Enhanced resistive switching memory characteristics and mechanism using a Ti nanolayer at the W/TaO$_x$ interface

Amit Prakash$^1$, Siddheswar Maikap$^1$,*, Hsien-Chin Chiu$^1$, Ta-Chang Tien$^2$ and Chao-Sung Lai$^1$

Abstract
Enhanced resistive memory characteristics with 10,000 consecutive direct current switching cycles, long read pulse endurance of $>10^5$ cycles, and good data retention of $>10^4$ s with a good resistance ratio of $>10^2$ at 85°C are obtained using a Ti nanolayer to form a W/TiO$_x$/TaO$_x$/W structure under a low current operation of 80 μA, while few switching cycles are observed for W/TaO$_x$/W structure under a higher current compliance $>300$ μA. The low resistance state decreases with increasing current compliances from 10 to 100 μA, and the device could be operated at a low RESET current of 23 μA. A small device size of 150 × 150 nm$^2$ is observed by transmission electron microscopy. The presence of oxygen-deficient TaO$_x$ nanofilament in a W/TiO$_x$/TaO$_x$/W structure after switching is investigated by Auger electron spectroscopy. Oxygen ion (negative charge) migration is found to lead to filament formation/rupture, and it is controlled by Ti nanolayer at the W/TaO$_x$ interface. Conducting nanofilament diameter is estimated to be 3 nm by a new method, indicating a high memory density of approximately equal to 100 Tbit/in$^2$.

Keywords: Resistive switching; W/TaO$_x$; Ti nanolayer; Oxygen ion migration; Nanofilament

Background
Resistive switching random access memories (RRAM) with simple metal-insulator-metal stacks are under intensive investigation owing to their great promise for use in next-generation memory applications [1-5]. However, their nonuniformity in switching, low yield, and unclear switching mechanism hinder their practical realization. RRAM devices with simple composition, easy fabrication process, and good 3D integration compatibility will be needed in the future. Methods such as doping, formation polarity control, bottom electrode modification, nanocrystal insertion, and interfacial engineering have recently been investigated to improve the characteristics of resistive switching memory [6-10]. Among other important switching materials such as TiO$_x$ [11,12], NiO$_x$ [13-15], HfO$_x$ [10,16-18], ZrO$_x$ [19-27], Na$_{0.5}$Bi$_{0.5}$TiO$_3$ [28], SrTiO$_3$ [29], ZnO [30,31], GeO$_x$ [32], and SiO$_x$ [33], tantalum oxide (TaO$_x$) is one of the most promising choices for future RRAM applications. However, TaO$_x$-based RRAM devices are infrequently reported [5,34-39]. Terai et al. [37] used a TiO$_2$ layer in a Ru/Ta$_2$O$_{5-x}$/TiO$_2$/Ru stack with good thermal stability. Ninomiya et al. [38] reported an Ir/Ta$_2$O$_{5-x}$/TaO$_x$/TaN structure, and Lee et al. [5] reported a Pt/Ta$_2$O$_{5-x}$/TaO$_2$-δ/Pt crossbar structure with two layers of TaO$_x$ and at least one of the inert electrodes such as Ru, Ir, and Pt. Generally, many researchers use one inert electrode to improve the performance of resistive switching memory [5,39]; however, tungsten (W) as both bottom and top electrodes in a W/TiO$_x$/TaO$_x$/W structure has not yet been reported. Furthermore, the RRAM devices with low current operation (<100 μA) is also a challenging issue. In this work, a resistive switching memory device using a Ti nanolayer at the W/TaO$_x$ interface and enhanced memory characteristics such as excellent 10,000 consecutive stable dc switching cycles, long read pulse endurance of $>10^5$ cycles, and good data retention of $>10^4$ s at 85°C with a large resistance ratio of $>10^2$ under a low compliance current (CC) of 80 μA are reported. Furthermore, the device can be operated with a small ‘RESET’ current of 23 μA. For comparison, the W/TaO$_x$/W memory device is also

