B-5-1

Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp614-615

Switching Model of TaO_x-based Non-polar Resistive Random Access Memory

Xin Tong,[1] Wenjuan Wu,[1] Zhe Liu,[1] Xuan Anh Tran,[2] Hong Yu Yu,[3] and Yee-Chia Yeo.[1,*]

[1] Department of Electrical and Computer Engineering, National University of Singapore.
[2] School of EEE, Nanyang Technological University, Singapore.
[3] South University of Science and Technology of China, Shenzhen, China.

*Phone: +65-6516-2298, Fax: +65-6779-1103, Email: yeo@ieee.org

Abstract

We report a novel TaO_x-based non-polar RRAM cell design with a $Cr/TaO_x/Al$ (top-to-bottom) structure. Extensive studies of the switching mechanism of our non-polar RRAM were performed. Evidence of co-existence of metallic ions and oxygen vacancies is observed, and a hybrid filament hypothesis is proposed for the first time to explain the observations. A switching model explains the microscopic change in the non-polar TaO_x-based RRAM.

1. Introduction

Resistive Random Access Memory (RRAM) is a promising next-generation non-volatile memory [1]-[5]. Just like HfO_x, TaO_x is a very promising RRAM switching material. Tantalum oxide TaO_x is CMOS-compatible and can be integrated in both front-end and back-end processes [6]. TaO_x has two stable redox pair of phases and allows realization of highly reliable RRAM [7]. While the non-polar behavior of some other RRAM switching materials has been explored, there is no report on the non-polar behavior of TaO_x-based RRAM devices [8]-[10].

In this paper, we report the first TaO_x-based non-polar RRAM with a $Cr/TaO_x/Al$ (top-to-bottom) structure. The switching mechanism of the non-polar TaO_x-based RRAM was also investigated. A switching model for TaO_x-based RRAM devices was derived through extensive electrical characterization.

2. Device Fabrication

Two structures were fabricated (Fig. 1): $Al/TaO_x/Cr$ [denoted as Al-top electrode (TE)] and $Cr/TaO_x/Al$ [denoted as Al-bottom electrode (BE)]. The process flow used (Fig. 2) is similar to that in our previous work [11]. The TaO_x layers in all RRAM devices were formed using identical conditions.

3. Results and Discussion

A. DC Characteristics

Fig. 3 shows the DC *I-V* characteristics of both Al-TE and Al-BE devices. While V_{reset} of the Al-TE device must be negative, the Al-BE device does not have such restriction and exhibits non-polar switching. Their switching behavior is summarized in Fig. 3(c). Fig. 4 compares the switching voltages. No significant difference was observed for V_{set} and V_{reset}. Since TaO_x in both devices were deposited under identical conditions, similar permittivity and thickness are expected, thus the smaller gradient of the Al-BE line in the capacitance vs. area plot (Fig. 5) could be due to a thicker interfacial layer. This is related to the higher thermal budget experienced by the Al/TaO_x interface in Al-BE structure. Fig. 6 shows the distribution of R_{on} in both devices from both bipolar and unipolar operations. Values of R_{on} are about the same, and are tightly distributed. In both structures, R_{on} does not scale with active area (Fig. 7), a typical feature of filament conduction [10].

B. Electrical Evidence of Hybrid Filament

Fig. 8 shows the change of R_{on} as fifty 0-to-1 V sweeps (hereafter referred as the sweeps) were applied. For the Al-BE device, R_{on} only decreased by 10% from points A to B, and roughly saturates thereafter. For the Al-TE device, a sudden decrease was observed (points D to E) initially, followed by a gradual reduction (points E to F).

To better understand the reduction in R_{on}, relationship between R_{on} and temperature was studied and the thermal coefficients of resistance α were obtained (Fig. 9-10). Before the sweeps, α was negative when the device is set by either positive or negative V_{set}. Negative α suggests that the conduction mechanism is similar to semiconducting behavior, sometimes related to charge hopping through oxygen vacancies [4]. α is more negative under positive V_{set}, as Al is a better oxygen reservoir than Cr, and is capable of creating more vacancies in the TaO_x layer.

