Competitive Mechanisms of Resistive Switching in Nanooxide Based Memory Cells

Dmitriy V. Stremous[1], Aleksandr L. Danilyuk[2], Denis A. Podryabinkin[3], Victor E. Borisenko[4]

Belarusian State University of Informatics and Radioelectronics

P. Browka 6, 220013, Minsk, Belarus

e-mails: stremous@list.ru[1], danilyuk@nano-center.org[2], arm@tut.by[3], borisenko@bsuir.by[4]

***Abstract* — Atomic migration and electronic switching of bi-stable centers in conducting filaments formed in nanooxide based resistive random access memory (RRAM) cells are modeled and analyzed as competitive mechanisms determining their operation frequency. They are demonstrated to be mediated by the filament growth dynamics. Atomic migration is shown to be responsible for a slow change of the filament resistivity with typical switching times in the millisecond range. Fast switching with the shortest nanosecond delay can be achieved using bi-stable electronic centers in the filaments. Possible configurations of such centers are discussed.**

Keywords - resistive switching; nanooxide; memory cell.

I. INTRODUCTION

Currently, metal nanooxide-based resistive switching memory is being studied extensively as one of the most competitive candidates for non-volatile memory applications because of its simple structure, rapid switching and excellent scalability. The mechanisms of resistive switching phenomena in oxides can be quite diverse. One possible mechanism is electronic switching, originating from a trap/de-trap process through defects in the oxides [1]. Another possible mechanism is ionic switching, which is usually attributed to the formation/rupture of conductive filaments (CFs), which may consist of oxygen vacancies or metal precipitates [2][3]. It is illustrated in Figure 1.

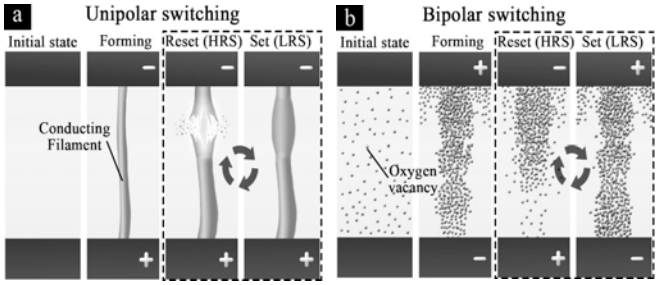

Figure 1. Dynamic growth and formation/rupture processes of filament-type resistive switching mechanism in unipolar (a) and bipolar switching (b) modes [3].

The process of CFs formation and their transition from an initial high resistance state (HRS) to a low resistance state (LRS) are interpreted as a dielectric soft breakdown associated with the migration of oxygen ions toward the anode, and the formation of CFs in the bulk oxide connecting both electrodes. In the unipolar reset process where the reset occurs at the same polarity as the set, joule-heating-assisted diffusion of oxygen ions from the anode occurs and the surrounding oxides rupture the CFs by recombining with oxygen vacancies or by the re-oxidation of metal precipitates. Cooling down and formation of a functional region in the CFs occur during the set process (Figure 1). In the bipolar reset process that occurs at the polarity opposite to the set process, oxygen ions drifting in the applied electric field rupture the CFs.

Combined diffusion and drift ion transport may be considered to be a driving mechanism of the slow switching [4]. Fast electronic switching is provided by the synchronized process of the capture and release of mobile charge carriers on the bi-stable trapping states in the regions of the formation/rupture of CFs. These states are caused by the presence of oxygen vacancies. Both atomic and electronic mechanisms are modeled and discussed in this paper.

The dynamic model of CFs formation and the switching model of bi-stable trapping states in the oxide are described in Section II. Section III presents results of the computer simulations based on the above models for HfO_2-based metal/insulator/metal nanostructures with the emphasis to their application for resistive random access memory (RRAM) cells.

II. MODELS

The dynamics of CFs formation are considered to be determined by the motion of their constituent ions in the electric field. The growth rate of the filament is defined by the drift speed of the moving ions. Supposing hope jumping of the ions over the energy barrier U it is [5]:

$$dl/dt = 2dv\exp(-qU/kT)\sinh(qVd/2kT(h-l)), \quad (1)$$

where l is the filament length, d is the hopping site distance, v is the characteristic ion hop attempt frequency, k is the Boltzmann's constant, T is the absolute temperature, q is the electron charge, h is the overall thickness of the oxide, V is the applied voltage.

In the model considering electronic states, switching of bi-stable traps in the oxide is supposed to be responsible for the interplay between its HRS and LRS. Such switching is induced by a thermal noise. We simulate it using the following equation [6]:

$$dy/dt = ay - by^3 + A\cos(\Omega t + \varphi) + \sqrt{2D}\xi(t), \quad (2)$$

 ISBN: 978-1-61208-431-2

where y is the generalized coordinate of the traps characterizing the type of its potential energy, a and b are the potential parameters, and A, Ω, and φ are the amplitude, frequency and the phase of the center of oscillations, respectively, D is the noise intensity, and the function $\xi(t)$ denotes a zero-mean Gaussian white noise.

A sub-circuit is used to calculate the switching threshold voltage and resistance of the resistive memory cell and its dependence on the sweep rate and operating temperature as it is described in [7].

III. RESULTS AND DISCUSSION

The length of CFs in HfO_2 was calculated to grow exponentially with time like it is shown in Figure 2a. The external bias determines the characteristic time of the growth. A significant increase of the growth rate is reached at the external bias of 2–2.5 V.