* Correspondence: sidhu@mail.cgu.edu.tw
$^1$Department of Electronic Engineering, Chang Gung University, Tao-Yuan 333, Taiwan
Full list of author information is available at the end of the article

© 2014 Prakash et al.; licensee Springer. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly credited.
fabricated. The device size of $150 \times 150 \text{nm}^2$ is observed using a high-resolution transmission electron microscope (HRTEM). The thicknesses of $\text{TiO}_x$ and $\text{TaO}_x$ nanolayers are 3 and 7 nm, respectively. The presence of oxygen-deficient $\text{TaO}_x$ conducting filaments is investigated by Auger electron spectroscopy (AES) before and after switching of the memory devices. The switching mechanism of the oxygen ion migration owing to a lower barrier height of electrons is investigated, and a filament diameter of approximately equal to 3 nm is calculated using a new method also reported in this work. Considering a small filament diameter, a high memory density of approximately equal to 100 Tbit/in.$^2$ could be designed in the future.

Methods

$\text{W/TaO}_x$/W-structured (device S1) and W/$\text{TaO}_x$/W-structured (device S2) resistive switching memory stacks were fabricated. A small via size of $150 \times 150 \text{nm}^2$ was etched into the SiO$_2$ on W bottom electrode (BE), which was about 100 nm in thickness. Standard photolithography and dry etching processes were used to open the via holes for the RRAM devices. The photoresist (PR) was coated and opened on active and top electrode (TE) regions for lift-off process. Then, a high-$\chi$ $\text{TaO}_x$ film with a thickness ($t_{\text{TaO}_x}$) of approximately equal to 7 nm was deposited by an e-beam evaporator, followed by the sequential deposition of a thin (approximately equal to 3 nm) interfacial layer of titanium (Ti) and approximately equal to 200-nm-thick W layer as a TE by radio-frequency (rf) sputtering. The W and Ti targets were used. Initial vacuum was approximately 10$^{-5}$ Torr. Argon gas (Ar) with a flow rate of 25 sccm and deposition power of 100 W was used to deposit W. The W deposition rate was 10 nm/min. For Ti deposition, Ar with a flow rate of 15 sccm and deposition power of 150 W were used. The Ti deposition rate was approximately 6.5 nm/min. For device S2, no Ti layer was deposited. The final devices were obtained after a lift-off process. Memory device structure and thicknesses of all layers were observed by transmission electron microscopy (TEM) with an energy of 200 keV. The $\text{TaO}_x$ material was also confirmed by quadrupole secondary ion mass spectroscopy (SIMS; ATOMIKA SIMS 4500, MA-Tek, Hsinchu, Taiwan) which had a high-depth resolution. Primary beam was O$^{2+}$ with an energy of 0.5 keV and analysis area of $37.5 \times 37.5 \mu\text{m}^2$. A bias was applied to the TE, and the BE was electrically grounded. Pristine S1 and S2 devices were electroformed by applying positive voltage to the TE before consecutive resistive switching cycle measurements.

