SET and RESET processes under the same voltage polarity (unipolar behavior); on the contrary, for a stack reported in Ref. [4], $Ti/HfO_2/TiO_x/Pt$, the devices show bipolar behavior, where the switching processes take place at different voltage polarities. The potential of RRAMs in the non-volatile memory realm is linked to features such as scaling simplicity, low program/erase currents, low switching voltages, fast switching speeds, excellent retention and endurance, capability of multi-bit storage, viability for 3D memory stacks and integration in the back-end-of-line (BEOL) of CMOS processes [1, 5-7]. The previously reported characteristics support RRAMs as viable candidates for the replacement of flash memory technology in future scaling nodes [5, 6].

To advance in RRAM development, and for the inclusion of these devices in future commercial ICs, good compact models are needed in circuit simulation tools. The link between process engineers and designers is made through compact models and reliable model parameters extraction algorithms which should be incorporated in future Electronic Design Automation (EDA) tools.

For these compact models to operate appropriately, the physics behind RS mechanisms has to be taken into account. Among the important physical effects to consider are thermal and quantum mechanical effects, parasitic effects, such as series resistances, redox reactions and other processes that affect the temporal evolution of the device conductance [1, 6-10]. In the last years, several compact models have been proposed by the scientific community [10-19] including different physical approaches to deal with the device temperature calculation. In few of these models the temperature is calculated at every simulation step; in addition, some of the models also consider the real shape and number of CFs, tunneling currents, etc. Parameter extraction has also been dealt with [11, 20-24]. In this work, we present a model for filamentary conduction in RRAMs accounting for the formation/disruption of CFs. The model has been validated with experimental data obtained from different technologies.

II. FABRICATED DEVICES

The devices based on the $TiN/Ti/HfO_2/W$ structure were fabricated on (100) p-type CZ silicon wafers. Wet thermal oxidation was performed at 1100 ºC, leading to a SiO_2 layer 200 nm thick. After that, a 200 nm W layer was deposited by magnetron sputtering. Then, a 10 nm HfO_2 layer was deposited by atomic layer deposition (ALD) at 225 ºC using TDMAH and H_2O as precursors, and N_2 as carrier and purge gas. A 200 nm TiN and a 10 nm Ti layer formed the top electrode, deposited by magnetron sputtering. The contact windows to the bottom electrode were opened by dry etching of the HfO_2 layer. The resulting device structures were square cells of 15 x 15μm^2. A schematic representation of the device cross-section is shown in Fig. 1(a).

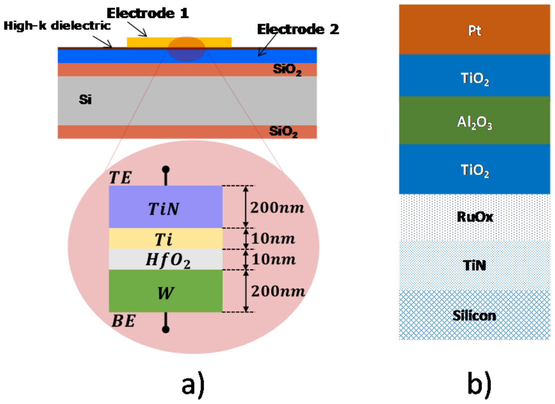

Figure 1: Cross-section sketch of the fabricated devices, a) $TiN/Ti/HfO_2/W$ structures fabricated at the Institute of Microelectronics of Barcelona, b) $Pt/TiO_2/Al_2O_3/TiO_2/RuO_x/TiN$ structures fabricated at the University of Tartu.

The devices made of $Pt/TiO_2/Al_2O_3/TiO_2/RuO_x/TiN$ stacks were deposited by ALD in a home-made flow-type reactor at substrate temperature of 350 °C. $TiCl_4$ was used as the Ti

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precursor, TMA as Al precursor and H_2O as the oxygen source. $TiCl_4$ and TMA were kept at room temperature. The film thicknesses are given in Table 1. The ALD cycles used for TiO_2 deposition exposed the substrate to a $TiCl_4$ vapor for 2 s, a purge with pure nitrogen for 2 s, H_2O for 2 s, and a purge with pure nitrogen for 5 s. The ALD cycles used for deposition of Al_2O_3 contained exposure of the substrates to a TMA vapor for 3 s, a purge with pure nitrogen for 2 s, an exposure to H_2O for 2 s, and a purge with pure nitrogen for 5 s. A schematic representation of the device cross-section is shown in Fig. 1(b).

