Microelectronic Engineering 94 (2012) 14–17

Contents lists available at SciVerse ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Resistive switching characteristics in HfO_x layer by using current sweep mode

Bin Gao, Lifeng Liu, Xiaoyan Liu, Jinfeng Kang *

Institute of Microelectronics, Peking University, Beijing 100871, China

ARTICLE INFO

Article history:
Received 1 August 2011
Received in revised form 29 October 2011
Accepted 28 December 2011
Available online 11 January 2012

Keywords:
Resistive switching
Conductive filament
Current sweep
Nonvolatile memory

ABSTRACT

A current sweep method is presented to probe the resistive switching behavior of hafnium-oxide-based resistive random access memory. The essentially gradual resistive switching process might be concealed by the sudden resistance transition observed in SET process using voltage sweep and RESET process using current sweep. Voltage-controlled RESET behavior is observed by the new measurement strategy such that memory device can be reset to different resistance states with the same RESET current and different compliance voltages. Under current sweep measurement, the sharp and gradual resistance transitions during SET process are observed in different types of devices. The different SET transition behavior could be used as a valuable criterion in selecting resistive switching layer materials for different targeted applications.

1. Introduction

As one of the most promising next-generation nonvolatile memory technologies, resistive random access memory (RRAM) has widely attracted research attention [1–5]. Due to its fast switching speed (<5 ns), low operating voltage (<2 V), simple structure and excellent scalability, RRAM has emerged as a promising candidate for future universal information storage applications. This memory device is based on resistive switching mechanism in certain oxide dielectrics, i.e., change of resistance under applied electric voltage or current [5]. Although formation and rupture of conductive filament in oxide layer has been widely accepted as the primary origin for resistive switching [5–9], it still needs to clarify the dominant factors behind the observed switching process. The unclear physical origin of switching behavior has been a major bottleneck in the RRAM research.

Generally, voltage sweep method is used to investigate the RRAM behavior [2–7]. By using voltage sweep, most of the resistive switching properties can be evaluated, but certain intrinsic behavior might be difficult to uncover due to monotonically increased voltage ramping. In this letter, a new current sweep method is introduced to explore the resistive switching behavior of HfO_x based RRAM. Based on the new approach, phenomena such as voltage-controlled RESET and different type of SET processes are discovered, which help to clarify the resistive switching mechanism and identify effective methodology for performance optimization in RRAM.

2. Experiments

In this study, Al-doped and undoped HfO_x RRAM devices were fabricated. For Al-doped samples (device A), Al/Hf/Al sandwiched layers with 5 nm/20 nm/5 nm respective thickness were deposited on substrate ($Pt/Ti/SiO_2/Si$) at room temperature by sputtering. For undoped samples (device B), 20 nm Hf layer was deposited on substrate ($Pt/Ti/SiO_2/Si$). Both types of samples then underwent a two-step furnace annealing process at 600 °C (10 min in N_2, followed by 20 min in O_2) to form the resistive switching layer. After TiN top electrode deposited, the devices were patterned by optical lithography to form isolated, square-shape memory cells with the area size of $100 \times 100\ \mu m^2$. Electrical measurements were performed using Agilent-4156C semiconductor parameter analyzers.

3. Results and discussion

The fabricated devices show reversible bipolar switching. Fig. 1(a) shows the *I–V* characteristics of device A using voltage sweep method. When a positive sweep voltage applied on the top electrode reaches about 0.7 V, an abrupt current increase is observed, indicating that the switching from high-resistance-state (HRS) to low-resistance-state (LRS) (SET process) occurs. A current compliance of 1 mA is applied to protect the devices from permanent breakdown during testing [4]. Changing the polarity of sweep voltage, a gradual current drop is observed when voltage reaches about −0.7 V. This bipolar switching behavior is consistent with previous publications [2–4]. However, by using current sweep method, new phenomena are observed in device A, as shown in Fig. 1(b). SET process shows a gradual current transition, whereas

* Corresponding author.
E-mail address: kangjf@pku.edu.cn (J. Kang).

