# Resistive switching characteristics of $Ni/HfO_2/Pt$ ReRAM

Zhang Xiao(张晓)†

Institute of Microelectronics, Xi'an Jiaotong University, Xi'an 710049, China

**Abstract:** This study investigated the resistive switching characteristics of the $Ni/HfO_2/Pt$ structure for nonvolatile memory application. The $Ni/HfO_2/Pt$ device showed bipolar resistive switching (RS) without a forming process, and the formation and rupture of conducting filaments are responsible for the resistive switching phenomenon. In addition, the device showed some excellent memory performances, including a large on/off ratio ($> 3 \times 10^5$), very good data retention ($> 10^3$ s @ 200 ℃) and uniformity of switching parameters. Considering these results, the $Ni/HfO_2/Pt$ device has the potential for nonvolatile memory applications.

**Key words:** resistive random access memory; programmable metallization cell; conductive filament; Ni electrode; $HfO_2$

**DOI:** 10.1088/1674-4926/33/5/054011 **EEACC:** 2550

## 1. Introduction

Programmable metallization cell (PMC) technology has recently sparked scientific and commercial interest as a replacement for traditional charge-based memories. The structure of this new concept memory is typically solid-state electrolyte materials based on ionic transport composed between the oxidizable anode and inert cathode. Particularly, a PMC features a simple structure and superior performance, for example fast operation speed, high density, and great scale-down potential[1, 2]. However, several problems, such as undesirably low operation voltages, destructive readout under stress voltage, and especially poor retention of the low resistance state (LRS) at elevated temperatures must be resolved before commercial applications can be realized[1, 3]. To solve these issues, some new electrolyte materials (such as CuC[4] and SiC[5]) were applied or a buffer layer was inserted between electrolyte and active electrode. However, these new electrolytes increase the complexity of device fabrication procedures, which can impede the mass production of PMC devices.

Recently, Lin *et al.*[6] fabricated a $Ni/HfO_2/Si$ device and demonstrated that its switching mechanism was similar to PMC devices. Because Ni atoms have a higher activation energy in oxide than Cu or Ag atoms, Ni might resolve the stability issues in PMC devices. In addition, Ni is already used in current CMOS technology as a favorable material and hence may be a potential candidate for PMC electrode material.

However, the deposition of Si film needs high temperature[7], which is not advantageous for the integration of ReRAM both in 3D architecture and in back-end CMOS processes[8]. In this study, the $HfO_2$ functional layer with a Ni top electrode (TE) was deposited on Pt substrates at room temperature (RT) conditions. We focus on investigating the switching parameters and retention property of the device by using direct current (DC) electrical measurement. The $Ni/HfO_2/Pt$ device showed high temperature stability and uniform switching characteristics.

## 2. Experimental setup

The $Ni/HfO_2/Pt$ device in this study was fabricated as follows. First, a 100 nm thick $SiO_2$ layer was thermally grown on an n-Si substrate by using a dry-oxygen oxidation method. In the next stage, 20 nm thick Ti and 80 nm thick Pt layers are sequentially deposited on the $SiO_2/Si$ substrate by e-beam evaporation to form the bottom electrode. Subsequently, a 20 nm thick $HfO_2$ film was deposited on the Pt bottom electrode by e-beam evaporation using a $HfO_2$ target with a purity of 99.99%. After that, the top electrode layer consisting of Ni/Au (70/30 nm) was deposited by e-beam evaporation in succession without breaking the vacuum atmosphere. During e-beam evaporation, the chamber pressure was kept at $2.6 \times 10^{-6}$ Torr. The Au layer was used to avoid the Ni electrode from being scratched by the probe tip during testing. The top electrodes (with an area ranging from $100 \times 100$ $\mu m^2$ to $1000 \times 1000$ $\mu m^2$) were patterned as squares via photolithography and a lift-off process. All electrical characterization was performed under ambient conditions using a Keithley 4200 semiconductor characterization system by applying voltage to the TEs with reference to a Pt electrode, as shown in the inset of Fig. 1(a).

