Analysis of high resistive conduction mechanism in HfO 2 -based ReRAM devices

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Effects of the compliance current in the electroforming process of HfO_2-based ReRAM devices

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***Abstract*— Electroforming is the activation process of ReRAM devices that initiates the resistive switching response by creating filamentary conduction paths in the oxide film. This step is fundamental for the proper operation of the device, and it is controlled by a compliance current (I_c) that prevents the hard dielectric breakdown of the ReRAMs. In this work, we study the influence of this current during the electroforming process and operation in HfO_2-based ReRAM devices of different areas. Some parameters from the IV curve were extracted and analyzed to understand how the process could affect the device's performance. We found a maximum value of I_c needed to form the CF independent of the area device that does not provoke significant changes in the electrical behavior.**

Keywords— ReRAM, electroforming, compliance current, conductive filament, filamentary conduction

I. Introduction

The ReRAM is a nonvolatile memory device studied due to the favorable characteristics that could allow it to replace flash memory technology [1]. These devices have a metal-insulator-metal structure whose operating principle relies on resistive switching controlled by an external voltage [2]. After fabrication, these devices are in a highly resistive state, called a pristine state. They need to be activated by an electroforming process that creates a conductive filament (CF) inside the insulator that connects the electrodes. During operation, the ReRAM can change between a high resistive state (HRS) and a low resistive state (LRS) due to the local changes inside the CF. Indeed, electroforming is a critical step for the functioning of the ReRAM devices because it determines the switching characteristics, especially the resistance, during the HRS and LRS.

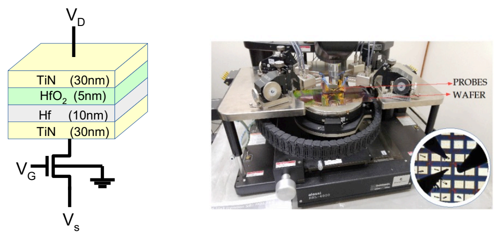
For the electroforming, a positive voltage is applied to the top electrode, and a compliance current (I_c), controlled by the MOSFET transistor, is fixed to avoid the hard dielectric breakdown of the insulator layer during the forming and the set process [3]. In this work, we study the effect of the compliance current on the electroforming process of devices with nine different areas. Section II describes the samples and shows the current-voltage electroforming curves. Section III corresponds to the results and the discussion where some parameters are used to analyze the electroforming process and the answer during the operation of the devices. Finally, in section IV, we give the conclusions of this work.

II. Electroforming

A. Samples

The HfO_2-based ReRAM devices consist of TiN/HfO_2/Hf/TiN stacks with heights of 30nm/5nm/10nm/30nm, respectively. The samples have nine different areas 55x55nm^2, 65x65nm^2, 75x75nm^2, 85x85nm^2, 105x105nm^2, 135x135nm^2, 1x1µm^2, 3x3µm^2 and 5x5µm^2 [4] Due to the small size, the devices have a one-transistor one-resistor (1T1R) architecture to enable accurate electrical characterization (Fig. 1 (a)). The 1T1R array eliminates the sneak path current, decreasing energy consumption and causing higher reliability [5]. The metal-oxide-semiconductor field effect transistor (MOSFET) acts as an access device and allows the programming operation of a selected cell.

For electrical characterization, we used a four-probe station Cascade Alessi REL 4800 (Fig. 1 (b)). The measurements were programmed using the Keithley Interactive Test Environment (KITE).



(a) (b)

Fig. 1. (a) HfO2-based ReRAM devices consist of TiN/HfO_2/Hf/TiN stacks with heights of 30nm/5nm/10nm/30nm, respectively. (b) Cascade Alessi REL 4800 equipment and a wafer load probe station. The measurements were programmed using the Keithley Interactive Test Enviroment (KITE).

B. Electroforming process

During the electroforming step, the effect of compliance current, I_c, was studied under two conditions. First, all samples described in section A were electroformed with I_c=5mA. Second, another group corresponding to the samples of 55x55nm^2, 65x65nm^2, 1x1µm^2, 3x3µm^2, and 5x5µm^2 were electroformed with I_c=10mA.

