Investigation of low current operations in HfO$_2$ and Al$_2$O$_3$-based RRAM stacks

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I. Introduction

Resistive Random Access Memory (RRAM) is a promising new design for future semiconductor non-volatile memories. They show very good downscaling possibilities, high speed, and compatibility with the CMOS process flow used for common circuit fabrication. In order to reduce power consumption, low current operations have been investigated to assess the functionality of the cells in this current range.

II. Working principle and stack description

An RRAM unit cell is composed of an active layer sandwiched between two electrodes (top TE and bottom BE). The cell shows at least two stable states: a low resistance state (LRS) and a high resistance state (HRS), allowing bit storage. The cell can be switched from one state to another upon applying a voltage:
- HRS to LRS operation is called set.
- LRS to HRS operation is called reset.

In HRS, the change of resistance is due to the width change of a conductive filament (CF) bridging both electrodes, composed of oxygen vacancies (V$_{O}$). The conductivity of the CF is determined by the geometry of its narrowest region called constriction. A narrower CF is more resistive because of quantum mechanical confinement. Applying a positive voltage to the TE causes V$_{O}$ pair creation and drift of the mobile O$^-$ to the TE, and a negative voltage causes the O$^-$ to drift back to the constrictor, narrowing it through recombination of O$^-$ into O$_2$. A similar mechanism is assumed to take place in HfO$_2$ cells.

The CF is not present in as-deposited cells. The creation of the CF is called forming. The maximum current experienced during forming $I_{f}$ and during subsequent operations determines the CF geometry and hence the $V_{f}$. The $V_{f}$ and $V_{r}$ of an as-deposited cell and a post-formed cell were used to keep control of the current flow.

Three different stacks were studied. The HF TE Capping layer acts as an oxygen reservoir and scavenges O$_2$ from the active layer, increasing the V$_{f}$ density near the TE.

III. Low current operations (continued)

Moreover A1H2 and A3 show a cell size dependence of HRS resistance levels in SBD (right). This is due to the high resistivity of the CF, close to the leakage resistance of the cell. In H3 the higher scavenging sensitivity results in a more conductive CF outweighing the leakage contribution to the overall current, even in H5.

III.2 Kinetics

At low currents the temperature in the CF is limited, and therefore so is the $O^-$ drift speed. This speed is lower in HfO$_2$. This results in high voltages needed to set the cells in pulse operations. Extrapolation of the pulse traces at different gate voltages yields a pulse width (PW) of about 15 ns for pulse heights lower than 6 V. Very low reset pulse height for A3 cells shows the intrinsic instability of the CF in Al$_2$O$_3$. The slower drift speed is also visible in constant current stress (CCS) tests. The greater increase of the resistive window in A1H5 (Al$_2$O$_3$, 11 nm, HfO$_2$ 5 nm) suggests that the CF is less localized at the interface between the Al$_2$O$_3$ and HfO$_2$ layers in A1H2 cells.

In conclusion the study provided a good insight into the mechanisms involved in low current operations of all stacks. The intrinsically high variability and above all the very slow response of the stacks lead to the conclusion that low currents are not an operational range. The lower power consumption is achieved at the expense of reliability and speed.

IV. Further investigations

IV.1 CF geometry influence

A study of the CF geometry was carried out by applying a negative voltage to the TE to create a filament from the bottom oxide into the cell. The voltage drop in this CF indicates the CF location. A CF located at the interface leads to a higher hysteresis effect.

A3 cells show poor retention under constant voltage stress (CVS). A study of the CF geometry was made before and after CVS tests showed that retention loss during tests was associated with abrupt transition between the constrictor and the rest of the CF. This is presumably due to confined field drop, short constrictions result into abrupt CF rupture.

IV.2 CVS study of Al$_2$O$_3$ (3nm)/Hf (10nm) (A3H10) stacks

As voltage and important temperature influence the cell behavior, their influence has been investigated for A3H10 stacks which shows better retention properties than A3 stacks. The thicker HF capping layer leads to more scavenging and $R_{SET}$ saturation. This saturation level is clearly visible on the current distributions after test. However the increased scavenging does not improve the CF stability in Al$_2$O$_3$.