0167-9317/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.mee.2011.12.016

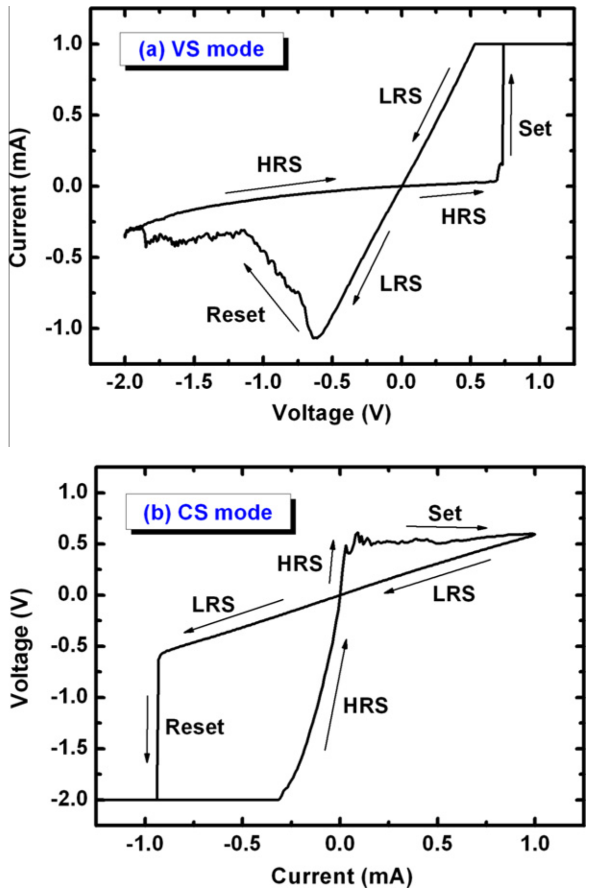

Fig. 1. Typical resistive switching behavior of Al-doped HfO_2 based RRAM by: (a) voltage sweep and (b) current sweep.

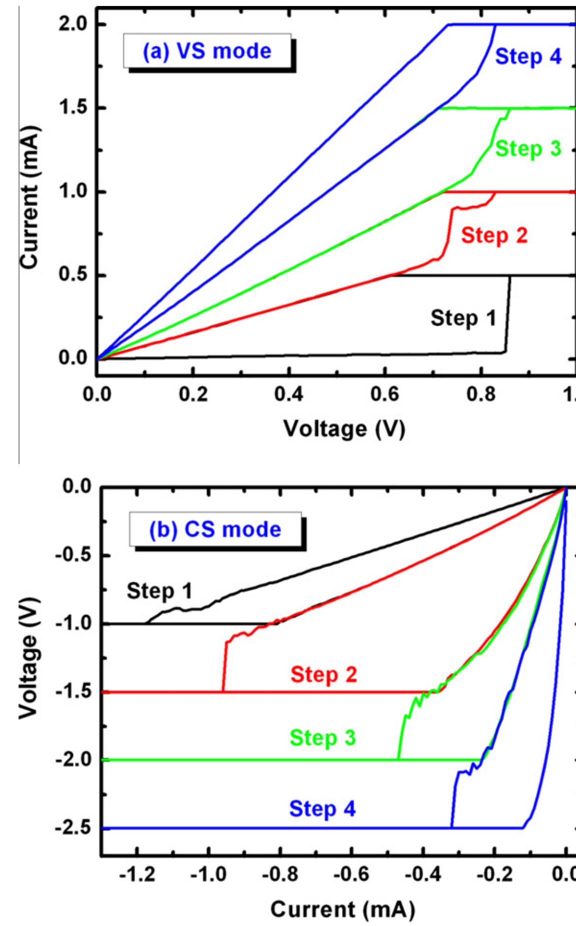

Fig. 2. (a) Different SET steps controlled by current compliance. (b) Different RESET steps controlled by voltage compliance.

a sharp transition is observed in RESET process. In this case, a compliance voltage is required for reset to protect the devices.

It is easy to clarify that the sharp current transition during SET by voltage sweep and the sharp voltage transition during RESET by current sweep are not the essential behavior. In fact, these observed phenomena are mainly caused by the defect of measurement in which monotonically increased sweep parameters (voltage or current) and compulsive compliance are used. For example, in voltage sweep SET process, supposing that SET process includes multi-steps of resistive switching [2–4], once the first step requires higher SET voltage than the subsequent steps, the voltage read from the equipment cannot decrease but keep constant when SET process starts, even though a lower SET voltage is required afterwards. The following SET processes finish quickly under the large applied voltage until current reaches to the compliance value. Therefore, a sudden jump of current is observed at the critical voltage corresponding to the SET voltage of the first step. When current compliance reaches, the voltage is applied in part on the compliance circuitry. The applied voltage on the device is smaller than read from equipment, and keeps on changing to maintain the current lower than the compliance value. Therefore, another sharp transition is observed, although resistance does not change during this process. The multi-step switching effect is demonstrated by changing the current compliance [2,3], as shown in Fig. 2(a). Once the SET voltages of the subsequent steps are higher than the first step, SET process might show gradual resistive transition as reported in Refs. [10,11].

Similar interpretation is valid for the sharp RESET process with current sweep. The voltage-controlled multi-step RESET is demonstrated by changing the compliance (Fig. 2(b)), showing that the required current in the following RESET step is smaller than the first step. In this case, current cannot decrease although resistance is increasing after RESET process starts, resulting in the sharp voltage transition. When voltage compliance reaches, the current through the device is smaller than the read current. The resistance does not change although current is changing and voltage keeps constant. Based on these discussions, it is concluded that the resistance change is gradual in both SET and RESET processes.