The IV characteristic curve allows us to recognize the point where the CF has been created inside the insulator due to an abrupt current increase (see Fig. 2). Initially, there is a low current answer due to the disconnection of the electrodes that maintain the system in a high resistive state. Thus, by applying a high voltage, the ReRAM switches into a LRS due to the formation of conductive paths [6]. We extract two parameters to quantify the process: the forming voltage (V_{form}) and current (I_{form}).

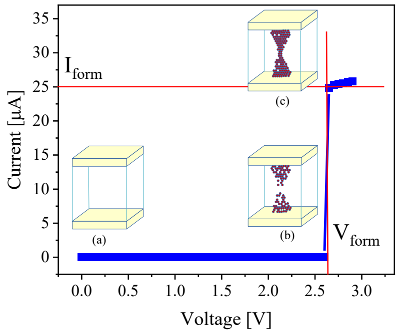


Fig. 2. Electroforming IV curve along with a schematic creation of the conductive filaments of oxygen vacancies during the process. The IV characteristic curve allows us to recognize the point where the CF has been created inside the insulator because of an abrupt current increase. The forming voltage (V_{form}) and the forming current (I_{form}) were extracted for all curves.

Comparing the IV electroforming curves under the two compliance currents, one can see that the influence of I_c is more significant in nm-size samples, where the I_{form} is larger with I_c=10mA. However, there is no apparent difference in um-size samples, as shown in Fig 3.

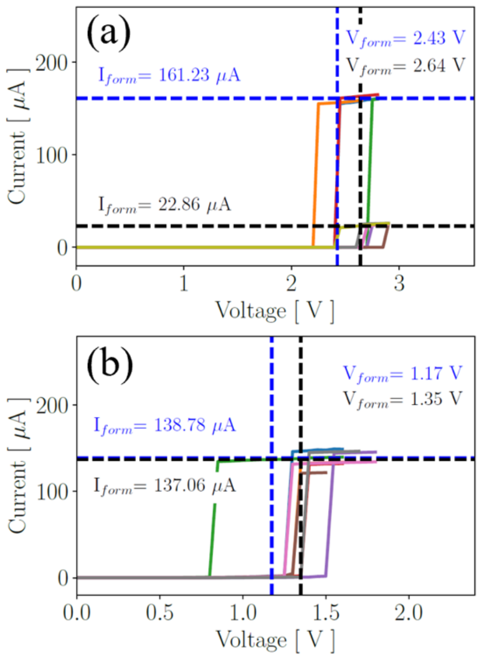


Fig. 3. IV curves during electroforming of two samples (a) 55x55nm^2 and (b) 5x5um^2. The results for I_c=5mA are in black, while for I_c=10mA, the results are in blue. One can see that the compliance current significantly affects the response of the nanometer size samples.

III. Results and Discussion

The sudden current jump presented in the IV curve suggests the formation of the CF (see Fig. 2). In HfO_2-based ReRAMs, the electroforming is a field-driven process [7] where the electric field provides the required energy for moving the pre-existing vacancies. In addition, the field creates new oxygen vacancies due to the breaking of Hf-O bonds and allows the subsequent diffusion of oxygen ions [8]. It must be noted that all devices studied in this work have been fabricated under the same process, so all of them are expected to have similar pre-existing oxygen vacancy profiles [4]. However, we found that the response strongly depends on the sample area, as shown in Fig. 4, where the V_{form} and I_{form} as a function of the device area are presented.

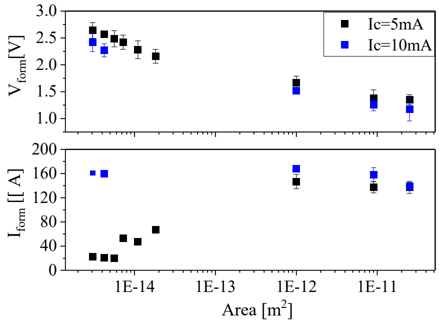


Fig. 4. Area scaling trends for (a) forming voltage (V_{form}) and (b) forming current (I_{form}), comparing the effect of I_c.