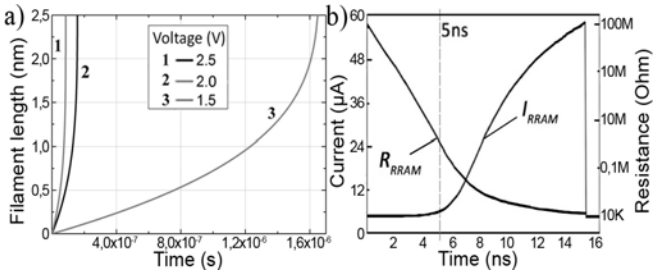

Figure 2. Dynamics of conductive filament growth in 5 nm HfO_2 under various applied voltages (a). RRAM dynamics during pulse programming (5 V) at 300 K (b).

SPICE Modeling of the dynamics of the CFs growth in HfO_2 during programming voltage pulse of 5 V that depends on the operating temperature shows that the RRAM cell does not switch on immediately. It takes approximately 4–6 ns. The switching event is determined by the sharp increase in the conductivity marked by the dotted line in Figure 2b. Switch-ON time depends exponentially of the external bias. This result shows an importance of the dynamic effects involving a range of transient processes.

As for atomic mechanisms of ON/OFF switching of the FCs formed, oxygen and/or metal atom diffusion for the distances comparable to the FCs diameters (few nanometers) was calculated to proceed within milliseconds even at the melting point of HfO_2.

Modeling of electronic switching of bi-stable traps was carried out for HfO_2 with the following parameters: the thermal ionization energy of the traps of 0.5 eV, the oscillation frequency of 10–12 GHz, the trap concentration of 10^{19} cm^{-3}, and the noise intensity of 0.08–0.15. The bi-stable potential of the traps under an influence of a weak periodic modulation was confirmed to make a transition from one state to another only under the effect of the noise.

Figure 3a shows that the impact of noise leads to the switching of the traps in HfO_2 from one metastable state to another within few nanoseconds. An increasing intensity of the noise stimulates variations in the output signal $y(t)$, causing formation of metastable states. The switching time decreases with an increase of the amplitude A and the impact frequency of the noise.

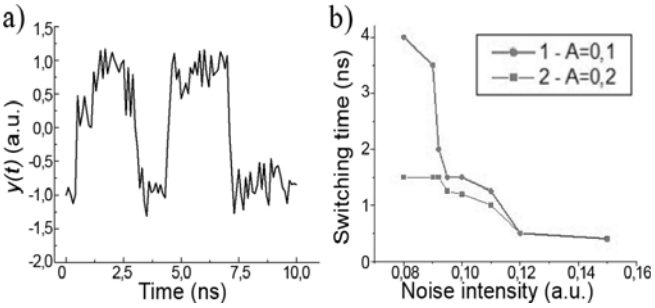

Figure 3. Switching dynamics (a) and the switching time *vs* noise intensity at different amplitudes noise amplitudes A (b).

Numerical estimations of the electron switching time of the trapping states showed it to be of about few nanoseconds. It can decrease below 1 ns at relatively high amplitudes and intensities of the noise (Figure 3b).

IV. CONCLUSION

The performed modeling shows that comprehensive understanding of the mechanisms of resistance switching in RRAM cells should include consideration of ion migration, the growth of conductive filaments and their rupture, as well as the capture and release of electrons including metastable trapping states. Experimental identification and numerical characterization of these states are important to increase operating frequencies of RRAMs.

ACKNOWLEDGMENT

The authors thank Belarusian Fund for Fundamental Researches for the financial support.

REFERENCES

[1] M. A. Danilyuk, *et al.*, "Multiphonon ionization of traps formed in hafnium oxide by electrical stress," Phys. Stat. Sol. A, vol 210, no 2, Feb. 2013, pp. 361–366, doi:1002/pssa.201228083.

[2] X. Wu, *et al.*, "Intrinsic nanofilamentation in resistive switching," J. Appl. Phys. vol. 113, no. 11, Nov. 2013, pp. 114503 (6 pages), doi:dx.doi.org/10.1063/1.4794519.

[3] A. Mehonic, *et al.*, "Electrically tailored resistance switching in silicon oxide," Nanotechnology, vol. 23, no. 45, Nov. 2012, pp. 455201 (9 pages), doi:10.1088/0957-4484/23/45/455201.

[4] F. Pan, S. Gao, C. Chen, C. Song, and F. Zeng, "Recent progress in resistive random access memories: Materials, switching mechanisms, and performance," Mater. Sci. & Eng., vol. 83, Sep. 2014, pp. 1–59, doi:10.1016/j.mser.2014.06.002.

[5] A. Sawa, "Resistive switching in transition metal oxides," Materials Today, vol. 11, no. 6, June 2008, pp. 28–36, doi:10.1016/S1369-7021(08)70119–6.

[6] L. Gammaitoni, P. Hänggi, P. Jung, and F. Marchesoni, "Stochastic resonance," Rev. Mod. Phys., vol. 70, no. 1, Jan. 1998, pp. 223–287, doi:10.1103/RevModPhys.70.223.

[7] P. Sheridan, *et al.*, "Device and SPICE modeling of RRAM devices," Nanoscale, vol. 3, no. 9, Aug. 2011, pp. 3833–3840, doi:10.1039/C1NR1.

 ISBN: 978-1-61208-431-2