The gradual change of resistance might be attributed to multiple conductive filament effect [12]. In SET process, new oxygen vacancies are generated successively as the current increases. The amount of filament branches increases, resulting in the decrease of resistance. In RESET process, the filament branches are ruptured successively, and thus resistance increases gradually. For device A, the interim resistive states are steady [2,3], which can be switched to by using different SET current compliance or RESET voltage compliance, as shown in Fig. 2(a) and (b).

Fig. 3 shows that HRS resistances are different under various compliance voltages in current sweeping. With the same RESET current (shown in the inset), resistance increases with voltage compliance. This supports the viewpoint that RESET process is voltage-controlled. Meanwhile, by using current sweep method, it is easy to extract the RESET voltage and current accurately. As shown in Fig. 4, setting different stop current in SET process could cause significant change of RESET current, while change in RESET voltage is negligible. With the same compliance voltage, the device is reset to the same resistance at various RESET current. These observed switching behaviors indicate that RESET process is

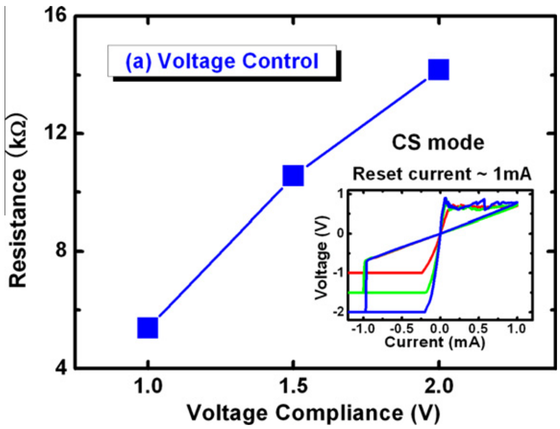

Fig. 3. Voltage compliance dependence of HRS resistance. Inset: switching behavior under different RESET voltage compliance by current sweep.

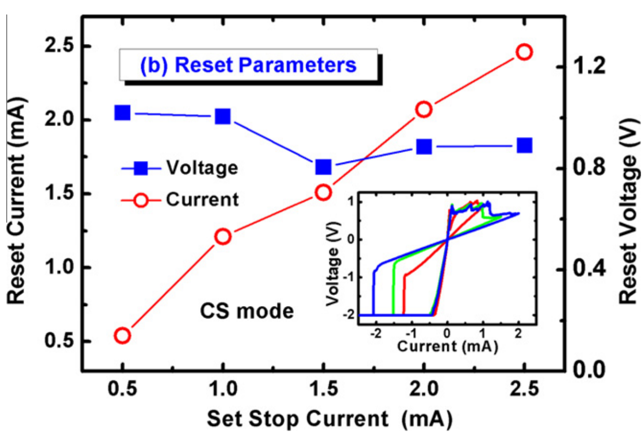

Fig. 4. SET stop current dependence of RESET current and voltage by using current sweep. Inset: switching behavior under different set stop current by current sweep.

voltage-controlled rather than current-controlled, which are consistent with the previous conclusion [8,13]. Therefore, these results provide evidences to support the model that RESET process is due to the movement of oxygen ions or vacancies under critical electric field [13–15]. Under a higher applied electric field, more oxygen ions are activated, resulting in significant rupture of conductive filaments and higher HRS resistance.

The *I–V* characteristics of devices A and B during SET process using current sweep method are measured (see Fig. 5). Compared to the gradual resistance transition in device A, device B shows a sudden resistance jump. The different resistance switching behavior might be correlated with the amount of conductive filaments formed in the device. In device B, only one or several strong filaments are formed at the critical current. Each filament makes significant contribution to the current. When a new filament is formed, resistance decreases significantly. In contrast to this, in device A, a large number of weak filament branches are formed, resulting in the gradual resistance change [12]. The difference between these two devices is believed to be correlated to the amount of intrinsic oxygen vacancies in the oxide layer. In device A, the vacancy amount is quite larger than device B due to the effect of Al diffusion [16]. Thus conductive filaments are more easily to be formed. The smaller SET voltage and higher HRS current of device A also support this conclusion. The gradual resistance transition implies better current controllability over resistance. In contrast to this, the sudden change

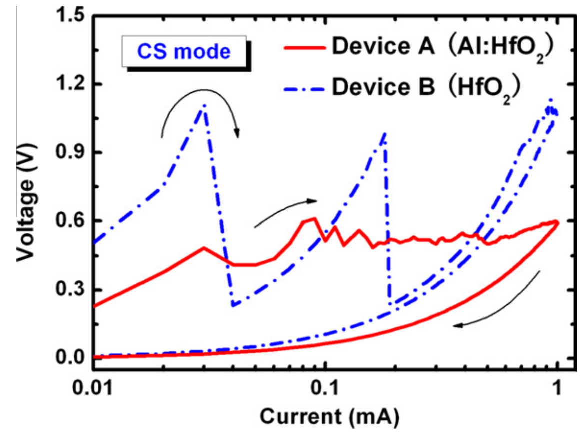

Fig. 5. Sharp and gradual SET process for undoped and Al-doped HfO_2 based RRAM measured by current sweep method.

of resistance in device B is disadvantageous to the reduction of RESET current and multilevel data storage application, as it is difficult to achieve steady interim resistance states by controlling SET current or RESET voltage as in device A (Figs. 2–4). However, device B could be used as switch or selector since it is easier to achieve high resistance ratio comparing to device A.