V_{form} decreases with the area when the samples are electroformed under both I_c, although V_{form} has a slightly smaller value when I_c is larger. This behavior has been reported before by Chen [9], and it is explained because a small area limits the locations to trigger electroforming. This V_{form} behavior could represent a problem from the point of view of memory scalability. Conversely, we found that I_{form} significantly differs between nm-size and um-size samples when I_c is 5mA, while it is almost independent when I_c is 10mA (see Fig. 2.6b). It could suggest that I_c=10mA could be a saturation value for this HfO_2-based ReRAM samples.

After the electroforming process, the CF is complete, and it is possible to consider that the dominant conduction mechanism is Ohmic, following the relationship $I_{form}=G_{form}V_{form}$. We determine the value of G_{form} and compare it along the area. As shown in Fig. 5, the tendency shows that the conductance increases with the area device. Further, the conductance value is more significant in all samples when the I_c=10mA. These G_{form} values would be related to the filament size, which is more significant in µm-size samples due to a higher concentration of available oxygen vacancies [10]. A higher compliance current provides more energy for CF formation.

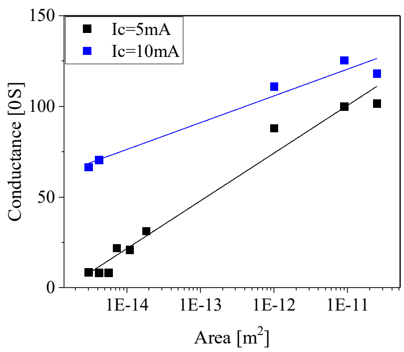


Fig. 5. Form conductance, G_{form}, as a function of the area. The tendency shows that the conductance increases with area device.

To analyze the effect of the electroforming process, under two values of compliance current, the I–V curves during the resistive switching of the two devices are presented in Fig. 6. The curves show the typical bipolar resistive switching behavior, and we cannot identify considerable differences in the LRS region. On the contrary, the curves tend to move away when the system is in HRS, especially under negative voltages. However, the variability during the HRS has already been reported before, and it is explained due to the conduction mechanism during this state [1,4,11]. According to the QPC model, once a CF is formed inside the HfO_2 switching layer, the tunnel barrier is the dominant factor that controls I-V characteristics with barrier thickness modification [12]. When the system is in LRS, the conduction through the CF is ideally ballistic, while in HRS is mainly due to the tunneling process.

During operation, in LRS the primary conduction mechanism is Ohmic. The continuous distribution of oxygen vacancies that creates the CF gives it a metallic behavior. Thus, we obtain the device's conductance to analyze how the compliance current affects the ReRAM operation during this state. In Fig. 7, one can observe G as a function of the area device.

The main characteristic is the clear conductance difference between nm-size and um-size samples. The greater conductance suggests a wider CF due to a more significant number of conductive paths [10]. However, G has a similar value among samples whose areas are in the same order of magnitude, independently of the compliance current used during electroforming. A detailed analysis of electrical parameters associated with resistive switching can be found in [4].

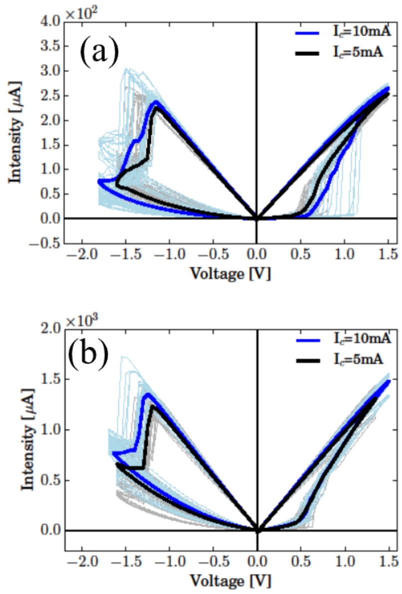


Fig. 6. I-V characteristic for a RRAM device of (a) 55x55nm^2 and (b) 5x5μm^2 during 50 cycles. The curves show the typical bipolar resistive switching behavior. We cannot identify considerable differences in the transition points, set and reset voltages, and in the LRS region.

