Interface engineered HfO$_2$-based 3D vertical ReRAM

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Received 16 February 2016, revised 25 March 2016
Accepted for publication 4 April 2016
Published 29 April 2016

Abstract

We demonstrate a double-layer 3D vertical resistive random access memory (ReRAM) stack implementing a Pt/HfO$_2$/TiN memory cell. The HfO$_2$ switching layer is grown by atomic layer deposition on the sidewall of a SiO$_2$/TiN/SiO$_2$/TiN/SiO$_2$ multilayer pillar. A steep vertical profile was achieved using CMOS-compatible TiN dry etching. We employ in situ TiN bottom interface engineering by ozone, which results in (a) significant forming voltage reduction which allows for forming-free operation in AC pulsed mode, and (b) non-linearity tuning of low resistance state by current compliance during Set operation. The vertical ReRAM shows excellent read and write disturb immunity between vertically stacked cells, retention over $10^4$ s and excellent switching stability at 400 K. Endurance of $10^7$ write cycles was achieved using 100 ns wide AC pulses while fast switching speed using pulses of only 10 ns width is also demonstrated. The active switching region was evaluated to be located closer to the bottom interface which allows for the observed high endurance.

Keywords: ReRAM, V-RRAM, resistive-switching, HfO$_2$, TiON, ozone, filament

Online supplementary data available from stacks.iop.org/JPhysD/49/215102/mmedia

(Some figures may appear in colour only in the online journal)
Additionally, using a selector in series with a ReRAM cell (1S1R design) would short the neighbouring stacked cells in V-RRAM through the conductive vertical middle electrode, so the implementation of high non-linearity (NL) ReRAM cells in a selector-less (1R) cross-point V-RRAM design is essential for preventing the sneak-current issue [14].

HfO2 has been thoroughly studied as a promising ReRAM material and HfO2/TiN-based ReRAM devices still attract considerable attention [15–21] showing reliable switching characteristics even in extremely scaled 10 × 10 nm cells [6]. The switching mechanism in HfO2-ReRAM was confirmed by several thorough studies as an oxygen-vacancy (V O) mediated filamentary resistive-switching [21, 22]. A double-layer V-RRAM device has been recently reported [23], fabricated in a trench configuration with planar Pt bottom electrodes, ALD HfO2 and TiN top electrodes. Besides numerous excellent characteristics of this device, authors also claim its non-linear current–voltage (I–V) curve makes it suitable for an application in a 1R array [24] and ascribe this NL to the TiO interfacial layer engineering at the top electrode. Many other works on HfO2/TiN-based ReRAM also emphasize the important role of this interlayer acting as oxygen reservoir [15, 24, 25].

One remaining challenge for the filamentary ReRAM device integration is the necessity of the forming operation [2], i.e. soft breakdown of a pristine device (first Set), typically occurring at voltages much higher than subsequent Set and Reset events during stable operation [23] and usually requiring a current compliance (CC) to protect the device from an irreversible (hard) breakdown. Previous studies have shown that tight control of the forming conditions indeed has a direct relation to the performance and reliability of the ReRAM devices, but on the other hand, the stochastic nature of filament formation makes the forming process a phenomenon which can be controlled only in a limited manner [26]. Different technological approaches are being researched in order to either overcome the necessity of forming completely, or at least to reduce the forming voltage (V F) to a range compatible with subsequent operation voltages. These approaches for HfO2 ReRAM include:

- doping the oxide with another element which promotes the VO formation, like aluminium [27],
- doping the oxide with VO directly, i.e. creating a VO profile desirable for a forming-free operation technologically, either using a reduction treatment like annealing during or after deposition [25] or depositing an oxygen exchange layer (OEL) like Ti or Hf between the oxide and one of the electrodes [28],
- scaling the thickness of the oxide, often to the limits of a reliable operation [29].

