Influence of magnetic field on the operation of TiN/Ti/HfO₂/W resistive memories

D. Maldonado¹, A. M. Roldán¹, M. B. González², F. Jiménez-Molinos¹, F. Campabadal², J. B. Roldán^{1*}

¹*Departamento de Electrónica y Tecnología de Computadores, Universidad de Granada. Facultad de Ciencias. Avd. Fuentenueva, s/n, 18071, Granada, Spain.*

²*Institut de Microelectrònica de Barcelona, IMB-CNM (CSIC), Campus UAB, 08193 Bellaterra, Spain.*

E-mail address of corresponding author: jroldan@ugr.es

Abstract

A characterization process for resistive RAM (RRAMs) based on TiN/Ti/HfO₂/W stacks has been performed. In addition to conventional electrical measurements, the effects of the magnetic field (MF) have also been considered. The influence of the Lorentz force on resistive switching (RS) processes and on the device conduction was explored both in the Low Resistance State (LRS) and in the High Resistance State (HRS). The MF influences the set/reset voltages and current distributions, spreading the range of current values obtained in a long RS series of successive set and reset cycles and modifying set voltage values. For the reset voltage, the influence is less significant than the cycle-to-cycle variability.

Keywords: Magnetic field effects; RRAM; Resistive switching; Set voltage; Reset voltage.

1. Introduction

Resistive random access memories (RRAM) devices have shown great possibilities for applications related to non-volatile memories, neuromorphic circuits and physical unclonable functions implementation [1-8]. RRAM new designs consume much less power than traditional non-volatile NAND flash memories. In addition, read and writing speeds are higher and their technology is CMOS compatible. The scaling possibilities as well as the potential for

building 3D structures based on crossbar architectures are also of great interest [1-4]. Nevertheless, the full-scale industrial use of this technology has faced several hurdles such as variability, lack of simulation and modeling tools, etc. In this respect, different facets of resistive switching (RS) physics have not been explained yet completely; therefore, there are outstanding research efforts going on [1, 3-10]. In this context, new characterization techniques are needed. Moreover, although in the last few years different

* Corresponding author. Tel.: + 34 958244071;
E-mail address: jroldan@ugr.es (J.B. Roldán)

results in relation to RRAM physical simulations and modeling have been published [1, 6-7, 11-17], greater efforts should be put to develop accurate and easy-to-use physical simulation tools and reliable compact models for circuit simulation.

In this manuscript we show the main results of RRAM characterization employing different magnetic fields (MFs). The use of MFs presents an advantage from the characterization viewpoint since it adds a new control variable. We have performed conventional electrical RS measurements [7, 18] while the devices are under the effects of a controlled MF perpendicular to the charge conduction direction. Different reports related to characterization including MF effects have been presented previously [19-24]. In general, these studies [21-23] show a shift of the transition voltages (set and reset voltages) towards higher absolute values. These works are based on devices made of different materials, among them only one has been performed on RRAMs with HfO_2 as dielectric [19], although this oxide shows promising RS performance both for non-volatile memories [3] and for mimicking biological synapsis in the context of neuromorphic circuits [25]. We have focused our study on HfO_2 devices; in particular, we studied the conduction levels as well as the set and reset voltages and currents (extracted as reported in Ref. [17]) for different MFs both in the HRS and LRS.

Some of the studies devoted to analyze MF effects used high MFs (several thousands Oe). However, in our case we chose lower MFs; this is a more representative situation, closer to real cases of multifunctional devices whose operation would be modulated by different physical variables (electric field, magnetic field or light intensity [23]), as it is the case of some sensor devices.

In Section 2 of this paper, the device and measurement process are described. Section 3 is devoted to explain and discuss the main results and, finally, the main conclusions are drawn in Section 4.

2. Device fabrication and measurement

The field-oxide isolated $\text{TiN}/\text{Ti}/\text{HfO}_2/\text{W}$ devices were fabricated on an N-type ($\rho = 4 \text{ m}\Omega\cdot\text{cm}$) silicon wafer. First, a Ti adherence layer (20nm-thick) was deposited on the silicon substrate, and subsequently, a 50 nm-thick W film was deposited. The 10 nm-thick HfO_2 layer was grown by ALD at 225°C using TDMAH

and H_2O as precursors and N_2 as carrier and purge gas. The top metal electrode consists of a 200 nm-thick TiN and 10nm-thick Ti scavenging layer. The electrical contact to the bottom electrode is made through the aluminum-metallized back of the silicon wafer. The resulting $\text{TiN}/\text{Ti}/\text{HfO}_2/\text{W}$ structures are square-shaped with an area of $15\times 15 \mu\text{m}^2$.

The current-voltage (I-V) measurements were performed by means of a semiconductor parameter analyzer. The voltage was applied to the TiN/Ti top electrode, while the bottom electrode was grounded. A forming process was needed prior to the long RS series measurement with a current compliance of 0.1 mA. These series were programmed with a Matlab software tool that controls the instrumentation via GPIB. The voltage ramp employed was 0.15 V/s and the voltage step was 0.02 V.