Results and discussion

Figure 1a shows a typical cross-sectional TEM image of the W/$\text{TiO}_x$/TaO$_x$/W structure. The device size is $150 \times 150 \text{nm}^2$. HRTEM images of the S2 and S1 devices are shown in Figure 1b,c. The thicknesses of the $\text{TiO}_x$ and $\text{TaO}_x$ layers are approximately 3 and 7 nm, respectively, and both films show an amorphous characteristic. The film deposited by rf sputtering is not a conformal deposition. Therefore, the $\text{TiO}_x$ layer can be seen clearly on outside and active regions of the via hole (Figure 1a,c); however, this layer is not observed clearly on the sidewall of the via hole. It is also obvious that the switching material on the sidewall is not necessary for switching properties of the RRAM devices because the electrons will find least path to move from TE to BE. This $\text{TiO}_x$ layer is also confirmed on outside and active region of the device by energy dispersive X-ray spectroscopy (not shown here). Figure 2 shows typical SIMS depth profiles of $^{16}\text{O}$, $^{184}\text{W}$, and $^{181}\text{Ta}$ materials for the S2 sample. The thickness of the TaO$_x$ layer is about 15 nm; however, this is higher than the deposited film thickness of 7 nm. This is due to the trail effect and surface roughness of W BE, as we can see from the depth of 57 to 65 nm (or approximately 7 nm) of the $^{184}\text{W}$ depth profile. The average surface roughness of 200-nm-thick W layer on SiO$_2$/Si substrate is approximately 2.8 nm, which is observed by atomic force microscopy (AFM) with a scan area of $1 \times 1 \mu\text{m}^2$, as shown in Figure 3. Therefore, the remaining thickness of approximately 4.2 nm ($=7 \text{to} 2.8 \text{nm}$) is coming from the trail effect of the SIMS depth profile. The depth from 50 to 57 nm is the thickness of the TaO$_x$ layer, which is approximately 7 nm, as shown in Figure 2a,c. It is interesting to note that the $\text{TaO}_x$/W interface is found to be an oxygen-deficient layer, which makes it a more conducting interface. On the other hand, the conducting filament will be formed after breaking the Ta-O bonds in the bulk $\text{TaO}_x$ layer rather than the W/TaO$_x$ interface. This is because the $\text{TaO}_x$ layer is more insulating than the W/TaO$_x$ interface, so the electric field will drop across the $\text{TaO}_x$ film rather than the W/TaO$_x$ interface which probably results in multi-filaments or an uncontrolled nanofilament diameter. As Ti removes oxygen from the $\text{TaO}_x$ film in the W/$\text{TiO}_x$/TaO$_x$/W structure, the $\text{TaO}_x$ film becomes more oxygen-deficient, which is vital to achieve an improved resistive switching. Considering Gibbs free energies of TiO$_2$, $\text{Ta}_2\text{O}_5$, and $\text{WO}_3$ films, which are $\approx 887.6$, $\approx 760.5$, and $\approx 506.5$ kJ/mol, respectively, at 300 K [40], Ti will consume the highest oxygen content owing to its stronger reactivity than those of the other materials, thereby forming a Ta-rich (or defective TaO$_x$) film. This also prevents oxidation of the W TE at the TaO$_x$/W interface of device S1 owing to the migration of oxygen from the underlying films towards the Ti film, which contributes to the improved resistive switching memory performance as will be described.