TABLE I. DESCRIPTION OF THE EXPERIMENTAL DEVICES

Set	#1	#2	#3
Top electrode	Ti/TiN	Pt	
Bottom electrode	W	RuO_x/TiN	
Dielectric TMO	HfO_2	$TiO_2/Al_2O_3/TiO_2$	
Dielectric thickness (nm)	10	28.2 TiO_2 0.2 Al_2O_3	19.2 TiO_2 0.4 Al_2O_3

III. MODEL DESCRIPTION

The geometrical features of the model are shown in Fig 2. It is based on the migration of oxygen ions and the formation/disruption of CFs made of oxygen vacancies. The master equations that control the CF geometry evolution and, therefore, the RRAM operation are given below:

$$\frac{dV_{TC}}{dt} = v_0 \exp\left(-\frac{E_a - \alpha_a Zq\xi}{k_b T}\right) \qquad (set) \qquad (1)$$

$$\frac{dV_{TC}}{dt} = -v_0 \exp\left(-\frac{E_r - \alpha_r(g) Zq\xi}{k_b T}\right) \qquad (reset) \qquad (2)$$

where V_{TC} stands for the CF volume, v_0 stands for the product of the oxygen atom vibration frequency and the oxygen vacancy volume and E_a is the average activation energy for the generation of oxygen vacancies.

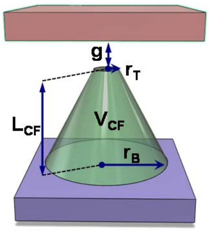

Figure 2: Three-dimensional geometrical representation of the modeled RRAMs.

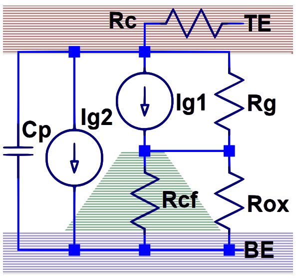

Figure 3: Equivalent circuit of the modeled RRAMs.

Other parameters in the above equations are the following: α_a is the enhancement factor of the electric field for the lowering of E_a, Z is the charge number of oxygen ions, q is the unit charge, ξ is the electric field, k_b is the Boltzmann's constant, T is the local temperature, E_r is an average energy that accounts for the processes involved in the RESET process and $\alpha_r(g)$ is a linear function of the dielectric gap between the CF tip and the electrode (g) that takes into account the electric field enhancement factor that induces a lowering of the hopping barrier and the external voltage enhancement factor during oxygen ions release. The equivalent RRAM circuit is shown in the Fig. 3, where R_c stands for the ohmic resistances of the electrodes, R_{cf} for the resistance of the CF, I_{g1} and I_{g2} are hopping current components; finally, R_{ox}, R_g are the resistances of the dielectric surrounding the CF and the dielectric region filling the gap g, respectively [24].