In this work, we have fabricated and characterized a double-layer V-RRAM stack with Pt/HfO2/TiN memory cells where a 5 nm thick HfO2 switching layer is deposited on the sidewall of TiN wordlines (bottom electrodes) by ALD. A steep vertical profile of the wordline stack has been obtained by conventional dry etching methods. We have achieved significant reduction of the DC forming voltage (V F) by utilizing an in situ O3 pre-treatment of the TiN bottom electrode prior to HfO2 ALD. The most significant outcome is the forming-free operation in the AC pulsed mode. Also, the non-linearity of the low resistance state (LRS) of the O3 pre-treated samples can be tuned by applying CC during Set. This work paves the way to the realization of a 1R high-density V-RRAM array. The devices show stable bipolar resistive-switching (BRS), zero top-to-bottom cell interference, stable retention trend over 104 s at 400 K, AC pulsing endurance over 106 cycles with stable memory window and fast 10 ns switching speed. We also discuss the behaviour of the filamentary switching mechanism where the active switching region is confined near the TiN bottom interface.

2. Methods

The fabrication flow of the prepared devices is depicted in detail in figure 1. First, a SiO2/TiN/SiO2/TiN/SiO2 multilayer was deposited by sputtering with each layer being 100 nm thick, on a wafer with a 550 nm thick SiO2 layer used as a substrate. For etching of a dog bone-shaped pillar structure (figure 1(a)) defined by the first photolithography mask, a CMOS-compatible TiN dry etching using HBr and CCl4 etchants was used to etch TiN and SiO2 layers, respectively, until the SiO2 substrate layer was exposed. This structure had two stacked TiN wordlines (bottom electrodes) of the ReRAM structure separated (and covered) by SiO2 isolation layers. Then, a 5 nm thick HfO2 switching layer was deposited by ALD (Beneq TSF-200) using 70 cycles of the TEMAHf precursor and ozone at 300 °C, as shown in figure 1(b). More details on the ALD process can be found in ref. [19]. Selected samples were in situ pre-treated by 30 ozone-only cycles prior to HfO2 deposition in order to alter the chemical state of the TiN bottom electrodes, later in text marked as O3–TiN cells (samples without treatment marked as TiN-cells). Next, active areas for the vertical Pt top electrode (bitline) were defined by the second photolithography mask. A 30 nm thick Pt layer was deposited by vacuum evaporation using an electron gun, then capped by Au of 30 nm in the same chamber and finally patterned by a lift-off procedure (figure 1(c)). Different line widths of top electrodes were defined, in the range of 4–100 μm. Thus, the active area of the smallest cell was 0.4 μm2 and was defined by HfO2 sandwiched between a 100 nm thick TiN wordline sidewall and a vertically running 4 μm wide Pt bitline. Finally, contact openings for both TiN bottom electrodes had to beetched using a similar dry etching procedure and two photolithography masks (figures 1(d) and (e)). The third mask was used for etching both contact openings until the upper TiN layer (top cell’ s bottom electrode) and the fourth mask was used to etch one of the contacts to the bottom TiN layer (bottom cell’s bottom electrode). The finalized V-RRAM structure is depicted in figure 1(c) with a cross-section sketch displayed in figure 1(f). Transmission electron microscopy (TEM) images were acquired using 26.5 and 530 kV accelerating voltage and the TEM cross-section specimen was prepared by focused ion beam (FIB). X-ray Photoelectron Spectroscopy (XPS) signals were recorded using a Thermo
Scientific K-Alpha XPS system (Thermo Fisher Scientific, UK) equipped with a micro-focused, monochromatic Al Kα x-ray source (1486.6 eV). Thermo Scientific Avantage v5.954 software and XPS Knowledge Base (Thermo Fisher Scientific, UK) were used for digital acquisition and data processing. Spectral calibration was determined by using the automated calibration routine and the internal Au, Ag and Cu standards supplied with the K-Alpha system. For the electrical characterization, HP 4156B semiconductor parameter analyser (SPA) was used for measuring DC I–V characteristics, and Agilent B1500A equipped with a waveform generator fast measurement unit (WGFMU) was used for the AC measurements in every-cycle-read mode. For the testing of AC pulsed endurance, HP 8110 A pulse generator (PG) was used. All the results in this article are presented for the case where the Pt top electrode was biased while the TiN bottom electrodes were grounded unless otherwise mentioned.