For the Al-TE device, α became positive after the sweeps. The polarity inversion of α suggests that filament becomes slightly metallic, and the R_{on} reduction is likely due to metallic ions, most probably Al ions, being introduced into the filament. We propose that the metallic filament exists together with the filament formed by oxygen vacancies. For the Al-BE devices, after the sweeps, α became even more negative, hence the conduction mechanism is likely to remain unchanged. Magnitude of α increased as more oxygen is drawn to the TE, as discussed in previous paragraph.

C. Proposed Switching Mechanism for Non-polar RRAM

Based on the observations, we propose a model to explain the microscopic changes in both Al-TE and Al-BE devices, shown in Fig. 11 and 12, respectively.

For the Al-TE device, the as-fabricated device is shown in Fig. 11 (a). The forming process creates a dominant conical oxygen vacancy filament [12]. During bipolar switching [between Fig. 11 (b) and Fig. 11 (c)], negative V_{reset} breaks the filament by reversing the filament connection process, and positive V_{set} is analogous to forming and reconnects the filament. In the case of unipolar switching [between Fig. 11 (c) and Fig. 11 (d)], the reset operation can be explained by thermally-assisted local re-oxidation [13]. In the set process, oxygen atoms at the filament rupture point are pushed towards Cr. They can hardly react with Cr which is already oxidized at the surface, and probably escapes to the surrounding SiO_2 while leaving behind oxygen vacancies. Meanwhile some oxygen from AlO_x moved into TaO_x and oxidized part of the filament, making it thinner. This explains why α is more negative after positive V_{set}. The sweeps cause Al ions to drift into the dielectric [Fig. 11(e)], making the dominant filament more metallic. The AlO_x layer at the Al/TaO_x interface in the Al-TE device is confirmed by Transmission Electron Microscopy (TEM) [Fig. 11 (f)].

For the Al-BE device, the as-fabricated device is shown in Fig. 12 (a). Transition among Fig. 12 (b)-(d) was explained in previous paragraph. In unipolar switching [between Fig. 12 (b) and Fig. 12 (e)], reset can be explained by thermally-assisted local re-oxidation, and the positive V_{set} reconnects the filament, similar to the forming process. For bipolar switching [between Fig. 12 (d) and Fig. 12 (e)], reset can be similarly explained, and set is similar to that between Fig. 11 (d) to Fig. 11 (c).

When the sweeps are applied to the Al-BE device, Al ions tend to drift into the dielectric, as in the case of the Al-TE device. However, the thicker interfacial AlO_x helped to prevent drifting of Al by trapping them inside the layer. The sweeps therefore only helped to widen existing filament [Fig. 12 (f)], and the device can still be reset back after the sweeps. The AlO_x thickness may play a key role in determining whether non-polar switching can be realized, which can be affected by the fabrication process.

4. Conclusion

A novel non-polar $Cr/TaO_x/Al$ RRAM was reported. Both oxygen vacancies and metallic ions can be present in the dominant filament, and the hybrid filament hypothesis was proposed for the first time. The interfacial AlO_x layer helps to prevent the drifting of Al ions from electrode to switching layer, and its thickness may play a key role in determining the switching behavior of the device.

Acknowledgement. We thank Dr. J. Huang, Dr. R. Zhao, and Dr L. Shi of Data Storage Institute and A. Gyanathan of NUS for discussions.

References

[1] F. Nardi *et al.*, IEDM 2011, pp. 709
[2] Z. Wei *et al.*, IEDM 2011, pp. 721
[3] Y.-B. Kim *et al.*, VLSI Symp 2011, pp. 52
[4] M.-J. Lee *et al.*, Nature Materials 10, pp. 625, 2011
[5] Y. Sakotsubo *et al.*, VLSI Symp. 2010, pp. 87
[6] Z. Wei *et al.*, IEDM 2008, pp. 294
[7] J. J. Yang *et al.*, Appl. Phys. Lett. 97, pp. 232102, 2010
[8] H.-H. Huang, Appl. Phys. Lett. 96, pp. 193505, 2010
[9] K.-L. Tin *et al.*, J. Appl. Phys. 109, pp. 084104, 2011
[10] R. Waser, Adv. Mat., vol. 21, pp. 2632, 2009
[11] W. Wu *et al.*, 11th Annual NVMTS, pp. 1-5, 2011
[12] D.-H. Kwon *et al.*, Nature Nanotech. 5, pp. 148, 2010
[13] C. Cagli *et al.*, IEDM 2008, pp. 301