4. Conclusion

In this work, we investigated the switching behavior and physical origin of HfO_2 based RRAM by comparing the conventional voltage sweep method and the newly introduced current sweep method. The sudden current jump in voltage sweep SET process and voltage resistance jump in current sweep RESET process is often observed from *I–V* curve even though the essential resistive switching processes are gradual. The origin of these phenomena is attributed to the defect of electric measurement mode. The sharp and gradually resistance transition could be distinguished by suitable measurement mode. The uncovered resistive switching behavior supports the conductive filament theory, clarifying that RESET is voltage-controlled rather than current-controlled. The observations bring in in-depth understanding on the resistive switching mechanism, pointing to the direction to better control and optimize the RRAM memory performance.

Acknowledgements

This work is supported in part by the 973 and NSFC Programs (2010CB934203, 2011CBA00600, and 60906040).

References

[1] A. Sawa, Mater. Today 11 (6) (2008) 28–36.
[2] H.Y. Lee, P.S. Chen, T.Y. Wu, Y.S. Chen, C.C. Wang, P.J. Tzeng, C.H. Lin, F. Chen, C.H. Lien, M.-J. Tsai, IEDM Tech. Dig. (2008) 297–300.
[3] D. Lee, D.-J. Seong, H.J. Choi, I. Jo, R. Dong, W. Xiang, S. Oh, M. Pyun, S.-O. Seo, S. Heo, M. Jo, D.-K. Hwang, H.K. Park, M. Chang, M. Hasan, H. Hwang, IEDM Tech. Dig. (2006) 796–799.
[4] N. Xu, L.F. Liu, X. Sun, C. Chen, Y. Wang, D.D. Han, X.Y. Liu, R.Q. Han, J.F. Kang, B. Yu, Semicond. Sci. Technol. 23 (2008) 075019.
[5] R. Waser, M. Aono, Nat. Mater. 6 (2007) 833–840.
[6] B. Sun, L.F. Liu, D.D. Han, Y. Wang, X.Y. Liu, R.Q. Han, J.F. Kang, Chin. Phys. Lett. 25 (6) (2008) 2187.
[7] Y. Wang, Q. Liu, S.B. Long, W. Wang, Q. Wang, M.H. Zhang, S. Zhang, Y.T. Li, Q.Y. Zuo, J.H. Yang, M. Liu, Nanotechnology 21 (2010) 045202.
[8] D. Ielmini, F. Nardi, C. Cagli, IEEE Trans. Electron Devices 58 (10) (2011) 3246–3253.
[9] K.M. Kim, B.J. Choi, C.S. Hwang, Appl. Phys. Lett. 90 (2007) 242906.
[10] C.-Y. Lin, C.-Y. Wu, C.-Y. Wu, T.-C. Lee, F.-L. Yang, C. Hu, T.-Y. Tseng, IEEE Electron Device Lett. 28 (5) (2007) 366–368.

[11] H. Choi, H. Jung, J. Lee, J. Yoon, J. Park, D.-J. Seong, W. Lee, M. Hasan, G.-Y. Jung, H. Hwang, Nanotechnology 20 (2009) 345201.
[12] B. Gao, B. Sun, H.W. Zhang, L.F. Liu, X.Y. Liu, R.Q. Han, J.F. Kang, B. Yu, IEEE Electron Device Lett. 30 (12) (Dec. 2009) 1326–1328.
[13] S. Yu, H.-S.P. Wong, IEEE Electron Device Lett. 31 (12) (Dec. 2010) 1455–1457.
[14] W. Shen, R. Dittmann, U. Breuer, R. Waser, Appl. Phys. Lett. 93 (2008) 222102.
[15] W.Y. Chang, K.J. Cheng, J.M. Tsai, H.J. Chen, F. Chen, M.J. Tsai, T.B. Wu, Appl. Phys. Lett. 95 (2009) 042104.
[16] S.M. Yu, B. Gao, H.B. Dai, B. Sun, L.F. Liu, X.Y. Liu, R.Q. Han, J.F. Kang, B. Yu, Electrochem. Solid State Lett. 13 (2) (2010) H36–H38.