## 3. Results and discussion

Figure 1(a) shows the typical $I$–$V$ characteristics of the $Ni/HfO_2/Pt$ memory device under a DC sweeping mode. The device was initially in the high resistance (OFF) state (HRS). When a positive voltage was applied on the top electrode, the device switched from the off-state to the on-state (denoted as the set process) at $\sim$5 V. In this process, a 1 mA compliance current was set to protect the device from permanent damage. Surprisingly, no forming process was observed in the $Ni/HfO_2/Pt$ structure, though it is commonly reported in metal–oxide–metal (MOM) devices. Haemori *et al.*[9] has reported a similar phenomena in a $Cu/HfO_2/Pt$ device, which was proved due to columnar paths formed in a $HfO_2$ thin film. When we applied a negative voltage without current limitation,

† Corresponding author. Email: zhangshev@stu.xjtu.edu.cn
Received 18 October 2011, revised manuscript received 24 December 2011

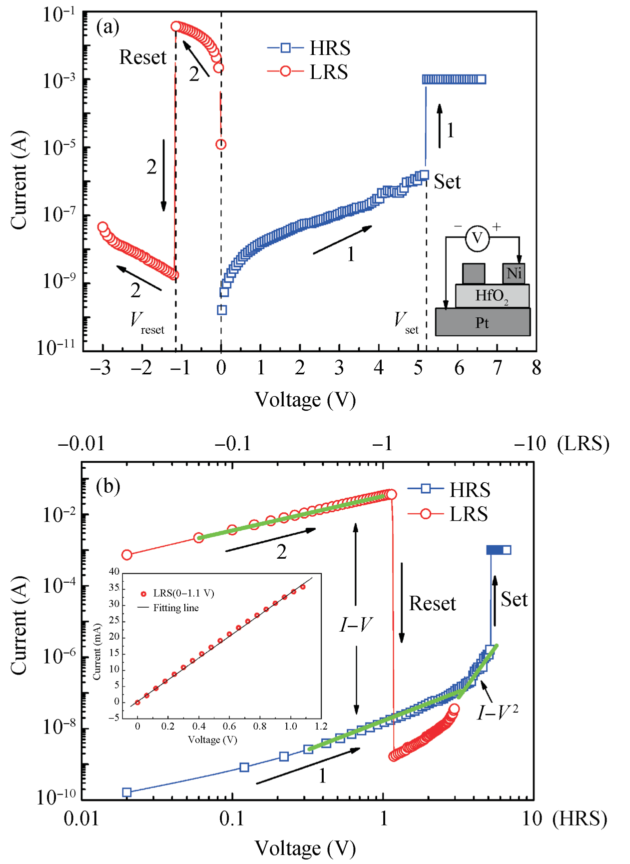


Fig. 1. Typical plots of the $I$–$V$ characteristics of the device under a DC voltage sweep. (a) Semi-logarithmic scale. The inset of (a) shows a schematic diagram of the measurement setup. (b) Logarithmic scale. The inset of (b) shows the $I$–$V$ curve at low voltages in the LRS branch. The arrows indicate the sweeping directions.

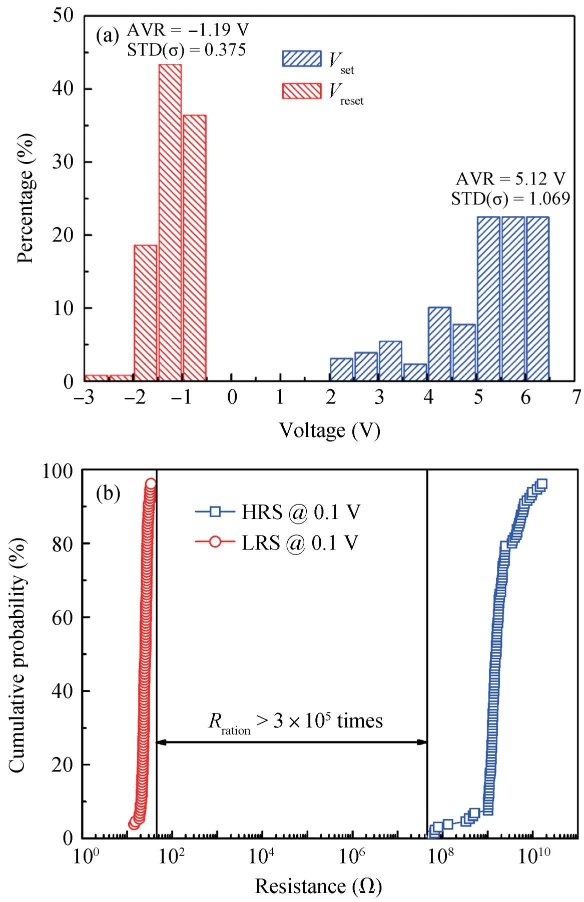


Fig. 2. (a) Distribution of $V_{set}$ and $V_{reset}$ during testing cycles. (b) Distribution of $R_{HRS}$ and $R_{LRS}$ during testing cycles.

the device switched back to the off-state at ~ –1 V (denoted as the reset process). Herein, we define the transition voltages of the set and reset process as $V_{set}$ and $V_{reset}$, and define the resistances of the off-state and on-state as $R_{HRS}$ and $R_{LRS}$, respectively.