3. Results

3.1. Material analysis

As mentioned in the Introduction, a V-RRAM device similar to ours has been recently reported [23], fabricated in a trench configuration with an opposite order of MIM layers, utilizing planar Pt bottom electrodes, ALD HfO2 and TiN top electrodes. It is well-known that Pt is difficult to etch due to its inert nature. On the other hand, TiN is an industry standard electrode material and can be patterned by a CMOS-compatible dry etching processes. Therefore, a much steeper vertical profile of the SiO2/TiN/SiO2/TiN/SiO2 multilayer pillars was achieved in this work using a transformer coupled plasma (TCP) dry etching, as shown in the cross-section TEM image of the fabricated 3D vertical ReRAM stack structure (figure 2). We assume that the air gap visible on the TEM image between the Au capping layer and Pt top electrode was formed during TEM specimen preparation by FIB. More importantly, the Pt top electrode layer shows continuous coverage over HfO2 throughout the entire pillar profile. The inset of figure 2 shows the magnified high-resolution image of the conformally deposited 5 nm thick amorphous ALD HfO2 conformally deposited on the sidewall of the stacked wordline pillar.

XPS was performed to clarify the effect O3 treatment on TiN. First, we analysed two blanket TiN films: one treated by O3 in the ALD chamber and one which was loaded and unloaded in the heated ALD chamber but not treated with O3. The resulting surface spectra are shown and described in figure 3. Clearly, in O3-treated film, an increased amount of oxidized TiN and lower carbon contamination were detected.

Figure 1. Fabrication process flow of a double-layer V-RRAM stack fabricated in this work: (a) SiO2/TiN/SiO2/TiN/SiO2 multilayer dry etching, (b) HfO2 ALD (with in situ O3 pre-treatment), (c) lithography, deposition and lift-off of Pt top electrodes, (d) etching of the contact openings till the upper TiN wordline, and (e) finalized structure after etching of the contact opening to the bottom TiN wordline. (f) Sketch of the cross-section of the double-layer V-RRAM stack showing the location of the top and bottom Pt/HfO2/TiN ReRAM cells.

Figure 2. Cross-section TEM image of the double-layer V-RRAM stack showing a steep vertical profile. Active area of both (top and bottom) Pt/HfO2/TiN memory cells is defined between vertically running Pt bitline and the sidewall of planar 100 nm thick TiN wordlines. Inset shows the magnification of the 5 nm thick amorphous ALD HfO2 conformally deposited on the sidewall of the stacked wordline pillar.
in both N 1s and O 1s spectra, as well as higher TiO2 content in O 1s and Ti 2p spectra. The assignment of the peaks is consistent with other reports [37, 38]. This result suggests that TiN treated with an optimized dose of O3 prior to HfO2 ALD can form a TiO2Nx interfacial layer (TiON) with a critical oxygen composition, which can have numerous beneficial effects on the BRS characteristics of the HfO2-based ReRAM cells, as discussed later in this work. In-operando hard XPS analyses have shown that increased carbon content in HfO2 films can have negative impacts on the ReRAM endurance [37], so its reduction during O3-treatment can also be one of the reasons of the good switching endurance achieved in this work. To get more insights we also deposited and analysed a thin, ~3 nm HfO2 films on TiN with and without in situ O3-treatment. Spectra from HfO2 surface were almost identical (not shown) and spectra after Ar ion dry etching of the topmost ~2 nm revealed small differences (figure S1 of SD) consistent with findings from TiN surface scans.