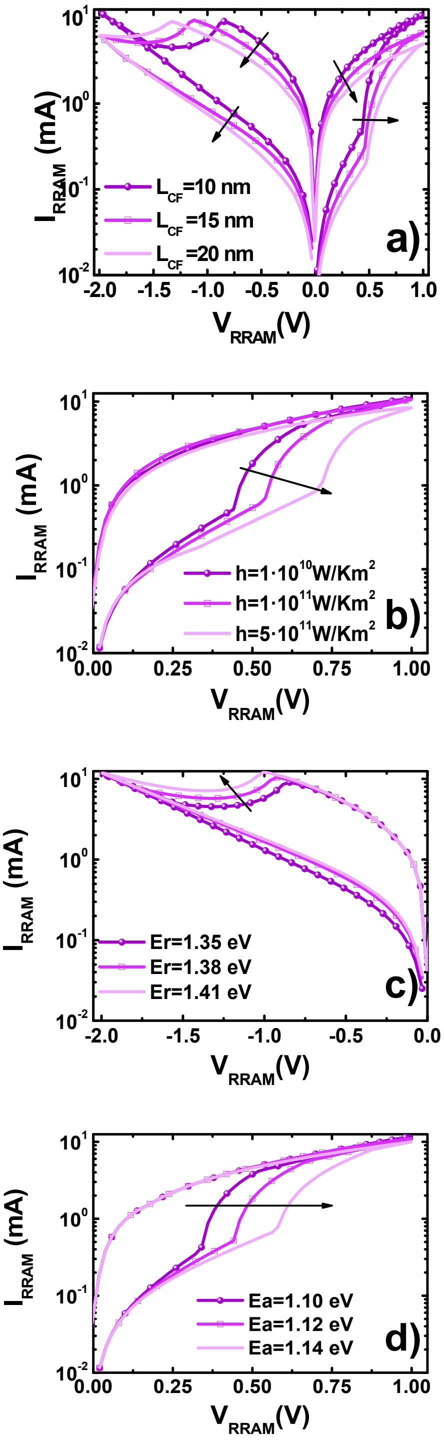

Figure 4: Modeled RRAM current versus applied voltage accounting for variations of different parameters used in the physical analysis: a) dielectric layer thickness, b) lateral heat transfer coefficient for dissipation between the CF and the surrounding dielectric, c) average activation energy accounting for the processes involved in the RESET process, d) activation energy for the generation of oxygen vacancies.

IV. RESULTS AND DISCUSSION

The influence of some key model parameters on the device I-V characteristics has been studied in Fig. 4. Some changes in the parameters account for device-to-device variability while other features describe cycle-to-cycle variability. The proposed model was tested for different technologies (see Table I). Three types of RRAMs were employed: Set#1 TiN/Ti/HfO_2/W with a 10 nm-thick dielectric, Set#2 Pt/TiO_2/Al_2O_3/TiO_2/RuO_x/TiN with 28.4 nm oxide thickness (0.2nm of Al_2O_3) and Set#3 with the same structure than Set#2 but 19.6 nm oxide thickness (0.4 nm of Al_2O_3).

First, the model parameter fitting was carried out on the mean curve of the experimental data set for each technology. After that, considering random distributions for the geometric model parameters, a set of simulated curves was obtained that fitted well the experimental data (see Fig.5 Set#1 and Fig.6 Set#2 and Set#3). Some details of the model accuracy for some specific cycles of the three technologies are given in Fig.7 and Fig.8. It is shown that the proposed model reasonably fits the experimental data for different technologies and for a variety of dielectric thicknesses.

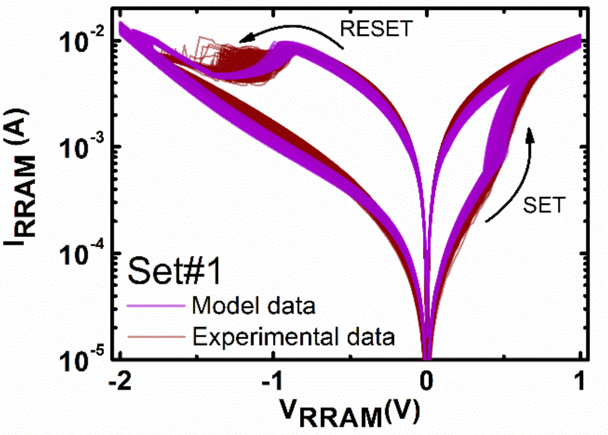

Figure 5: RRAM current versus applied voltage for Set#1 of 700 experimental RS cycles in TiN/Ti/HfO_2/W devices (fabricated at the IMB) and the corresponding modeled curves. For the modeled data a Gaussian distribution for the maxima of the main CF geometrical parameters (r_{Tx}, r_{Bx} and g_x) was used.

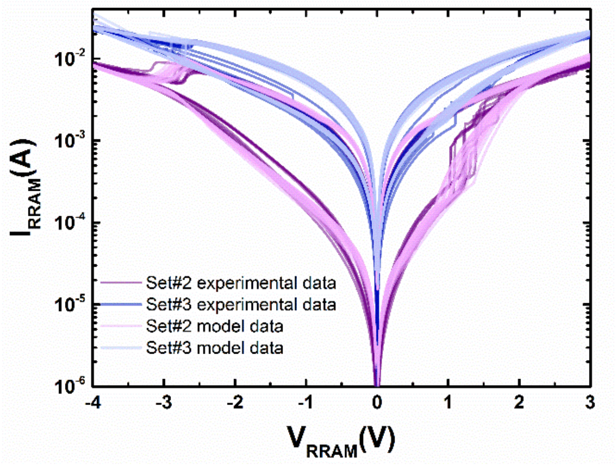

Figure 6: RRAM current versus applied voltage for Set#2 and Set#3 of experimental RS cycles in Pt/TiO_2/Al_2O_3/TiO_2/RuO_x/TiN devices and the corresponding modeled curves. For the modeled data a Gaussian distribution for the maxima of the main CF geometrical parameters (r_{Tx}, r_{Bx} and g_x) was used.