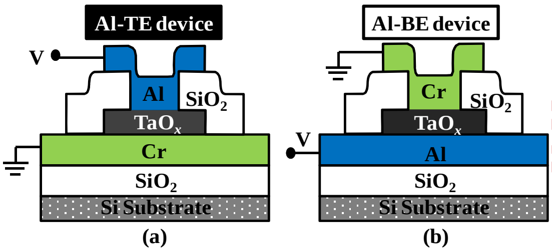

Fig. 1 Schematic of structure of an (a) Al-TE and (b) Al-BE device. Despite structural symmetry, only the Al-BE device exhibits non-polar switching.

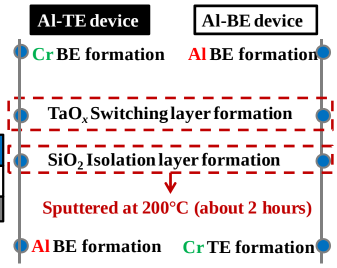

Fig. 2 Process flow of both devices. Al/TaO$_x$ layer in Al-BE experienced more thermal budget, and is expected to be thicker.

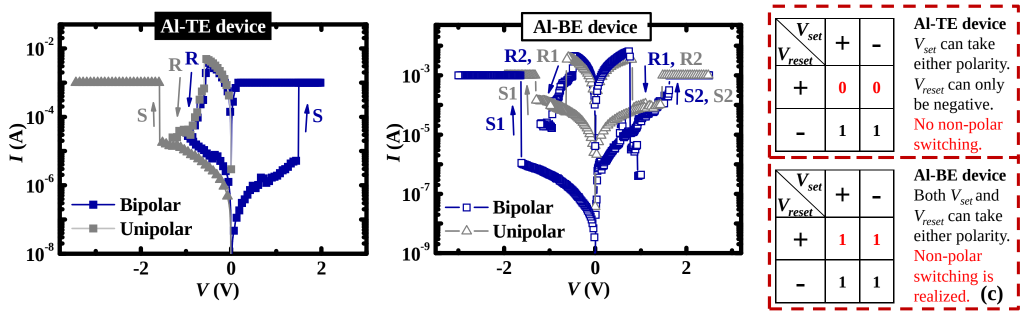

Fig. 3 Typical *I-V* characteristic of an (a) Al-TE, (b) Al-BE devices and (c) Truth table of the two devices. "S" denotes set and "R" denotes reset process, respectively. The Al-TE device only satisfied the condition of "unipolar and bipolar coexistence", but its V_{reset} must be negative, hence it is not non-polar.

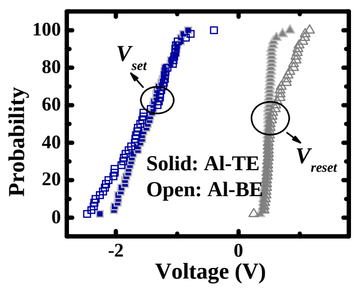

Fig. 4 Comparison of V_{set} and V_{reset}. Both V_{set} and V_{reset} are small in magnitude.

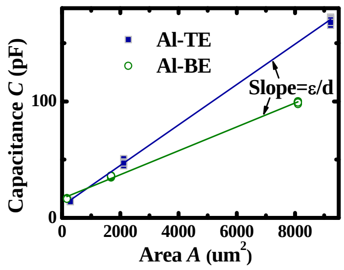

Fig. 5 *C* vs. Area of Al-TE and Al-BE devices. Gentler slope of Al-BE line further confirms physically thicker dielectric in Al-BE.

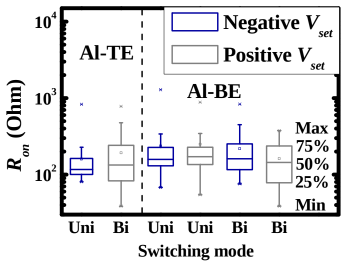

Fig. 6 R_{on} vs. various switching modes for both devices. Little variation across different modes is observed. Resistance values are tightly distributed.

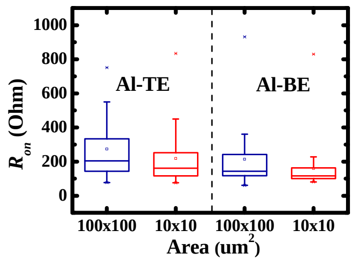

Fig. 7 Area dependence of R_{on}. Area independence is an indication of filamentary conduction.