The leakage current values of most of the S1 pristine devices at a read voltage ($V_{read}$) of 1 V are higher than
that of the S2 devices because of the presence of more oxygen vacancies in the TaO$_x$ layer owing to the oxygen-getter nature of the TiO$_x$ layer (Figure 4a). Typical current-voltage ($I$-$V$) curves (inset of Figure 4a) of both devices were asymmetrical with higher current at a negative voltage ($\approx 281$ pA for S1 and $\approx 12.6$ pA for S2 at $V_{\text{read}} = -1$ V) compared with that measured at a positive voltage ($\approx 9.8$ pA for S1 and $\approx 0.6$ pA for S2 at $V_{\text{read}} = 1$ V). This suggests that the W TE/TaO$_x$ interface has more oxygen vacancies than the TaO$_x$/W BE interface, owing to oxygen migration towards W TE during deposition. The ideal leakage current is plotted in Figure 5a and is explained as follows: It is reported that the work function ($\Phi_m$) of W and bandgap ($E_g$) of amorphous Ta$_2$O$_5$ and TiO$_2$ are 4.55 [41], 4.2 [42], and 3.3 eV [43], respectively. The conduction band offsets of Ta$_2$O$_5$ and TiO$_2$ with Si are 0.3 [44] and 0.9 eV [45], respectively. Taking the electron affinity of Si as 4.05 eV, the electron affinities of Ta$_2$O$_5$ and TiO$_2$ are calculated to be 3.75 and 3.15 eV, respectively. The corresponding energy
diagram is shown in Figure 5a as solid lines. Considering that the $E_g$ of TiO$_2$ for the pristine S1 device will be much lower because of oxygen vacancy creation during the deposition of W TE, the band diagram is shown in dotted lines (Figure 5a). In this case, electron injection dominates rather than hole injection because of a lower barrier height for electrons than for holes (0.8 to 1.4 vs. 3.4 eV). Both S1 and S2 devices show bipolar resistive switching behaviors. The S2 device shows few switching cycles with a higher leakage current of $\approx 10 \, \mu A$ at $V_{\text{read}} = 1 \, V$ and a higher CC of 300 $\mu A$ (Figure 4b). In this case, negatively charged oxygen ions (O$^-$) migrate from the switching material towards W TE, and this has a lesser possibility to form an oxygen-rich layer at the W TE/TaO$_x$ interface, leading to the formation of multi-conduction filaments. In the same way, no resistive switching is observed under negative forming voltage for either the S1 or S2 devices because oxygen ions migrate towards the W BE and permanent breakdown is observed (not shown here). The negative forming will lead to high switching current, which is similar to the W/TaO$_x$/W structure, and there is no oxygen-rich interfacial layer at the W/TaO$_x$ interface. This interfacial layer will have series resistance and protect from current overshoot effect. However, the insertion of a thin ($\approx 3$ nm) Ti layer in between the W and TaO$_x$ layers in the S1 device makes a vast difference because Ti can be used as an oxygen reservoir. Moreover, the S1 device exhibits $>10,000$ consecutive repeatable dc switching cycles with a better resistance ratio of $10^7$ under a low CC of 80 $\mu A$ (Figure 4c). The transport mechanism follows the trap-charge-controlled space-charge-limited current conduction (not shown here). However, a thicker Ti layer (5 nm) results in unstable switching cycles because it gets more oxygen and behaves as an insulating layer. This may lead to the conducting filament formation/rupture in the TiO$_x$ layer rather than the TaO$_x$ layer. It is reported that the TiO$_2$ switching layer has a Magneli phase and the memory window is collapsed after a few cycles [46]. That is the reason of having unstable switching using thicker (5 nm) Ti interfacial layer. Therefore, thickness optimization is very important and we have chosen those thicknesses of TaO$_x$ and TiO$_x$ layers here. The thinnest Ti layer of $<3$ nm is also not to be used because of direct current flow through this layer. Therefore, the thinner (3 nm) Ti layer will control the current overflow as well as will control the filament diameter. The yield of the S1 device is very high (>95%), while that of the S2 device is very low (approximately 10%). In addition, the S2 device cannot be switched below a CC of 300 $\mu A$ (discussed later) with non-ohmic current conduction. The average values and standard deviation/average are found to be 39.7 and 0.11, 38.4 k$\Omega$ and 0.08 for low-resistance state (LRS).
and 1.9 and 2.11, 8.6 MΩ and 0.43 for high-resistance state (HRS) at $V_{\text{read}}$ of 1 V and −1 V, respectively (Figure 4d). This suggests that the LRS has a tighter distribution than the HRS because of the formation of the TiO$_2$ layer, which will have a higher $E_g$ than the pristine one. Similarly, the leakage current at $V_{\text{read}}$ of −1 V is lower than that at +1 V because of the lower electron injection barrier at the TE/TiO$_2$ interface than that at the BE/TaO$_x$ interface after switching. Under ‘SET’, O$^{2-}$ will migrate from TaO$_x$ towards the TE, resulting in a TiO$_2$ layer which controls the conducting vacancy filament diameter in the TaO$_x$ layer by controlling current overflow and producing a tighter distribution of the LRS. Owing to this series resistance, the S1 devices exhibit non-ohmic-simulated (or nonlinear) ideal current, as shown in Figure 5b, whereas an ohmic current is observed for the S2 devices under SET (Figure 5c). It is true that the conducting filament is formed through the TaO$_x$ film (Figure 5b,c), which is also confirmed by the AES spectra of the TaO$_x$ film for pristine and after-switching of the TaO$_x$-based devices (Figure 6). The differentiated counts with respect to kinetic energy (dC/dE) versus kinetic energy (E) are plotted. The spectrum positions are in the middle of the TaO$_x$ switching layer with a typical device size of 0.4 × 0.4 μm$^2$. Different RRAM devices of pristine and switching were used to get the AES spectra. Even though different devices were used, the spectra of both the pristine (blue open square symbols) and switched (yellow solid triangle symbols) devices were maintained from the same depth. Ta-MN (1.737 and 1.680 eV) and O-KL (468, 483, and 503 eV) are observed, which confirms the formation of a TaO$_x$ layer. The atomic percentages of Ta-MN and O-KL are 37.38% and 62.62% for the pristine device and 44.69% and 55.31% for the switched device, respectively. It is believed that the spectra difference is not a variation, and the oxygen ion migration from the TaO$_x$ switching layer. Due to a small amount of oxygen migration, the difference of the two spectra will be small. The atomic percentages were calculated by using commercial software for AES spectra. Basically, this decrease in oxygen content and increase in Ta content after switching is of the evidence.
Figure 5 Schematic illustration of switching mechanism using simple energy band diagrams with I-V characteristics. (a) Energy bands of pristine S1 structure device and ideal leakage current. For TiO$_2$, the solid line is due to the smaller energy gap of the defective TiO film. I-V of LRS and corresponding energy bands with conducting filaments for (b) S1 and (c) S2 devices. For TaO$_x$, the solid line is due to the lower energy gap caused by the presence of oxygen-deficient filament. The S1 devices show non-ohmic I-V due to TiO$_2$ layer formation at the W/TaO$_x$/interface. (d) Filament oxidation and leakage current at HRS are shown for the W/TiO$_2$/TaO$_x$/W devices. Filament formation/rupture is controlled by the TiO$_2$ layer due to O$^{2-}$ ion migration.

