Extended Abstracts of the 2013 International Conference on Solid State Devices and Materials, Fukuoka, 2013, pp566-567

A-6-1 (Invited)

Modeling of Transition Metal Oxide Based RRAM Devices

Jinfeng Kang, Bin Gao, Bing Chen, Peng Huang, and Xiaoyan Liu

Institute of Microelectronics, Peking University, Beijing 100871, China
Phone: +86-10-6275-6745 E-mail: kangjf@pku.edu.cn

Abstract

This paper addresses the physical mechanism and models of resistive switching in transition metal oxide based resistive switch random access memory (TMO-RRAM). A unified physical mechanism is firstly introduced to elucidate unipolar and bipolar resistive switching behaviors of TMO-RRAM. Based on the unified physical mechanism, the physical models of the switching and reliability properties in TMO-RRAM were developed to quantify and predict the SET/RESET, endurance, and retention behaviors.

1. Introduction

Transition metal oxide (TMO) based resistive switching random access memory (RRAM) is emerging as one of the most promising candidates for next generation memory technologies due to its superior characteristics such as low operating voltage, fast switching, high packing density, and excellent scalability [1-2]. Understanding the physical mechanism and developing effective technical solutions to control the resistive switching behaviors is highly demanded. Various mechanisms have been proposed to explain the resistive switching behaviors occurred in the RRAM devices [3-7]. In this paper, we will introduce a unified physical mechanism proposed by our group to clarify the physical origin of both unipolar and bipolar resistive switching behaviors of oxide-based RRAM [6,7]. Based on the unified physical mechanism, several physical models are developed to quantify and predict the critical resistive switching and reliability behaviors including SET and RESET, endurance, and retention issues [8-11].

2. Unified Physical Mechanism [6,7]

It has been widely accepted that the formation and rupture of conducting oxygen vacancy (Vo) filaments dominate the resistive switching of TMO-RRAM [3]. Based on the theory calculations and experiment verifications, we proposed a unified physical mechanism [6,7], which clarify the microscopic physics natures of the conduction of low and high resistance states and resistive switching. In the mechanism (as shown in Fig. 1), the conducting filaments are consisted of oxygen vacancies (V_O) and the conduction in low resistance and high resistance states is due to the electron transport among Vo along the conducting filaments. When the Vo in filaments are separated from each other, the conduction shows the semiconductor-like behavior. In contrast to this, the conduction shows the metallic behavior when the Vo are closely accumulated into the clusters. The forming and SET processes are corresponding to the generation of new Vo induced by electric-field and thermal energy, which causes the formation or reconstruction of filaments. For the RESET process, the recombination of electron depleted Vo (V_O^{2+}) induced by electric-field with the moveable oxygen ions (O^{2-}) causes the rupture of filaments, which results in the RESET process.

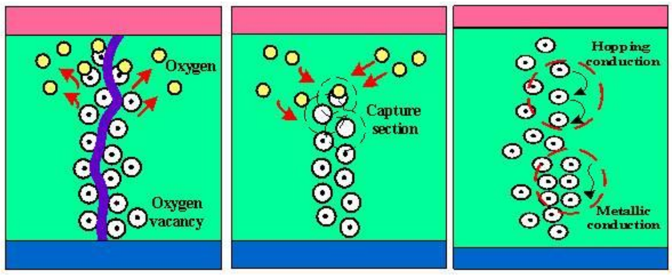

Fig. 1 Schematic unified switching mechanism for both unipolar and bipolar RRAM dominated by the generation and recombination of oxygen vacancies (V_O) with dissociative oxygen ions (O^{2-})

Based on the unified switching mechanism, various resistive switching behaviors observed in TMO-RRAM devices can be explained.

3. Models of Resistive Switching Behaviors

Based on the understanding of the unified physical mechanism on the resistive switching, various physical models are developed to quantify the resistive switching and reliability behaviors of TMO-RRAM.

1) *Ion-Transport-Recombination Model* [8]

By introducing the ion transport equation, an ion-transport-recombination model is developed to quantify the RESET process. According to the unified physical mechanism, the reset process is due to recombination of the electron-low-occupied V_O^+ with O^{2-} [8]. The O^{2-} are mainly accumulated at the interface of electrode and resistive layer due to localization effect of the electrode, and can jump over the interface barrier under applied electric field. The transport of O^{2-} can be described by the ion transport equation: [8]

$$\frac{\partial C_i}{\partial t} = B_i \left(Z_i e \frac{\partial \phi}{\partial x} \frac{\partial C_i}{\partial x} + k_B T \frac{\partial^2 C_i}{\partial x^2} \right)$$

In the equation, C_i refers to the concentration of the O^{2-}, φ is the electric potential in the layer, *Bi* is the diffusion coefficient, T is temperature, and Z_ie is the electric quantity of O^{2-}. Considering the influence of boundary conditions, the reset characteristics, such as switching speed, current, uniformity/stability of HRS and LRS, and scalability can be evaluated.