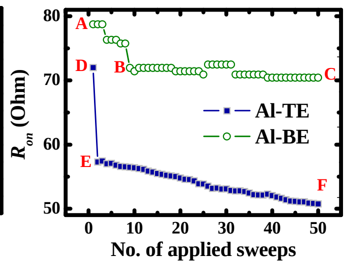

Fig. 8 Change of R_{on} during fifty 0 to 1V sweeps. The rate of decrease is faster in Al-TE than in Al-BE.

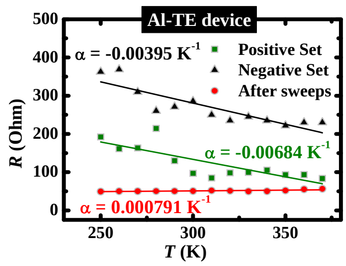

Fig. 9 Temperature dependence of R_{on} of an Al-TE device. Polarity of α inversed after sweeps, suggesting a change in conduction mechanism.

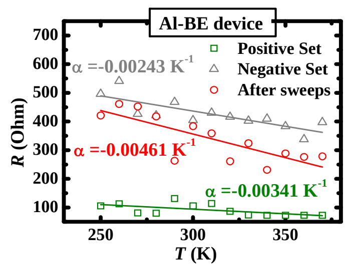

Fig. 10 Temperature dependence of R_{on} of an Al-BE device. Only magnitude of α changes, suggesting that conduction mechanism is the same before and after sweeps.

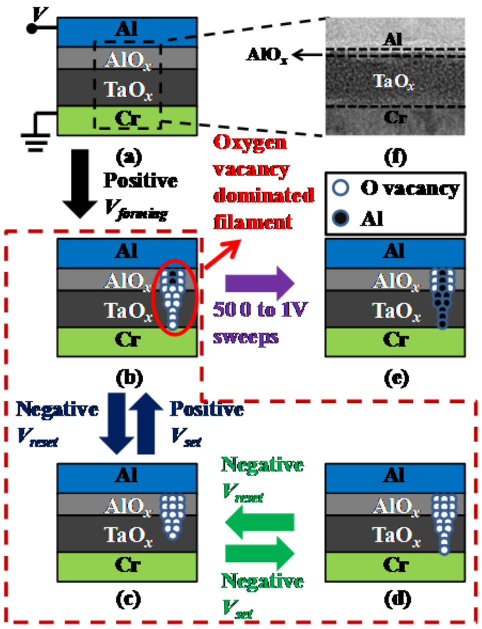

Fig. 11 (a) to (e) Schematic of microscopic changes during switching in an Al-TE device. Device starts at (a) in its as- fabricated state. Voltage is applied on Al. Enclosed region denotes standard RRAM switching. (f) TEM picture confirm the formation of interfacial AlO$_x$ layer.

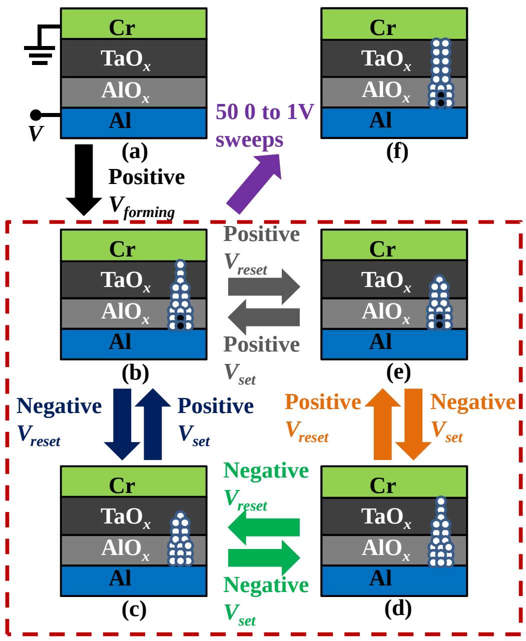

Fig. 12 (a) to (f) Schematic of microscopic changes during switching of an Al-BE device. Device starts at (a) in its as-fabricated state. Voltage is applied on Al. Enclosed region denotes standard RRAM switching.