Figure 6 Differentiated counts with respect to kinetic energy (dC/dE). AES spectra vs. kinetic energy for pristine and after-switching RRAM devices. The spectra are from a typical via size of 0.4 x 0.4 $\mu$m$^2$ and measured inside the middle of via regions (open blue square symbols for pristine and yellow solid triangle symbols for switched devices). An oxygen-deficient TaO$_x$ layer is observed after few switching cycles, confirming oxygen-deficient TaO$_x$ filament formation after SET.

Figure 7 Voltage shift vs. stressing time under a current of $\pm 80$ $\mu$A for SET/RESET operations. The conducting filament diameter is calculated to be approximately 3 nm.
that an oxygen-deficient filament is formed owing to oxygen ion migration as well as the lower energy gap of the TaO\(_x\) layer, as shown by the dotted line in Figure 5b. When negative voltage is applied to the TE, oxygen ions are pushed from the TiO\(_2\) layer towards the conducting filament where they recombine with oxygen vacancies or oxidize the conducting filament. The device will be in HRS (Figure 5d). Control of oxygen-deficient filament formation and rupture is facilitated by insertion of the thin Ti layer at the TE/TaO\(_x\) interface, which results in repeatable and reproducible resistive switching characteristics.

The conducting filament diameter is estimated using a new method under a constant current stress of 80 \(\mu\)A (Figure 7). The voltage decreases (or increases) under positive (or negative) current stress after a SET (or RESET) operation. First, it is considered as a parallel plate metal-insulator-metal (MIM) capacitor. Under external constant current stress, the Ta-O bonds break and create the defects due to oxygen ion migration, which results a reducing voltage across the capacitor. The captured cross section of the defects will lead to the diameter of the filament.