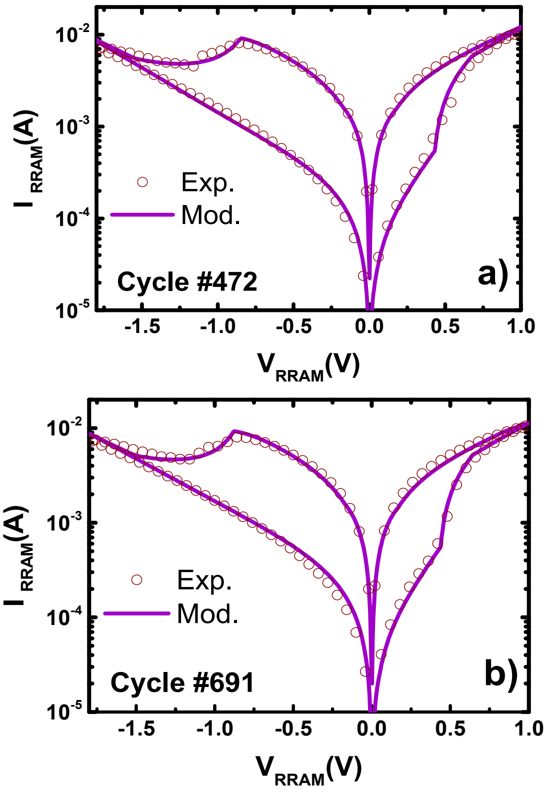

Figure 7: Current versus voltage for different cycles of samples Set#1 a) cycle #472 and b) cycle #691. The model reproduces accurately the experimental results.

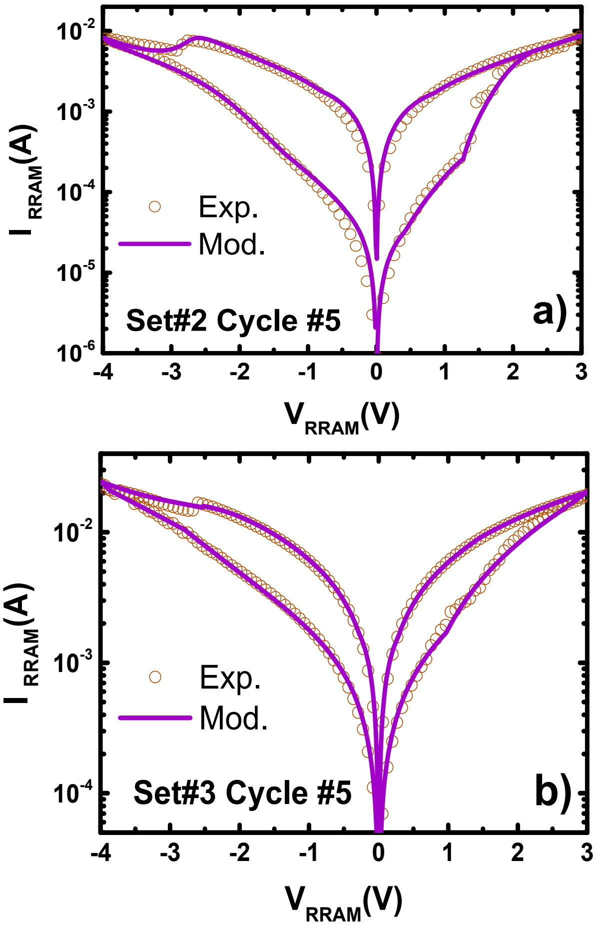

Figure 8: I-V curves corresponding to the cycles of samples a) Set#2 cycle #5 and b) Set#3 cycle #5. The experimental data are correctly fitted by the model.

V. CONCLUSSIONS

A physically based model to describe resistive switching has been proposed. The model works well for several RRAM technologies that include different transition metal oxides (TMO), such as deposited HfO_2 and a three layer stack, $TiO_2/Al_2O_3/TiO_2$, with two combinations of layer thicknesses. The model is based on the migration of oxygen ions and the formation/disruption of CFs made of oxygen vacancies. The master equation proposed takes into account the variation of the volume of a conductive filament with a truncated-cone shape, a detailed thermal description, the influence of parasitic resistances of the dielectric surrounding the CF and the dielectric region filling the gap. The influence of some key model parameters on the device I-V characteristics has been also studied. The model reasonably fits experimental single I-V curves and several sets of RS cycles including SET and RESET transitions.

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