ARTICLE IN PRESS
MR-12120; No of Pages 4
Microelectronics Reliability xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Microelectronics Reliability
journal homepage: www.elsevier.com/locate/mr

Resistive RAM variability monitoring using a ring oscillator based test chip

H. Aziza *, J.-M. Portal
IM2NP-UMR7334, Polytech'Marseille, Aix-Marseille University, CNRS, Marseille, France

ARTICLE INFO

Article history:
Received 1 July 2016
Accepted 8 July 2016
Available online xxxx

Keywords:
Resistive RAM
Oxide based RAM
Oscillator
Test structure
Variability

ABSTRACT

Common problems with Oxide-based Resistive Random Access Memory (so-called OxRRAM) are related to high variability in operating conditions and low yield. Although research has taken steps to resolve these issues, variability remains an important characteristic for OxRRAMs. In this paper, a test structure consisting of an OxRRAM matrix where each memory cell can be configured as a ring oscillator is introduced. The oscillation frequency of each memory cell is function of the cell resistance. Thus, the test structure provides within-die accurate information regarding OxRRAM cells variability. The test structure can be used as a powerful tool for process variability monitoring during a new process technology introduction but also for marginal cells detection during process maturity.

1. Introduction

Resistive RAM (ReRAM) generally denotes all memory technologies relying on resistance change to store information. In ReRAM, the data is stored as two or multiple resistance states of the resistive switching device. In its simplest form, the resistive memory element relies on a Metal/Insulator/Metal (MIM) stack that can be easily integrated into Back-End Of Line (BEOL) [1,2]. Resistive switching in transition metal oxides was discovered in thin NiO films decades ago. Since then, a large number of materials showing a resistive switching have been reported in the literature [3]. Among them, metal oxides as HfO_2, NiO, TiO_2 and TaO_2 are promising candidates due to their compatibility with CMOS processes. In this study, an HfO_2-based Oxide-based RAM stack is considered.

Oxide-based RAM (also called OxRRAM) elements present a lot of interesting features as high integration density and high-speed operations [4]. Although OxRRAM-based devices have shown encouraging properties, challenges remain, among which the device variability (or reproducibility) is the main [5]. The presented test structure is based on a simple memory matrix of addressable memory cells where each cell can be configured as a ring oscillator during the read operation. Based on a very simple measurement methodology, the structure provides an evaluation of the variability of OxRRAM resistance states.

Section 2 introduces OxRRAM technology and presents the test chip. Section 3 presents in detail simulation results and Section 4 concludes the paper.

2. Test chip presentation

2.1. OxRRAM technology

In memory devices relying on a resistance change, complex physical mechanisms are responsible for reversible switching of the electrical conductivity between high and low resistance states. This resistivity change is generally attributed to the formation/dissolution of conductive paths between metallic electrodes. Due to the stochastic nature of the switching process in OxRRAMs, variability monitoring test structures became mandatory.

OxRRAM cell operation is depicted in Fig. 1. After an initial electroforming process, the memory element may be reversibly switched between two distinct resistance states. Electroforming stage corresponds to a voltage-induced resistance switching from an initial very high resistance state (virgin state) to a conductive state. After FORMING, resistive switching corresponds to an abrupt change between a High Resistance State (HRS or OFF state) and a Low Resistance State (LRS or ON state). This resistance change is achieved by applying specific voltage (i.e. V_{SET} and V_{RES}) to SET and RESET the memory cell.

It is important to note that the FORMING stage is the first and most critical step as it determines the switching characteristics during the future operation of the memory cell. Thus, the Forming Resistance State (R_{FRS}) which characterizes the filament creation is a key parameter in terms of OxRRAM reliability. Besides, the forming step requires high voltage levels (more important than V_{SET} and V_{RES}).

2.2. OxRRAM model

The proposed OxRRAM modeling approach relies on electric field-induced creation/destruction of oxygen vacancies within the switching

* Corresponding author at: IM2NP/Polytech'Marseille, 60 rue F. Joliot Curie, Bâtiment NEEL, Technopôle de Château Gombert, 13453 Marseille Cedex 13, France.
E-mail address: hassen.aziza@univ-amu.fr (H. Aziza).

http://dx.doi.org/10.1016/j.microrel.2016.07.097
0026-2714/

Please cite this article as: H. Aziza, J.-M. Portal, Resistive RAM variability monitoring using a ring oscillator based test chip, Microelectronics Reliability (2016), http://dx.doi.org/10.1016/j.microrel.2016.07.097

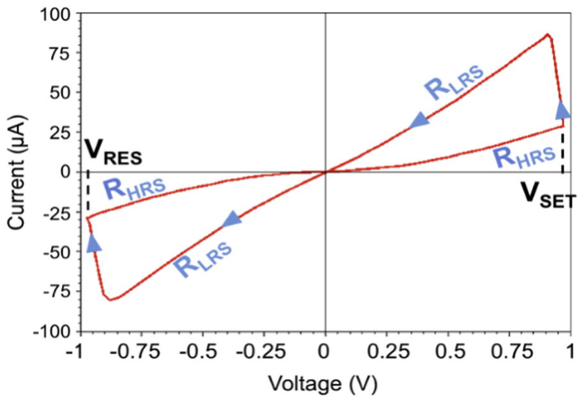

Fig. 1. I-V characteristic of a bipolar OxRRAM cell.

layer. The model enables continuously accounting for both SET and RESET operations into a single master equation in which the resistance is controlled by the radius of the conduction pathways [6,7].