### 3.2. Improvement of the ReRAM cell characteristics by using O3 pre-treatment

Typical DC I−V curves of the O3−TiN ReRAM cells (fabricated using O3 pre-treatment) are shown in figure 4. Cells show BRS behaviour in a clockwise direction (CW, negative Set and positive Reset), as is typical in this kind of structure [15, 19, 23]. There are several notable differences in comparison to the TiN-cells (fabricated without O3 pre-treatment):

First, in the DC I−V sweep mode, the average value of $V_F$ of the O3−TiN cells was reduced to $-1.6$ V as compared to $-4.3$ V of the TiN cells (which also show higher statistical variation), as shown in the inset of figure 4. This is very close to the actual Set voltage (post-forming operation), which is around $-1.0$ V for both types of cells. The reduction of the $V_F$ for the O3−TiN cells was accompanied by the significant increase of the current flowing through the pristine cell for $V < V_F$. Although this current was still lower than the HRS current of the formed sample (figure 4), the pristine current of the TiN cells was in the $\sim$μA range (figure S2), as is typical for an ALD-grown HfO2 [23, 29].

Second, the TiN cells after forming show high conductivity with ohmic character and a Reset current in the order of several mA, which is independent of the forming CC. Also, the Reset voltage of this first Reset sweep was typically higher compared to a Reset during stable BRS operation. This behaviour was reported in the literature by others [15, 30] and has been ascribed to the current overshoot during the forming due to the discharge of parasitic capacitances or to the inefficient current limitation in combination with the relatively high electric fields applied to the cell during forming [31, 32]. On the other hand, the lower $V_F$ of the O3−TiN cells results in a less dramatic current overshoot. Consequently, the O3−TiN cells do not require higher voltage for the first Reset and the conductivity of their first-LRS can be limited by the CC applied during the forming. In the same manner, during subsequent stable BRS operation the LRS conductivity is controlled by the Set CC, both in the O3−TiN cells as shown in figure 5, as well as in the TiN cells, as we have shown previously [29, 33]. The typical DC I−V curves for forming, first Reset and subsequent stable CW BRS operation of the TiN cells are included in the SD, figure S2.

Third, if sufficiently low Set CC ($\leq 0.5$ mA) is applied, the LRS of the O3−TiN cells shows pronounced non-linear character (figure 4), as compared to the TiN cells which show ohmic (linear) character of the LRS even when low Set CC is used (figure S2) [29, 33]. NL of the LRS is a highly desired property for the selector-less memory array design to cope with the sneak current issue [34]. The non-linearity is defined as

$$\text{NL} = \frac{I(V_{\text{READ}})}{I(V_{\text{READ}}/2)}$$

[35]. In this work, the highest NL = 8 for the O3−TiN cells was achieved under the Set CC = 0.3 mA and $V_{\text{READ}} = 0.8$ V (corresponding I−V curves in linear scale and NLS for different $V_{\text{READ}}$ and CC are shown in the figure S3 of SD). Simulation results by Chen et al [36] suggest that a Mb-sized selector-less array is achievable using reversely designed TiN/HfO2/Pt cells, with lower NL than our cells but higher $R_{\text{ON}}$ (lower operation currents). The NL of their cells is ascribed to the TiON interfacial layer intentionally sputter-deposited under the TiN top electrode [23, 36].

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**Figure 3.** Surface XPS spectra of the TiN films with (blue circles) versus without (red triangles) O3 treatment. (a) N 1s spectra show an increased intensity at 396.0 eV assigned to the oxidized TiN, at the expense of the 397.1 eV TiN peak. (b) O 1s spectra also shows higher 531.8 eV oxidized TiN peak as well as higher TiO2 content (530.0 eV peak) for O3−TiN. Carbon contamination (532.6 eV) is lower after O3 treatment. (c) Among minor differences, Ti 2p spectra also shows higher 548.7 eV TiO2 peak. A plausible explanation is the TiO2 contribution on the TiN surface during O3 treatment. Solid (dashed) lines represent fitted peaks of O3-treated (untreated) films, respectively. The background (dash-dotted line) was subtracted.
3.3. Performance of the O3-TiN V-RRAM

In this part we evaluate the performance of the prepared double-layer V-RRAM stacks employing the O3-TiN cells. We have measured the cells in a self-compliant regime, i.e., without applying any Set CC. Although the non-linear LRS regime induced by the Set CC discussed above seems promising for the selector-less memory array applications, testing the devices in a self-compliant, high-current linear LRS regime puts the stack under higher electrical stress and provides more insights on the evaluation of cycling stability and cell-to-cell interference.

