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Anomalous random telegraph noise and temporary phenomena in resistive random access memory

Francesco Maria Puglisi [a,*], Luca Larcher [b,c], Andrea Padovani [c], Paolo Pavan [a]

[a] DIEF, Università di Modena e Reggio Emilia, Via P. Vivarelli 10/1, 41125 Modena, MO, Italy
[b] DISMI, Università di Modena e Reggio Emilia, Via Amendola 2, 42122 Reggio Emilia, RE, Italy
[c] MDLab s.r.l., Località Grand Chemin 30, 11020 Saint-Christophe, AO, Italy

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A B S T R A C T

In this paper we present a comprehensive examination of the characteristics of complex Random Telegraph Noise (RTN) signals in Resistive Random Access Memory (RRAM) devices with TiN/Ti/HfO_2/TiN structure. Initially, the anomalous RTN (aRTN) is investigated through careful systematic experiment, dedicated characterization procedures, and physics-based simulations to gain insights into the physics of this phenomenon. The experimentally observed RTN parameters (amplitude of the current fluctuations, capture and emission times) are analyzed in different operating conditions. Anomalous behaviors are characterized and their statistical characteristics are evaluated. Physics-based simulations considering both the Coulomb interactions among different defects in the device and the possible existence of defects with metastable states are exploited to suggest a possible physical origin of aRTN. The same simulation framework is also shown to be able to predict other temporary phenomena related to RTN, such as the temporary change in RTN stochastic properties or the sudden and iterative random appearing and vanishing of RTN fluctuations always exhibiting the same statistical characteristics. Results highlight the central role of the electrostatic interactions among individual defects and the trapped charge in describing RTN and related phenomena.

1. Introduction

In the vast landscape of emerging memory devices, the Resistive Random Access Memory (RRAM) is among the most promising options to become the near-future memory device of choice for both embedded and stand-alone applications. Their excellent characteristics such as fast, low-power switching and CMOS-compatibility [1,2] configure RRAM as one of the best candidates for flash memories replacement. Nevertheless, reliability and variability problems [3,4] are hampering the full industrial exploitation of RRAM devices. Particularly, Random Telegraph Noise (RTN), i.e. the sudden shift of current among discrete values observed during readout operations, affects the reliability of these memory devices, as it could result in the failure of the readout operation, i.e. erratic bit detection [4–6]. RTN is generally associated with trapping and de-trapping of charge carriers into/from defects in the device structure [5,6]. Although the typology of the defects triggering RTN has not been unambiguously identified yet, recent studies suggest that RTN could be the result of the activation and deactivation of oxygen vacancy defects (Vo), which assist charge transport [5,6]. However, the state-of-the-art comprehension of RTN and related phenomena is quite incomplete: besides conventional RTN, also more bizarre signals have been detected, as the anomalous RTN (aRTN), i.e. RTN fluctuations appearing and disappearing over time in an iterative fashion [7], or RTN signals exhibiting temporary mutations of their statistical properties. The existence of these features further complicates the underlying physical picture and hinders its characterization, which is necessary to improve the reliability of these devices. In this paper, we exploit careful systematic experiment, dedicated characterization procedures, and comprehensive physics-based simulations to investigate aRTN behavior. The peculiar systematic experiment allows fully characterizing the aRTN signals in different operating conditions. A sophisticated data analysis technique is exploited to properly handle complex experimental data. Moreover, physics-based simulations able to reproduce multi-level RTN signals characteristics in different operating conditions are exploited to gain insights into the possible physical mechanisms responsible for the observed aRTN. The same physical framework is used to also predict the possible physical origin of other temporary phenomena related to RTN and detected in these devices, such

* Corresponding author.
E-mail address: francescomaria.puglisi@unimore.it (F.M. Puglisi).

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as the temporary change in RTN stochastic properties, i.e. mutant RTN (mRTN) and the sudden and iterative random appearing and vanishing of RTN fluctuations, i.e. temporary RTN (tRTN).

2. Devices and experiments

2.1. Device details

TiN/Ti/HfO_2/TiN cross-bar RRAM devices in 1T-1R configuration are considered. The access transistor is used to both select the memory cell and to limit the current flow in the device by imposing the requested current compliance, preventing current overshoots to occur during the forming operation [8]. Devices with 100×100 nm^2 area, 3.4 nm Atomic Layer Deposition (ALD) HfO_2, and 5 nm Ti layer are investigated. The Ti film on top of the switching oxide layer determines some oxygen deficiency in the underlying ALD-grown HfO_2, which has been proven to be crucial to achieve reliable resistive switching [9].