![Figure 8 I-V hysteresis characteristics of (a) LRS and RESET currents (b) with 10- to 100-\(\mu\)A CCs. A device could be operated with a low RESET current of 23 \(\mu\)A.](image)

![Figure 9 Long pulse endurance and good data retention. (a) Long read pulse endurance of \(>10^7\) cycles and (b) good data retention of \(>10^4\) s with a good resistance ratio of \(>10^2\) at \(85^\circ\)C are obtained at a low CC of 80 \(\mu\)A. (c) Program/erase endurance of \(>1,000\) cycles with a pulse width of 500 \(\mu\)s.](image)
Improvement in resistive switching performance, particularly 10,000 consecutive switching cycles with tight distribution in HRS/LRS of >10^2, long pulse endurance of >10^4, and good data retention of 10^4 s at 85°C, have been achieved under a low CC of 80 μA by exploiting the oxygen-getter nature of a Ti nanolayer in a W/TiO_2/TaO_x/W structure. A small device of 150 × 150 nm^2 and a defective TaO_x film are confirmed by TEM. O^{2-} ion migration because of lower barrier height for electrons leads to a switching mechanism based on filament formation/rapture. The presence of controllable oxygen-deficient TaO_x nanofilament after switching has been investigated by AES. Furthermore, the device could be operated with a small RESET current of 23 μA. A small nanofilament diameter of 3 nm under a low CC of 80 μA has been calculated using a new method, which has a high memory density of ≈100 Tbit/in.², expected to be very useful for future sub-10-nm applications.

Conclusions

Improvement in resistive switching performance, particularly 10,000 consecutive switching cycles with tight distribution in HRS/LRS of >10^2, long pulse endurance of >10^4, and good data retention of 10^4 s at 85°C, have been achieved under a low CC of 80 μA by exploiting the oxygen-getter nature of a Ti nanolayer in a W/TiO_2/TaO_x/W structure. A small device of 150 × 150 nm^2 and a defective TaO_x film are confirmed by TEM. O^{2-} ion migration because of lower barrier height for electrons leads to a switching mechanism based on filament formation/rapture. The presence of controllable oxygen-deficient TaO_x nanofilament after switching has been investigated by AES. Furthermore, the device could be operated with a small RESET current of 23 μA. A small nanofilament diameter of 3 nm under a low CC of 80 μA has been calculated using a new method, which has a high memory density of ≈100 Tbit/in.², expected to be very useful for future sub-10-nm applications.

Competing interests

The authors declare that they have no competing interests.

Authors’ contributions

AP carried out this research work under the instruction of SM. Fabrication process was also instructed by HCC and CSL. AES spectra were taken by TCT under the instruction of SM. All authors read and approved the final manuscript.

Acknowledgments

This work was supported by the National Science Council (NSC), Taiwan, under contract numbers NSC-98-2221-E-182-052-MY3, NSC-101-2221-E-182-061, and NSC-102-2221-E-182-057-MY2. The authors are grateful to the Electronic and Optoelectronic Research Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan for their support on W bottom electrode pattern.

Author details

1Department of Electronic Engineering, Chang Gung University, Tao-Yuan 333, Taiwan. 2Material and Chemical Research Laboratories, Industrial Technology Research Institute, Hsinchu 310, Taiwan.