Figure 5 shows fifty exemplary DC I–V BRS cycling loops measured at the room temperature on two adjacent V-RRAM cells stacked under the same shared 4 µm wide Pt bitline. Both cells show very reproducible switching loops with negative Set and positive Reset, but compared to each other, the I–V curves of the top cell show slightly wider current distributions. Based on the measurements on many different devices we ascribe this to intrinsic cell-to-cell variations between different ReRAM cells (irrespective if top or bottom), which are inevitably present due to the stochastic nature of the filament formation and rupture.

To evaluate the concurrent operation of the adjacent stacked V-RRAM cells a following measurement procedure was instrumented. With the shared Pt bitline grounded and top and bottom TiN wordlines (separated by 100 nm SiO2) biased, we have been testing the write and read disturb immunities by cycling (RS) the top cell (TC) ten times while the bottom cell (BC) was first in HRS, then switched to LRS and the TC was cycled (RS) for another 10 times. Afterwards the cells switched their roles with BC being cycled (RS) while TC was in HRS first, then switched to LRS, both for 10 cycles. The resulting characteristics are shown in figure 6, showing robust read/write disturb immunity of the adjacent cells with no measurable cell-to-cell interference and at least 10 × memory window (IHS/IHRS), both for the room temperature (300 K) measurement as well as for the cycling under elevated temperatures at 360 and 400 K. What is noteworthy however, is a slight increase of the LRS currents and a wider distribution of the HRS currents with temperature. This can be also seen in figure 7 where the read-out current cumulative probability distributions are summarized for 50 DC I–V loops measured at 300 and 400 K for both top and bottom cells.

We explain these variations by an increased mobility of mobile oxygen species (ions/Vo) in the film at elevated temperatures, leading to (a) filament growing slightly thicker in diameter during Set, and thus to a slightly more conductive LRS, and, (b) faster re-oxidation (shrinking) of the filament during Reset leading to a thicker insulating gap governing the current flow in the HRS, and thus to a more insulating HRS with higher cycle-to-cycle variations (see also section 4 Discussion).

The retention of memory states was also measured at the elevated temperature for both cells, showing no trace of the memory window shrinkage (figure 8). This robust behaviour is typical for a good filamentary ReRAM device [23] and is required for the non-volatile memory application.

The reduced Vf of the O3-treated devices mostly benefits the AC pulsed operation, where no forming nor DC training of the devices is necessary for stable operation. As the pulse amplitudes employed during the fast AC pulse switching are typically higher than the Set, Reset and Vf voltages used during DC I–V sweeps, these devices can operate stably without the forming procedure, as shown in figure 9(a), where 30 ns wide switching pulses were used with amplitudes of −2.5 V for Set and +3.8 V for Reset. The data shown in this figure were acquired by a high precision WGF MU (see Methods) with read-out after every switching pulse. Higher
fluctuation of the HRS current during switching reflects the cumulative probability distributions obtained in DC cycling (figure 7). The memory window of at least $\sim 10 \times$ was maintained with zero unsuccessful writes out of $10^3$ Set/Reset cycles recorded.

To investigate the endurance, we have employed the PG to cycle the device with a series of logarithmically increasing number of Set/Reset pulses, while the state was read by SPA in between series. Due to a non-ideal impedance matching of the PG and the device, the pulses sensed by the device might have been slightly different to a measurement with WGFMU so pulses of 100 ns width had to be utilized in this measurement. The endurance data gathered can be seen in figure 9(b).

