Impact of the Incremental Programming Algorithm on the Filament Conduction in HfO$_2$-Based RRAM Arrays

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ABSTRACT In this paper, the set operation of HfO$_2$ based 1T-1R arrays is studied by applying incremental step pulse with verify algorithm. To evaluate the impact of the voltage step increment on the conduction mechanism of filaments, the voltage increments between consecutive pulses are varied between 0.05 and 0.4 V. The extracted leakage values after the set operation were discussed in the framework of the quantum point contact model. In the so called low resistive state, the conductive filaments demonstrate a defined signature of conductance quantization.

INDEX TERMS RRAM, HfO$_2$, QPC model, programming algorithm.

I. INTRODUCTION

Resistive Random Access Memories (RRAM) based on HfO$_2$ is one of the most promising technology candidates for replacing Flash memories [1], [2]. This technology has shown fast low-power switching operations, high-integration density [3], [4], and compatibility with CMOS processes [5]. However, an intensive research activity has still to be performed on this innovative technology in order to increase RRAM reliability and performance. After the concept validation on single cells [6], [7], the characterization of array structures is mandatory to bring such technology to a maturity level [8]–[10].

RRAM behavior is based on the electrical modification of the conductance of a Metal-Insulator-Metal (MIM) stack: the Set operation moves the cell into a Low Resistive State (LRS), whereas Reset operation brings the cell back to a High Resistive State (HRS) [8], [11]. In order to control the formation and rupture of the conductive filament (CF), the Incremental Step Pulse with Verify Algorithm (ISPV A) [12]–[14] is applied instead of a simple DC voltage sweep [15]. The drawback of ISPV A guided Set and Reset operations is the increased power consumption per writing cycle. One way to minimize the consumption is to enlarge the incremental voltage steps. For this purpose, a complete study of the voltage increment variation between consecutive pulses on array RRAM devices was performed. The extracted experimental results were analyzed in the framework of the quantum point contact (QPC) model [16].

II. SAMPLES CHARACTERISTICS

The measurements were performed over 4 kbits memory devices organized in 64 pages (rows) each consisting of 64 cells (bits), as Fig. 1 shows including also the peripheral circuitry. Each cell is a 1T-1R RRAM single device constituted by a select NMOS transistor manufactured in 0.25 $\mu$m BiCMOS technology: $W=1.14$ $\mu$m and $L=0.24$ $\mu$m. Such a transistor also sets the current compliance, whose drain is in series to a variable resistor connected to the bitline (BL). The variable resistor is a Metal-Insulator-Metal (MIM) device integrated on the metal line 2 of the CMOS process. The schematic and cross-sectional SEM image of the integrated RRAM cell including the metal lines and the W based Via-connections are shown in Fig. 2. The MIM resistor is a TiN/HfO$_2$/Ti/TiN stack of 150 nm TiN layers deposited by magnetron sputtering, a 7 nm Ti layer (under TiN top electrode), and a 8 nm HfO$_2$ layer grown by Chemical Vapor Deposition (CVD), which results in amorphous films (determined by
X-Ray Diffraction measurements). The resistor area is equal to 0.4 μm².

### III. EXPERIMENTAL RESULTS AND DISCUSSION

The electrical characteristics were obtained by means of a set-up based on the RIFLE SE test system working together with the Cascade PA200 semi-automatic probe system. In order to ensure a reliable accuracy for statistical calculations 128 1T-1R cells (two 64-bits pages) were characterized at each voltage step.

The ISPVA technique consists of a sequence of increasing voltage pulses (Fig. 3) on the BL during Set operation, whereas this sequence is applied on the source line (SL) during Reset operation: \( V_{\text{pulse}} = 0.2 - 3.5 \text{ V}, \ t_{\text{pulse}} = 10 \mu\text{s}, \ t_{\text{fall/rise}} = 1 \mu\text{s} \). In order to analyze its effect over the RRAM cells behavior, several measurements were done using different voltage step values between consecutive pulses \( (V_{\text{step}}): 0.05, 0.1, 0.2 \text{ and } 0.4 \text{ V} \). The applied transistor gate voltage values through the wordline (WL) were 2.7 V for Reset and 1.4 V for Set. After every pulse a Read-verify operation is performed with \( V_{\text{WL}} = 1.4 \text{ V}, V_{\text{read}} = 0.2 \text{ V} \) (applied over the Drain) for 10 μs. When the Read current reaches the target value of 18 μA the Set operation is stopped, whereas the Reset operation is stopped when the target value of 6 μA is achieved.