Received: 21 February 2014 Accepted: 4 March 2014 Published: 17 March 2014

References

1. Waser R, Dittmann R, Staikov G, Szot K: Redox-based resistive switching memories - nanoionic mechanisms, prospects, and challenges. Adv Mater 2009, 21:2632.
2. Sawa A: Resistive switching in transition metal oxides. Mater Today 2008, 11:28.
3. Liu Q, Sun J, Lv H, Long S, Yin K, Wan N, Li Y, Sun L, Liu M: Real-time observation on dynamic growth/dissolution of conductive filaments in oxide-electrolyte-based ReRAM. Adv Mater 2014, 22(24):24.
4. Sato Y, Kinoshita K, Aoki M, Sugiyama Y: Reduction in the reset current in a resistive random access memory consisting of NiO, brought about by reducing a parasitic capacitance. Appl Phys Lett 2007, 90:33503.
5. Lee MJ, Lee CB, Lee D, Lee SR, Chang M, Hur JH, Kim YB, Kim CJ, Seo DH, Seo S, Chung UI, Yoo IK, Kim K: A fast, high-endurance and scalable nonvolatile memory device made from asymmetric Ta_xO_y/TaO_x bilayer structures. Nat Mater 2011, 10:625.
6. Yoon J, Choi H, Lee D, Park JB, Lee J, Seong DJ, Ju Y, Chang M, Jung S, Hwang H: Excellent switching uniformity of Cu-doped MoO_x/GdO_y bilayer for nonvolatile memory applications. IEEE Electron Device Lett 2009, 30:157.
7. Prakash A, Malikap S, Lae CS, Lee HY, Chen WS, Chen F, Kao MJ, Tsai MJ: Improvement uniformity of resistive switching parameters by selecting the electroformation polarity in IrO_x/TaO_y/WO_3/W structure. Jpn J Appl Phys 2012, 51:045706.
8. Banerjee W, Malikap S, Lae CS, Chen YY, Tien TC, Lee HY, Chen WS, Chen FT, Kao MJ, Tsai MJ, Yang JR: Formation polarity dependent improved resistive switching characteristics using nanoscale (1.3 nm) core-shell IrO_x nano-dots. Nanoscale Res Lett 2012, 7:194.
9. Yoon JH, Kim KM, Lee MH, Kim SK, Kim GH, Song SJ, Seok JY, Hwang CS: Role of Ru nano-dots embedded in TiO_x thin films for improving the resistive switching behavior. Appl Phys Lett 2010, 97:252904.
10. Lee HY, Chen PS, Liu WH, Wang SM, Gu PY, Hsu YY, Tsai CH, Chen WS, Chen F, Tsai MJ, Lien C: Robust high-resistance state and improved endurance of HfO2 resistive memory by suppression of current overshoot. IEEE Electron Device Lett. 2011, 32:1585.

11. Choi BJ, Jeong DS, Kim SK, Rohde C, Choi S, Oh JH, Kim HJ, Hwang CS, Sato K, Waser R, Reichenberg G, Tredicke S: Resistive switching mechanism of TiO2 thin films grown by atomic-layer deposition. J Appl Phys. 2005, 98:033715.

12. Kwon DH, Kim JM, Kang JH, Jeon JM, Lee MH, Kim GH, Li XS, Park GS, Lee B, Han S, Kim M, Hwang CS: Atomic structure of conducting nanofilaments in TiO2 resistive switching memory. Nat Nanotechnol. 2010, 5:148.

13. Lee SR, Char K, Kim DC, Jung R, Seo S, Li XS, Park GS, Yoo YK: Resistive memory switching in epitaxially grown NIO. Appl Phys Lett. 2007, 91:202115.

14. Long S, Cagli G, Ielmini D, Liu M, Sun J: Reset statistics of NIO-based resistive switching memories. IEEE Electron Device Lett. 2011, 32:1570.

15. Yu S, Guan X, Wong HSP: Conduction mechanism of TiN/HfO2/Pt resistive switching memory: a trap-assisted-tunneling model. Appl Phys Lett. 2011, 99:063507.

16. Chen YY, Goux L, Clima S, Govoreanu B, Degraeve R, Kar GS, Fantini A, Chen LJ, Chueh YL: Bipolar resistive switching memory using bilayer TaOx/WOx films. Nat Nanotechnol. 2010, 5:1570.

17. Wei Z, Kanzawa Y, Annta K, Kato H, Kawai M, Murakoa S, Mitani S, Fujii S, Katayama K, Iijima M, Mikawa T, Ninomiya T, Miyanga R, Kawashima Y, Tsuji K, Himeno A, Okada T, Azuma A, Shimakawa K, Sugaya H, Takagi T, Yasuhara R, Honba K, Kugisahira H, Oshma M: Highly reliable TaOx/ReRAM and direct evidence of redox reaction mechanism. Tech Dig - Int Electron Devices Meet. 2008, 283:293.