The device shows stable switching with a memory window of $\sim 10 \times$ up to $10^6$ cycles after which there has been one false Set operation recorded and the memory window started to shrink down to $\sim 3 \times$ in the order of $10^7$ operations. The device remains operable however and didn’t breakdown. We expect that using a dedicated switching-control circuit and/or fine-tuning of the pulsing operation scheme can lead to an even higher endurance [23].

Finally, we have investigated the ultimate switching speed, again using WGFMU. As we narrowed both Set and Reset pulses down to 10 ns width, the Set pulse amplitude could have been kept at $-2.8$ V but the Reset pulse amplitude had to be increased to $+4.7$ V in order to maintain the memory window over $10 \times$, as shown in figure 9(c). Lower read-out currents in this case are due to the read-out voltage reduced to 0.3 V in order to minimize a possible read disturb in this ultra-fast switching range. The trade-off between switching speed and $V_{RST}$ is plotted in figure S4 of SD.
Different mobilities and redox rates of O in systems with and TiN/Ti/HfO$_2$/TiN [6, 37] stacks. Reports on stacks employing OEL metals (Ti, Hf, Zr). Different studies on Pt/HfO$_2$/Ti [15, 18, 23–25, 41] and TiN/HfO$_2$/TiN [20, 45–47] stacks suggest that polarity of stable BRS is related to the details in technology and/or forming process polarity. As the active region location determination is crucial for the reliable ReRAM design and the $V_F$ and accompanying current overshoot are minimized in our O$_3$–TiN cells, these indeed provide a valuable source for these evaluations.

4. Discussion

In this work we have studied 3D and planar ReRAM cells with active areas in a range of 0.4–10$^4$ $\mu$m$^2$. The switching currents were independent on the cell area, as shown in figure S5 of SD, in accordance with the valence change mechanism (VCM) [2]. Here the switching is driven by $V_O$ generation, migration and resulting filament formation/rupture (Set/Reset) under the applied electric field, while a pre-existent $V_O$ profile in the oxide layer is highly favourable for stable BRS [39]. This can be achieved using a deliberate oxygen exchange layer (OEL) such as Ti (or Hf) like in reports on Pt/HfO$_2$/Ti [39–41] and TiN/Ti/HfO$_2$/TiN [6, 37] stacks. Reports on stacks employing OEL typically agree that under stable BRS a conical filament grows from the OEL side, with the active region where connection/rupture takes place being closer to the inert electrode (Set cathode). This rather simplified assumption finds support in studies employing more detailed physical models [18] as well as direct nanoscale filament observations [21, 22].

A recent experimental study utilizing a semiconducting electrode, monitoring minority carriers [42] found that in OEL-containing stacks the filament base is always located on the OEL side, as the $V_O$ concentration in the TiON layer is not percolated and provides for the observed NL of the LRS. Loosely bound oxygen anions stored in TiON layer is not percolated and provides for the observed NL of the LRS. These findings were well reasoned by different mobilities and redox rates of $V_O$ in systems with and without OEL [43].

The case of TiN electrode is more peculiar, as its oxygen affinity is higher than that of Pt but lower than that of typical OEL metals (Ti, Hf, Zr). Different studies on Pt/HfO$_2$/TiN [15, 18, 23–25, 44] and TiN/HfO$_2$/TiN [20, 45–47] stacks suggest that polarity of stable BRS is related to the details in technology and/or forming process polarity. As the active region location determination is crucial for the reliable ReRAM design and the $V_F$ and accompanying current overshoot are minimized in our O$_3$–TiN cells, these indeed provide a valuable source for these evaluations.