2.2. Experiments

After the preliminary forming operation (employing a current compliance $I_c = 100$ μA), we verify the correct behavior of the device under test, which shows bipolar filamentary switching as expected [9]. Then, we drive the device in High-Resistive State (HRS) performing a DC sweep reset operation using $V_{RESET} = -1$ V. From the resulting *I-V* curve we estimate the conductive filament (CF) cross-section and the dielectric barrier thickness exploiting the compact model for HfO_2 RRAM devices in [10,11]. The device is now in the desired state for the RTN analysis, so henceforth it is not switched to any further extent. This implies we analyze the behavior of a single programmed bit in different operating conditions. The RTN current fluctuations in HRS are recorded in the time domain (I-*t* traces) applying a constant biasing voltage, V_{READ}. Since anomalous RTN signals may randomly appear and disappear, a careful design of experiment is required for a reliable characterization. Furthermore, RTN characteristics (amplitude of the RTN fluctuation, average capture and emission times) strongly vary with the operating conditions (i.e. applied voltage and temperature). Hence, different measurement settings (i.e. sampling and measurement times) may be required to accurately characterize anomalous RTN signals in different operating conditions. In our systematic experiment, schematically depicted in Fig. 1, characterization and measurement conditions are automatically changed. Each green block in Fig. 1 represents a specific RTN measurement operation, which is completely defined by the sampling time, τ_s, the applied bias voltage, V_{READ}, and the temperature, T. Each measurement contains 10k points, i.e. the total measurement time is $T_{meas} = 10\text{k} \cdot \tau_s$. Consecutive measurements are performed at different sampling times (ranging from 60 μs to 6 ms, Fig. 1) in the same operating conditions (voltage and temperature). This procedure (represented by blue blocks) is repeated at different voltages (from 10 mV to 100 mV, Fig. 1). This measurement cluster (represented by red blocks) is then repeated applying different temperatures (from 35 °C up to 65 °C, Fig. 1). The choice of the temperature, voltage, and sampling time ranges used in this experiment allows accurately observing RTN over time in different operating conditions while preventing the device resistive state from switching. Moreover, the accuracy of the RTN parameters estimation is improved by the availability of data recorded at different sampling times which allows optimizing the trade-off between accuracy and resolution during the RTN data analysis. The quantitative assessment of RTN parameters and their extraction from experimental multi-level RTN traces is achieved using a custom-developed software tool implementing the Factorial Hidden Markov Model (FHMM) algorithm [12,13]. This powerful tool allows decomposing multi-level RTN signals into many independent two-level signals, each attributed to the activation and deactivation of an individual defect. This allows correctly assessing the statistical characteristics of every individual defect contributing to the observed multi-level RTN [12,13].

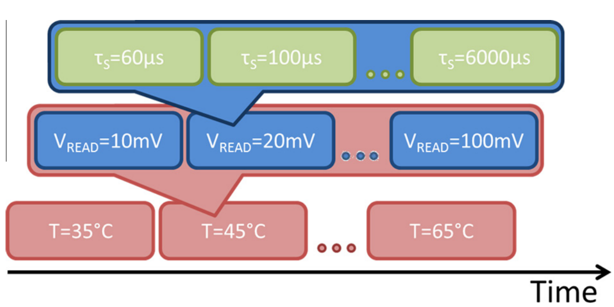

Fig. 1. Schematic representation of the systematic experiment. Different consecutive RTN measurements are performed using different sampling times (green blocks), V_{READ} (blue blocks), and temperatures (red blocks). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.3. Simulations

Simulations of I-*t* traces are performed using the MDLab simulations suite [14], accounting for the lattice relaxation, i.e. electron–phonon interaction, both trap-assisted and directing tunneling, charge transport through defects sub-bands, 3D temperature and potential maps (including the effect of trapped charge), metastable states, transitions among different defect charge states, and offers the possibility of performing kinetic Monte-Carlo (kMC) simulations. Moreover, it is possible to include the effects of defects generation (Hf-O bond breakage), recombination among complementary defect species, and defects drift-diffusion. Additional details about the simulation environment may be found in [14–16].

3. Anomalous RTN: results and discussion

The experiment reveals the presence of RTN signals with anomalous characteristics (aRTN) besides the conventional two-level and multi-level RTN. These aRTN signals display more than two levels but strongly differ from multi-level RTN signals. Indeed, despite both the aRTN and the multi-level RTN signals are characterized by multiple discrete current levels, the aRTN cannot be represented by a superposition of *independent* two-level RTN fluctuations, as opposite to the multi-level RTN. Fig. 2(a) shows an example of aRTN: the signal, which displays three discrete current levels, consists of two RTN components (each component is a two-level RTN fluctuation), i.e. a fast and a slow one, Fig. 2(a). The main difference with a standard multi-level RTN fluctuation is that in this case the fast RTN occurs only when the slow RTN component is in the high current state, Fig. 2(b) and (c). This impedes describing aRTN as a superposition of *independent* two-level fluctuations. The straight application of the FHMM data analysis (or any other technique currently used to analyze RTN signal properties) to the signal as in Fig. 2(a) leads to equivocal results. Indeed the portions of the I-*t* trace in Fig. 2(c) highlighted with violet rectangles would be incorrectly considered in the estimation of the average emission time of the fast RTN component, resulting in an inaccurate evaluation. Contrariwise, aRTN signals can be described in terms of the superposition of *correlated* two-level fluctuations, as shown in Fig. 2(b) and (c). Indeed, the behavior of the fast component is directly influenced by the state of the slow one; green and