18. Prakash A, Maimak S, Lai CS, Tien TC, Lee HY, Chen WS, Chen F, Kao MJ, Tsai MJ: Enhanced resistive switching memory characteristics and mechanism using a Ti nanolayer at the Cu/TaOx interface. Nanoscale Res Lett. 2012, 7:295.

19. Lee HY, Chen PS, Liu WH, Wang SM, Gu PY, Hsu YY, Tsai CH, Chen WS, Chen F, Tsai MJ, Lien C: Robust high-resistance state and improved endurance of HfO2 resistive memory by suppression of current overshoot. IEEE Electron Device Lett. 2011, 32:1585.

20. Prakash A, Maimak S, Lai CS, Tien TC, Chen WS, Lee HY, Chen FT, Kao MJ, Tsai MJ: Excellent resistive memory characteristics and switching mechanism using a Ti nanolayer at the Cu/TaOx interface. Nanoscale Res Lett. 2012, 7:295.

21. Chiu FC, Li PW, Wang CY, Wong HSP: Conduction mechanism of TiN/HfO2/Pt resistive switching memory: a trap-assisted-tunneling model. Appl Phys Lett. 2005, 98:033715.

22. Schomburg S, Griesheim K, Tredicke S: Resistive switching mechanism of TiO2 thin films grown by atomic-layer deposition. J Appl Phys. 2005, 98:033715.

23. Kwon DH, Kim JM, Kang JH, Jeon JM, Lee MH, Kim GH, Li XS, Park GS, Lee B, Han S, Kim M, Hwang CS: Atomic structure of conducting nanofilaments in TiO2 resistive switching memory. Nat Nanotechnol. 2010, 5:148.

24. Lee SR, Char K, Kim DC, Jung R, Seo S, Li XS, Park GS, Yoo YK: Resistive memory switching in epitaxially grown NIO. Appl Phys Lett. 2007, 91:202115.

25. Long S, Cagli G, Ielmini D, Liu M, Sun J: Reset statistics of NIO-based resistive switching memories. IEEE Electron Device Lett. 2011, 32:1570.

26. Yu S, Guan X, Wong HSP: Conduction mechanism of TiN/HfO2/Pt resistive switching memory: a trap-assisted-tunneling model. Appl Phys Lett. 2011, 99:063507.

27. Chen YY, Goux L, Clima S, Govoreanu B, Degraeve R, Kar GS, Fantini A, Groesenneken G, Wouters DJ, Jurczak M: Endurance/retention trade-off on HfO2/metal cap 1T1R bipolar ReRAM. IEEE Trans Electron Devices. 2013, 60:1114.

28. Prakash A, Maimak S, Lai CS, Tien TC, Lee HY, Chen WS, Chen F, Kao MJ, Tsai MJ: Excellent resistive memory characteristics and switching mechanism using a Ti nanolayer at the Cu/TaOx interface. Nanoscale Res Lett. 2012, 7:295.

29. Lee HY, Chen PS, Liu WH, Wang SM, Gu PY, Hsu YY, Tsai CH, Chen WS, Chen F, Tsai MJ, Lien C: Robust high-resistance state and improved endurance of HfO2 resistive memory by suppression of current overshoot. IEEE Electron Device Lett. 2011, 32:1585.

30. Prakash A, Maimak S, Lai CS, Tien TC, Chen WS, Lee HY, Chen FT, Kao MJ, Tsai MJ: Excellent resistive memory characteristics and switching mechanism using a Ti nanolayer at the Cu/TaOx interface. Nanoscale Res Lett. 2012, 7:295.

31. Chiu FC, Li PW, Wang CY, Wong HSP: Conduction mechanism of TiN/HfO2/Pt resistive switching memory: a trap-assisted-tunneling model. Appl Phys Lett. 2005, 98:033715.