Figure 1(b) shows the $I$–$V$ curves of the Ni/$HfO_2$/Pt device redrawn on double-logarithmic scales. The fitting result of the $I$–$V$ curve in the LRS follows a linear ohmic conduction, as can be seen from the inset of Fig. 1(b). This indicates that the current in the LRS can be explained by the formation and rupture of conductive filaments inside the $HfO_2$ film[10]. For the HRS, the $I$–$V^2$ followed the trend of the $I$–$V$ character as a positive voltage increase, indicating that the HRS is dominated by a trap-controlled SCLC conduction mechanism[11]. Recently, Lin *et al.* demonstrated that the Ni element is the main component of the conductive filament inside the Ni/$HfO_2$/Si device by SIMS analysis. Hence, we have reason to believe that the conductive filaments comprise Ni atoms in our device, which is very similar to that of a solid-electrolyte-based ReRAM[12–15], such as Cu/$ZrO_2$/Pt[16] and Ag/$ZrO_2$/Pt[17] devices.

We tested 15 cells each with an area of 100 × 100 $\mu m^2$ for 10 cycles, and we found that the average values of $V_{set}$ and $V_{reset}$ of the Ni/$HfO_2$/Pt device were relatively high. Figure 2 shows the distribution of $V_{set}$, $V_{reset}$ and their average values and standard deviations. Mean values of $V_{set}$ and $V_{reset}$ achieved 5.12 V and –1.19 V, respectively. It is worth noting that even the minimum set voltage was larger than 2 V, which can be seen in Fig. 2(a), while the $V_{set}$ of the undoped device with a Cu TE generally shows a wide dispersion[16]. This indicates more energy is required to form Ni filaments. The increase of operation voltages may lead to a slight growth of power that the device may consume, but it also means the read voltage can be set higher to avoid outer electrical noise interference. Additionally, our device showed uniform switching parameters. As seen in Fig. 2, $V_{set}$ varied from 2.03 to 6.46 V and more than 80% were greater than 4 V, while $V_{reset}$ varied from –2.7 to –0.58 V. $R_{LRS}$ ranged from 14.41 to 196.86 Ω and $R_{HRS}$ ranged from 5.83 × $10^7$ to 1.61 × $10^{10}$ Ω. The storage window could achieve 3 × $10^5$.

Thermal stability is important for the purpose of memory applications. It has been reported that a PMC is stable in the HRS but lacks reliability in the LRS, especially in a high temperature environment[12]. Usually, the variation is attributed to the percolation process at the LRS when different ruptured filaments are reconnected randomly at each switching cycle[6]. However, as revealed in Fig. 3, our Ni/$HfO_2$/Pt device showed no degradation up to 200 ℃ both in the HRS and the LRS for a considerably long time, which is even ahead of the highly stable Cu/SiC/Pt device fabricated by Lee *et al.*[5]. This improvement of reliability can be attributed to the composition of the conductive filaments. Specifically, the retention property is

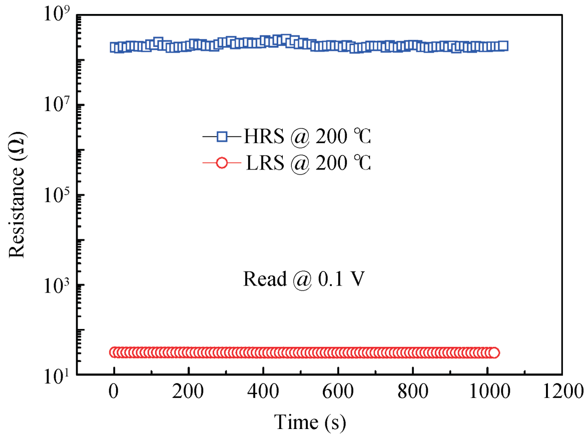


Fig. 3. Retention characteristics of both the LRS and HRS, which are stable even under 200 ℃.

determined by the energy required to disrupt conducting filaments or oxygen vacancies[5, 6]. Since a Ni TE owns a larger activation energy, much greater power is needed to drive the Ni atoms in the Ni filaments and rupture the conductive paths. Under the condition that temperature is not very high, the insufficient thermal density would keep Ni filaments inactive at the LRS. Consequently, the reliability of the low resistance state is significantly improved. This result is also supported by the cluster-connected filament model proposed by Lee *et al.*[18].