Figure 1. Measurement set-up. (a) Side view, the wafer is placed between Helmholtz coils that produce a nearly uniform magnetic field. (b) Top view, the MF created is perpendicular to the charge current direction.

The MF was generated by two Helmholtz coils (Figure 1), which are driven by a programmable current source. Sequences of 50 RS cycles were carried out at the same MF. Between the sequences of 50 RS cycles with a given MF value, 50 RS cycles were measured without an applied MF in order to allow comparison. In Figure 2 we show the magnetic field values applied during the whole experiment. By considering RS cycles for null magnetic field between every two

different MF values, a representative comparison of the results can be performed.

Figure 2: Applied magnetic field sequence for the 450 set/reset cycles measured during the experiment. The MF is increased in 50 Oe steps (from 0 Oe to 200 Oe) and between each MF value considered, 50 RS cycles were measured without MF.

Figure 3: Experimental I-V curves for 450 set/reset cycles. The MF is increased in 50 Oe steps (from 0 Oe to 200 Oe) and between each MF value considered, 50 RS cycles are measured without MF. Figure 2a shows the 250 curves measured without MF (after applying a MF value shown in

the legend), while Figure 2b shows the 200 curves obtained when applying a specific MF value.

3. Results and discussion

Figure 3 shows the measured I-V curves. Curves obtained at 0 Oe after applying a specific MF are shown in Figure 3a, while those obtained under different MFs have been plotted in Figure 3b. As can be seen, the MF spreads out the distribution of I-V curves. In order to check if there is any underlying trend, Figure 4 shows the current versus cycle number at different applied voltages.

Figures 4a and 4c show that the MF influences the HRS device resistance: a slight current increase is observed as the MF rises; therefore, the MF effects seem to affect the CF morphology during switching. Notice that the first cycle after MF removal is strongly affected by the previous MF value applied. However, the subsequent cycle-to-cycle variability measured at 0 Oe is again low, pointing out the influence of the MF during RS operation.

In Figure 4b a wider range of current values at HRS is obtained in comparison to Fig. 4c. This situation is different because the voltage considered here is close to the set voltage. At this operation point the CFs are almost formed and the conduction is ohmic.

Figure 4: Experimental HRS and LRS currents measured at different applied voltages: a) 0.2 V, b) 0.6V, c) -0.6V versus cycle number for the whole experiment (curves Figs. 3a and 3b).

The results show that the MF affects the stochasticity of the RS process, as indicated by the increase in set voltage variability. Regarding the LRS, the MF effects are significant, especially for values above 100 Oe. These effects seem to be cumulative, increasing the current cycle-by-cycle mean while the MF is applied (with some points out of this general

trend). However, this effect is not maintained after removing the MF, where the current levels during switching are stable. In addition, it should be noticed that only for the lowest MF values the current remains at the same level after switching off the MF, indicating that MF strongly influences CF morphology and stoichiometry.

Figure 5: Experimental set (a) and reset (b) voltages obtained for each measured cycle for the whole RS series.

Once the MF effect on the current has been shown, we focus on the MF influence on the set/reset currents and voltages. Previous studies performed for much higher MFs (few thousands Oe) have revealed an increase of the reset and set voltage absolute values with the magnetic field increase [21, 23]. These results were obtained for different dielectrics (none of which was HfO_2). Our measurements show different trends (Figure 5 and Figure 6). The set voltage (Figure 5a) and set current (Figure 6a) decreasing trend on the average values is observed when they are plotted cycle-by-cycle under MF effects. Regarding the reset voltage, MF effects are not significant. Nevertheless, it is remarkable that the first cycle of the RS series for

zero MF after the application of 150 Oe and 200 Oe shows an important increase in its absolute value, indicating the influence of the previous applied MF on the filamentary morphology and switching stability. Figure 6b shows the corresponding reset currents during cycling. A clear MF influence on the current levels is obtained for 150 and 200 Oe.

Figure 6: Experimental set (a) and reset (b) currents obtained for each measured cycle in the whole RS series.

Finally, Figure 7 shows the cumulative distribution functions of set/reset voltages and currents. Apart from the general trends commented above, a clear spreading in the measured values is observed under the MF influence in comparison with the corresponding values obtained without applying a MF. Notice that the average value for the 0 Oe curves is clearly affected by the morphological changes due to the previous MF applied.

Figure 7: Cumulative distribution functions for the measured V_{set} , V_{reset} , I_{set} and I_{reset} , parameters with and without applied MF.

4. Conclusions

The influence of the magnetic field (from 0 to 200 Oe) on the operation TiN/Ti/HfO₂/W resistive memories has been investigated. The results show that MF enhances the LRS current level in a cumulative manner in a successive RS cycle series. The HRS

current is also increased on average under MF effects. The set and reset voltages and currents have been also analyzed under MF influence. A decrease in the average value of the set voltages and set current with the cycle number is observed for high magnetic field values. However, The cycle-to-cycle variability of the reset voltages is larger than the influence of the MF in the range assessed, although the corresponding reset currents shows a cycle-by-cycle increase for the higher MF values assessed.

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