The model was confronted to quasi-static and dynamic experimental data before its implementation in electrical circuit simulators [6]. Due to the stochastic nature of the switching process in OxRRAMs, leading to large variability, the OxRRAM model features a variability dependency. The variation is chosen to fit experimental data as presented in Fig. 2 (I-V characteristic in logarithmic scale). The model behavior (lines) is consistent with experimental data (symbols).

2.3. Test chip architecture

The semiconductor industry has adopted a solution based on test chips to evaluate process variation. Memory arrays as SRAM are well known to be a good vehicle to detect hard defects. Other test structures, inspired from the STM-CAST structure [8,9] are composed of matrixes of not addressable memory cells connected in parallel and are extensively used in the non-volatile memory field to detect marginal cells. In the same way ring oscillators are widely used to characterize process variation [10–12]. The presented test chip has been designed in such a way it can be used in memory mode (MO) to monitor and localize hard defects (cell failures) and in ring oscillator mode (RO) to monitor process variability (cell variability).

The test structure is designed in a FDSOI 28 nm technology from STMicroelectronics. The elementary block of the test chip called « Hybrid memory cell », is based on a classical 1T-1R Resistive RAM cell with two pass gates and three inverters (see Fig. 3). The memory cell is modeled by the calibrated OxRRAM cell model presented in Section 2.2.

In RO mode, SE (sensing signal) and OS signals are set high. In these conditions, the three inverters form a RO and the oscillating signal

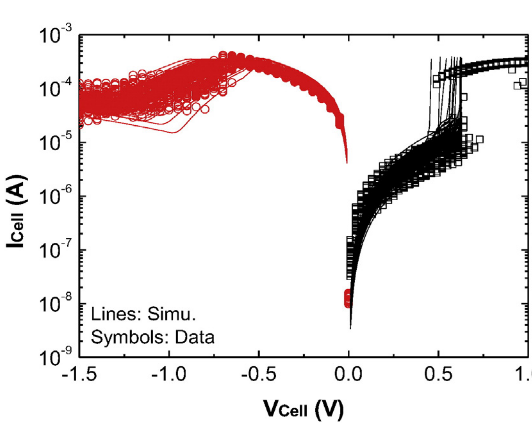

Fig. 2. Measured and corresponding simulated I-V characteristic obtained from TiN/Ti/HfO2/TiN devices showing strong variation on R_{LHS} and R_{HRS}.

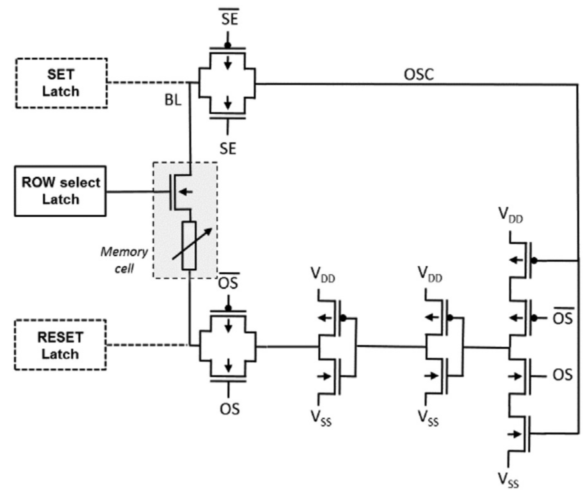

Fig. 3. Hybrid memory cell.

(OSC) depends on the memory cell resistance value. Note that the inverters are designed with long channel MOS to reduce the oscillation frequency in the MHz range. Pass gates are designed with large transistors to limit their effect on the oscillation frequency. Besides, SET and RESET latch outputs are set in a high impedance state in RO mode.

The memory cell normal operation mode is preserved. Indeed, FORMING, RESET and SET operations are available and only the READ operation is modified. The memory cell programming is done in 3 cycles. After a FORMING operation, the cell is RESET (logical “0”), then the memory cell is SET (logical “1”). Oscillation frequencies are extracted after each programming operation.

3. Results

3.1. FORMING/RESET/SET oscillation frequencies

Oscillation frequencies obtained after FORMING, RESET and SET operations are presented in Fig. 4. Table 1 presents nominal oscillation frequencies with the corresponding resistance values.

To validate the correlation between ON/OFF resistances and the oscillation frequency f_{osc}, a set of simulations are performed by changing the RESET and SET voltages (from 2.8 V to 3.1 V with a step of 50 mV). The effect is an impact on R_{OFF} and R_{ON} resistances. Fig. 5a shows a good correlation between R_{OFF} and f_{osc} (0.985 correlation factor) and Fig. 5b shows a perfect correlation between R_{ON} and f_{osc} (0.998 correlation factor). If the OFF state is considered, the resistance variation window represents 63 kΩ and its equivalent frequency window 57 KHz, allowing an accurate characterization of the cell state in terms of frequency.

3.2. Variability analysis

As already mentioned, the Forming Resistance State (FRS) which characterizes the first filament creation is a key parameter in terms of OxRRAM reliability. Thus, this parameter has to be monitored as well as possible. The variability analysis is conducted through Monte Carlo simulations and targets the FORMING resistance R_{FSR}. Variability introduced in the resistive element is chosen to fit experimental data (see Fig. 2).

After 300 Monte Carlo runs, R_{FRS} and f_{osc} frequency distributions are extracted and presented in Fig. 6. The correlation between resistance and frequency distributions is confirmed in Fig. 7, which presents normalized box plot distributions of R_{FRS} and f_{osc} for comparison purpose.

Please cite this article as: H. Aziza, J.-M. Portal, Resistive RAM variability monitoring using a ring oscillator based test chip, Microelectronics Reliability (2016), http://dx.doi.org/10.1016/j.microrel.2016.07.097