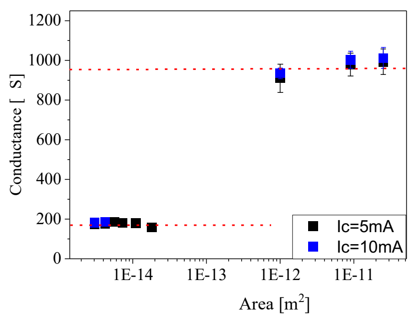


Fig. 7. Conductance as a function of the area during operation of the ReRAM device in the LRS.

IV. Conclusions

This paper analyzes the effect of the compliance current, I_c, during the activation process of Hf-based ReRAM devices of different areas. The results show that although there are some differences during the electroforming process, especially in nm-size samples, the devices' operation is unaffected during resistive switching. However, the conductance value of the devices during LRS, where the conduction could be considered as Ohmic, suggests that the size of the conductive filament in um-size samples is large.

References

[1] D. Ielmini, "Resistive Switching Memories based on Metal Oxides: Mechanisms, Reliability and Scaling," Semicond. Sci. Technol. 31, 063002 (2016).

[2] H. -S. P. Wong *et al*., "Metal–Oxide RRAM," in *Proceedings of the IEEE*, vol. 100, no. 6, pp. 1951-1970, June 2012.

[3] Zahoor, F., Azni Zulkifli, T.Z. & Khanday, F.A. Resistive Random Access Memory (RRAM): an Overview of Materials, Switching Mechanism, Performance, Multilevel Cell (mlc) Storage, Modeling, and Applications. *Nanoscale Res Lett* **15**, 90 (2020).

[4] S. Guitarra, L. Raymond and L. Trojman, "Stochastic multiscale model for HfO2 based resistive random access memories with 1T1R configuration," *Solid State Electronics*, 176, 2021.

[5] M. Mao, Y. Cao, S. Yu et al. "Optimizing latency, energy, and reliability of 1T1R ReRAM through appropriate voltage settings". In: *2015 33rd IEEE International Conference on Computer Design (ICCD)*. Oct. 2015, p. 359–366.

[6] Hu Q, Park MR, Abbas H, Kang TS, Yoon TS, Kang CJ (2018) Forming-free resistive switching characteristics in tantalum oxide and manganese oxide based crossbar array structure. Microelectron Eng 190:7–10.

[7] G. Bersuker, D. C. Gilmer, D. Veksler et al. "Metal oxide resistive memory switching mechanism based on conductive filament properties", In: *Journal of Applied Physics* 110.12 (2011), p. 124518.

[8] J Joshua Yang, Feng Miao, Matthew D Pickett et al. "The mechanism of electroforming of metal oxide memristive switches", In: *Nanotechnology* .20.21 (2009), p. 215201.

[9] A. Chen. "Area and Thickness Scaling of Forming Voltage of Resistive Switching Memories". In : *IEEE Electron Device Letters* 35.1 (jan. 2014), p. 57–59. issn: 0741-3106

[10] Zhu, L.; Zhou, J.; Guo, Z.; Sun, Z. Synergistic Resistive Switching Mechanism of Oxygen Vacancies and Metal Interstitials in Ta2O5 . *J. Phys. Chem. C* **2016**, *120* (4), 2456–2463.

[11] Chen Wang, Huaqiang Wu, Bin Gao, Teng Zhang, Yuchao Yang, He Qian, Conduction mechanisms, dynamics and stability in ReRAMs, Microelectronic Engineering, Volumes 187–188, 2018, Pages 121-133.

[12] LM. Prócel, L. Trojman, J. Moreno, F. Crupi, V. Maccaronio, R. Degraeve, et al. "Experimental evidence of the quantum point contact theory in the conduction mechanism of bipolar HfO_2-based resistive random access memories," *J. Appl. Phys*. 2013;114:74509.