2) *Analytic Model of RRAM Operation* [9]

For future memory application, a set of physical based analytic model of the RRAM cell at DC and pulse operation modes is developed and implemented in the circuit simulator [9].

In the model, the RESET operation is corresponding to the whole filament disconnecting firstly at the TE then extending towards the interior step by step with increasing voltage. During SET operation, CF growing process is corresponding to the formation of a fine filament in the rupture region firstly connecting the tip of the CF and TE then gradually enlarging along the radius direction with the current increase. The correlated model parameters such as gap distance (x) and filament width (w) and their evolutions with time are introduced to describe the SET and RESET behaviors. The developed analytic model can reproduce the characteristics of RRAM cell operation both under DC and pulse operation modes.

3) *Endurance Degradation Model* [10]

As one of the critical reliability issues, the endurance degradation characteristics and correlated models of HfOx-based RRAM have been developed. Three types of endurance failure behaviors are observed and the corresponding endurance degradation models are proposed to describe and predict these endurance degradation behaviors [10]. Oxidation Induced Interface Reaction, Extra Vacancy Attributed Reset Failure Effect, and Depletion of O^{2-} Induced R_{HRS} Reduction are responsible for the observed endurance degradation characteristics.

Based on the predictions of the proposed endurance degradation model, the optimized operation modes can be proposed to improve the endurance characteristics. The significantly endurance enhancement of more than 3 orders can be demonstrated in the HfOx-based RRAM devices.

4) *Retention Model*

The data retention is of great importance for nonvolatile memory operation. For TMO-RRAM devices, the sudden resistance transition in HRS usually occurs during a typical retention process as shown in Fig.2 [11]. This retention failure behavior is quite different from that observed in the traditional memories.

Based on the understanding of SET and RESET process in the unified physical mechanism, we develop a physical based model to elucidate the unique retention failure behavior of TMO-RRAM. In the model, the cumulative failure probability as a function of time (F(t)) is introduced to quantify the HRS retention failure behavior. The dependence of the failure probability and targeted retention time on the temperature and applied bias can be predicted. Based on the model, a temperature- and voltage-acceleration evaluation method can be developed to predict the lifetime and other retention behaviors of the oxide-based RRAM devices.

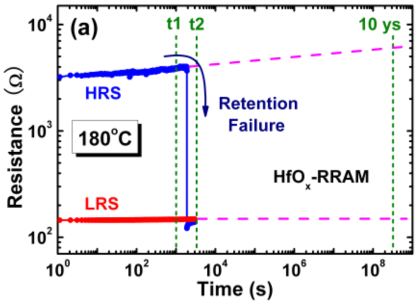

Fig.2 The typical retention behavior of a TMO-RRAM device and the projected lifetime by the traditional retention evaluation method.

4. Conclusions

This paper introduced a unified physical mechanism, which can clarify both unipolar and bipolar resistive switching behaviors of TMO-RRAM switching behaviors of TMO-RRAM. Based on the unified physical mechanism, various resistive switching behaviors observed in TMO-RRAM devices such as the SET/RESET processes, endurance, and retention can be modeled and predicted. Based on the prediction, the optimized operation schemes and reliability evaluation methods can be developed.

Acknowledgements

We would like to express our sincere thanks to all other collaborators such as B. Yu (New York Univ. at Albany), D-L. Kwong (IME@ASTAR), H-Y. Yu (SUST), H-P. Philip Wong (Stanford Univ.) and so on for their contributions to this work. This work is partly supported by 973 Programs (2011CBA00600).

References

[1] H. Y. Lee et al, IEDM Tech. Dig. (2010) 460.
[2] M. J. Kim et al, IEDM Tech. Dig.(2010) 444
[3] R. Waser, Nature Mat. 6 (2007) 833
[4] G. Bersuker et al, IEDM Tech. Dig (2010) 456
[5] L. Goux et al, VLSI (2011) 24.
[6] N. Xu et al, VLSI (2008) 100
[7] B. Gao et al, IEDM Tech. Dig. (2011) 417
[8] B. Gao et al, IEDM Tech. Dig. (2008) 563
[9] P. Huang et al, IEDM Tech. Dig. (2012)
[10] B. Chen et al, IEDM Tech. Dig. (2011) 283
[11] B. Gao et al, IEEE EDL