To activate the resistive switching behavior, the RRAM cells require a preliminary Forming operation [4]–[7]. This initial operation plays a fundamental role in determining the subsequent devices performance [17]. Therefore, the ISPVA procedure is also used for the Forming operation with the same parameters for each subsection (128 cells) of the 4 kbit array: \( V_{\text{pulse}} = 2 - 5 \text{ V}, \ t_{\text{pulse}} = 10 \mu\text{s}, \ t_{\text{fall/rise}} = 1 \mu\text{s}, \ V_{\text{step}} = 0.01 \text{ V} \text{ and } V_{\text{WL}} = 1.4 \text{ V} \). The cumulative distributions of the currents after forming are within the variability limit of the RRAM process technology as shown in Fig. 4. Therefore, the starting point for the following Reset/Set operations is similar for every subsection.
First of all, the impact of the ISPV A procedure on the filamentary conduction mechanism after the first Reset and Set operation was evaluated. As shown in Fig. 5(a), the first Reset operation is not affected by the variation of voltage steps. The currents in the High Resistive State (HRS) are quite similar within the limit of process variability. In contrast to the Reset operation, the currents in the Low Resistive State (LRS) are strongly affected by the increase of voltage increment. At small step increments, 80-90% of cells are set to the same LRS current values as after the Forming procedure. The remaining 10-20% cells tend to be set to higher current values. This trend is strongly pronounced at larger incremental voltage steps. Now, 40% of the cells show a second contribution of LRS currents with much higher values. As illustrated in Fig. 5(b), the Set operations with small voltage increments happen at voltages around 0.85 V. Caused by the increase of the voltage increment to 0.2 and 0.4 V the cells are forced to Set around 1 V.

In order to illustrate the distribution of LRS currents in a better way, the Set currents are plotted separately as function voltage step increment in Fig. 6. As shown in Fig. 6(b) and (c), a second peak occurs at about 48 μA. The first peak at about 24 μA is strongly reduced. It is obvious, that a kind of quantization of the conduction mechanism occurs at larger voltage step increments.

The observation of conductance quantization in oxide-based resistive memory cells was reported by Zhu et al. [18]. The conductance quantization behavior was attributed to the creation and annihilation of atomic scaled CF in the oxide layer. Later on Lian et al. [19] linked the conduction quantization with the quantum point contact model. Regarding the HfO₂-based RRAM cells, a CF is constructed by the Forming operation and its behavior can be explained by the QPC model. Focusing on the LRS, the current raises linear with applied voltage and can be expressed as [20]:

\[ I = \frac{NG_0V}{1 + NG_0R} \]  

where \( G_0 = 2e^2/h \) is the quantum conductance unit, \( N \) is the number of CF and \( R \) is a series resistance external to the constriction of the filament.

In order to evaluate the number of CF, additional DC measurements were performed, by using the same voltage values as in the ISPV A mode. Fig. 7 illustrates the experimental LRS I-V characteristics. The obtained I-V curve can be explained by the QPC model: the continuous line illustrates the fitting curve for LRS by using (1). The series resistance \( R \) is mainly generated by the select transistor and is determined by a separate simulation. The theoretical curve agrees with the experimental data, indicating that the QPC model is able to explain the conduction mechanism. According to Grossi et al. [21] \( G_0 \) value correspond to the bottom limit of the filament conduction: narrower filament implies the creation of a constriction and higher conduction values are caused by enlarged filaments. Since at large incremental steps the second peak appears at about 48 μA, we can conclude that the Set operation at 1.0 V results in the formation of two filaments, as illustrated in Fig. 8(b). It has to be mentioned, that the formation of two filaments is

![FIGURE 6. Distribution of currents after Set operation as function of voltage step increment: 0.05 V (a), 0.1 V (b), 0.2 V (c) and 0.4 V (d).](image-url)
examined by endurance cycling of 10 devices. Set process. cycling procedure over 11 of the considered devices.

(a) one CF with a mean current of about 24 V about 100 enabled by the saturation current of the select transistor of

Stability of the two LRS states and the HRS during endurance study of both conductance states reveals that the conduction path consisting of just one filament is stable, while the one consisting of two filaments is partially unstable.

REFERENCES


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