Following observations were made in this work:

- Ozone treatment of TiN leads to a significant $V_F$ reduction (inset of figure 4) and increase of the virgin leakage (forming curve in figures 4 versus S2).
- Resistance of the LRS can be controlled by CC during Set in both TiN and O$_3$–TiN cells, however TiN-cells require higher voltage (and current) for the 1st Reset (figure S2).
- Moreover, the Set with CC ≤ 0.5 mA in the O$_3$–TiN cells leads to NL LRS (figures 4 and S3) while higher (or no) CC yields linear LRS.
- Reset of the linear LRS obtained with high (or no) CC has two parts, steeper and gradual, marked as I. and II. in figure 4, respectively.
- In a virgin (pre-forming) state ($V < V_F$), where the current follows the area-dependence ($J \propto \text{const}$.), some devices show an unstable BRS with opposite (CCW) switching polarity, and from this state a sample can be formed into the HRS using positive $V_F$ without CC, as shown in figure S6, consistent with similar observations by other authors [48, 49].

These observations can be explained by the switching model with filament growing from the Pt side as a virtual cathode during Set, as sketched in figure 10. While the detailed discussion can be found in the SD (section 5), here we mention a few cornerstones of our representation. Significant reduction of the $V_F$ of the O$_3$–TiN cells is related to the delicate concentration of the $V_O$ in the TiON layer which is only partially oxidized, providing enough mobile $V_O$ to the HfO$_2$ during the negative forming to LRS [42] and serving as an oxygen sink at the same time. This layer remains relatively conductive with little voltage drop if low CC is used. Therefore, the TiON layer is not percolated and provides for the observed NL of the LRS. Loosely bound oxygen anions stored in TiON
during Set are utilized for smooth oxidation of the filament tip during Reset providing for the observed stable BRS with gradual Reset. In our earlier study [50], depositing an ultrathin stoichiometric TiO$_2$ in situ by ALD instead of TiON led to an abrupt, stochastic Reset with high span of $V_{RST}$, ascribed to the unavailability of the loosely bound oxygen species for the filament re-oxidation.

Finally, having an active switching region near the Pt top electrode might result in a serious reliability/endurance issues, as in such a case oxygen from the atmosphere (even moisture) is actively involved in the switching, through the oxygen-permeable Pt electrode [44, 51]. However, endurance of over $10^7$ cycles was shown in this work and even higher numbers were reported by others on analogical stack [23], further supporting the model with active region closer to the bottom electrode, more specifically to the HfO$_2$/TiON interface, as shown in figures 10(d) and (e) and in line with [24].

5. Conclusion

We have fabricated and characterized a double-layer 3D V-RRAM stack by implementing a Pt/HfO$_2$/TiN memory cell. The cell was prepared using an ALD-grown HfO$_2$ switching layer on the sidewall of SiO$_2$/TiN/SiO$_2$/TiN/SiO$_2$ multilayer pillar. A steep vertical profile was achieved using CMOS-compatible TiN dry etching. Prior to HfO$_2$ ALD, an in situ TiN bottom interface engineering by ozone was employed, which resulted in (a) significant forming voltage reduction allowing forming-free operation in AC pulsed mode, and (b) LRS non-linearity tuning by CC during DC operation. This behaviour is correlated with the TiO$_2$N$_x$ layer in situ formed during the O$_2$ pre-treatment and serving as an oxygen vacancy reservoir. The V-RRAM stack shows immunity against read and write interferences between vertically stacked cells. The retention of the memory states of over $10^4$ s and excellent switching stability are also shown, both at 400 K. Using 100 ns wide AC pulses we demonstrate endurance of over $10^7$ while switching speed using pulses of only 10 ns width is also shown. Finally, we discuss the switching mechanism which is concluded to be filamentary switching governed by oxygen vacancies with the active region confined near the bottom electrode interface.

Acknowledgments

This work was supported by Ministry of Science and Technology of Taiwan, Republic of China, under Grant NSC 102-2221-E-009-188-MY3, Winbond Electronics Corp. and VEGA project 2/0138/2014. B Hudec acknowledges the financial support of the International Visegrad Fund. T-H Hou acknowledges support in part by NCTU-UCB I-RiCE program, under Grant MOST 105-2911-I-009-301.

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