## 4. Conclusion

In summary, we fabricated the Ni/$HfO_2$/Pt structure and evaluated its potential for the nonvolatile memory application. Particularly, the ambient temperature fabricated device showed a long retention and forming free stable resistive switching, which are always pursued for the practical application of resistive random access memory. In addition, Ni is commonly used in microelectronics manufacturing technology with a simple fabricating process, while a $HfO_2$-based film is one of the most probable high-k dielectric gate materials. All of the above advantages make Ni/$HfO_2$/Pt cells highly promising for nonvolatile memory applications.

## Acknowledgement

The experimental work was performed at the institute of microelectronics of the Chinese Academy of Sciences (IMECAS). The author would like to thank Dr. Liu Qi and Dr. Li Yingtao of IMECAS for useful discussions.

## References


[1] Meijer G I. Who wins the nonvolatile memory race. Science, 2008, 319(5870): 1625

[2] Waser R, Aono M. Nanoionics based resistive switching memories. Nature Mater, 2007, 6(11): 833

[3] Sakamoto T, Sunamura H, Kawaura H, et al. Nanometer-scale switches using copper sulfide. Appl Phys Lett, 2003, 82(18): 3032

[4] Pyun M, Choi H, Park J B, et al. Electrical and reliability characteristics of copper-doped carbon (CuC) based resistive switching devices for nonvolatile memory applications. Appl Phys Lett, 2008, 93(21): 212907

[5] Wootae L, Jubong P, Myungwoo S, et al. Excellent state stability of Cu/SiC/Pt programmable metallization cells for nonvolatile memory applications. IEEE Electron Device Lett, 2011, 32(5): 680

[6] Lin K L, Hou T H, Shieh J, et al. Electrode dependence of filament formation in $HfO_2$ resistive-switching memory. J Appl Phys, 2011, 109(8): 3796

[7] Zhang Guobing, Hao Yilong, Tian Dayu, et al. Residual stress properties of polysilicon thin film. Chinese Journal of Semiconductors, 1999, 20(6): 463

[8] Yang Yuchao, Pan Feng, Liu Qi, et al. Fully room-temperature-fabricated nonvolatile resistive memory for ultrafast and high-density memory application. Nanoletters, 2009, 9(4): 1636

[9] Haemori M, Nagata T, Chikyow T, et al. Impact of Cu electrode on switching behavior in a Cu/$HfO_2$/Pt structure and resultant Cu ion diffusion. Appl Phys Express, 2009, 2(6): 061401

[10] Liu Q, Long S, Wang W, et al. Unipolar resistive switching of $Au^+$-implanted $ZrO_2$ films. Journal of Semiconductors, 2009, 30(4): 042001

[11] Liu Q, Long S, Wang W, et al. Resistive switching memory effect of $ZrO_2$ films with $Zr^+$ implanted. Appl Phys Lett, 2008, 92(12): 012117

[12] Symanczyk R, Bruchhaus R, Dittrich R. Investigation of the reliability behavior of conductive-bridging memory cells. IEEE Electron Device Lett, 2009, 30(8): 876

[13] Schindler C, Weides M, Kozicki M N, et al. Low current resistive switching in Cu–$SiO_2$ cells. Appl Phys Lett, 2008, 92(12): 122910

[14] Guan W, Long S, Liu Q, et al. Nonpolar nonvolatile resistive switching in Cu doped $ZrO_2$. IEEE Electron Device Lett, 2008, 29(5): 434

[15] Guan W, Liu M, Long S, et al. On the resistive switching mechanisms of Cu/$ZrO_2$:Cu/Pt. Appl Phys Lett, 2008, 93(22): 223506

[16] Liu Q, Long S, Wang W, et al. Improvement of resistive switching properties in $ZrO_2$-based ReRAM with implanted Ti ions. IEEE Electron Device Lett, 2009, 30(12): 1335

[17] Long S, Liu Q, Lv H, et al. Resistive switching mechanism of Ag/$ZrO_2$:Cu/Pt memory cell. Appl Phys A, 2011, 102(4): 915

[18] Lee S, Chae S, Chang S, et al. Scaling behaviors of reset voltages and currents in unipolar resistance switching. Appl Phys Lett, 2008, 93(21): 212105