Solid-State Electronics 102 (2014) 69–75

Contents lists available at ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

A study on HfO_2 RRAM in HRS based on *I–V* and RTN analysis

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ARTICLE INFO

Article history:
Available online 2 July 2014

The review of this paper was arranged by Prof. S. Cristoloveanu

Keywords:
RRAM
RTN
FHMM
Resistive switching
HRS

ABSTRACT

This paper presents a statistical characterization of random telegraph noise (RTN) in hafnium-oxide-based resistive random access memories (RRAMs) in high resistive state (HRS). Complex RTN signals are analyzed exploiting a Factorial Hidden Markov Model (FHMM) approach, which allows to derive the statistical properties of the RTN signals, directly related to the physical properties of the traps responsible for the multi-level RTN measured in these devices. Noise characteristics in different reset conditions are explored through consecutive switching cycles. Noise spectral analysis is also performed to fully support the investigation. An RRAM compact model is also exploited to estimate the physical properties of the conductive filament and of the dielectric barrier from simple *I–V* data. These tools are combined together to prove the existence of a direct statistical relation between the reset conditions, the volume of the dielectric barrier created during the reset operation and the average number of active traps contributing to the RTN.

1. Introduction

Resistive random access memories (RRAMs) are currently one of the most promising class of alternative non-volatile memories (NVMs), exhibiting reliable and fast switching [1], low-power operation [2], and high-density [3]. Among different resistive switching devices, hafnium-oxide-based RRAMs show superior performances [4] and excellent compatibility with standard CMOS back-end of line. Actual understanding of RRAMs switching mechanism relies on the formation and subsequent partial oxidation of a conductive filament (CF) during set and reset operations, respectively [5]. The formation of a CF sets the device in the low-resistance state (LRS) while its partial oxidation leads to the creation of a dielectric barrier, determining the high-resistance state (HRS) [6]. The charge transport in LRS exhibits quasi-ohmic behavior [5], whereas the conduction in HRS is dominated by a multi-phonon trap-assisted tunneling (TAT) process [7] via the traps in the barrier. Still, despite the recent progress with this technology, some phenomena as the random telegraph noise (RTN) are ultimately limiting the device reliability (e.g. speed-disturb dilemma) and the possibility of multi-bit storage [8]. In this paper a statistical analysis of random telegraph noise in HfO_x RRAMs in HRS is presented. RTN current fluctuations in HRS are believed to be related to the activation and deactivation of traps assisting the charge transport through the dielectric barrier, in agreement with the trap-assisted tunneling model [7]. Our previous works [8,9] exploited the color-coded time-lag plots and hidden Markov model [10] (HMM) to investigate the characteristics of RTN in RRAMs, showing that multi-level RTN can be seen as a superposition of many 2-levels RTN signals, each associated with a single trap [9]. We also proposed the factorial hidden Markov model [11,12] (FHMM), a more refined implementation of the HMM, as a tool to derive the statistical properties of multi-level RTN. In this paper the current noise in reading conditions is extensively characterized after reset operations performed at different voltages through the FHMM analysis [11,12]. This analysis methodology is also supported by noise spectral analysis. Moreover a compact model is exploited to estimate the physical properties of the dielectric barrier at each switching cycle: this allows evaluating the statistical properties of the traps and of the dielectric barrier. As a result, the number of active traps resulting in RTN is found to be proportional to the volume of the dielectric layer. This paper is organized as follows: devices and experiments are described in Section 2; in Section 3 we report on the experimental results of RTN and *I–V* characterization, and we introduce the tools used for the analysis of the experimental data, i.e., FHMM and Compact Model, respectively; in Section 4 we discuss the results; in Section 5 we suggest mechanisms responsible for RTN in these devices. Conclusions follow.

2. Devices and experiments

Measurements are performed on 20 $200 \times 200\,\text{nm}^2$ TiN/Ti/HfO_x/TiN RRAM devices, all showing the same behavior, with a

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http://dx.doi.org/10.1016/j.sse.2014.06.001
0038-1101/

5 nm thick ALD oxide layer in 1T1R configuration. The 6.5 nm thick Ti layer sputtered on top of the hafnium oxide acts as an oxygen exchange layer, inducing an oxygen deficiency in the oxide film during post-deposition annealing at 400 °C for 30 min. This is required to induce a given degree of oxygen sub-stoichiometry (needed for a reliable switching), which is caused by the interaction between the Ti capping layer and the hafnium oxide layer, as explained in [13–17]. A preliminary forming operation, under current compliance limit ($I_C \approx 100\ \mu A$), is performed to set the device into the initial condition enabling resistive switching; the use of 1T1R configuration allows minimizing the current overshoot due to parasitic capacitances [18]. Set and reset operations drive the device in LRS and HRS, respectively. After forming (occurring at a typical voltage of 3 V in these devices), which sets the device to LRS, one hundred complete switching DC cycles (set-reset-read) are performed. A semiconductor parameter analyzer is used to both acquire I–V curves during switching cycles (see Figs. 1 and 2) and properly bias the device (in reading conditions we consider V_{READ} = 0.1 V). Current fluctuations (I–t data) during the read operation are measured by sampling the current vs. time, collecting 10 k samples (i.e. current measures) with a sampling time of 2 ms, which corresponds to a total measurement time of 20 s. This measurement process allows to characterize 1 bit per reading operation, biasing the device for a prolonged time (i.e. 20 s in this experiment) in order to detect RTN events also in the long-time scale. Noise fluctuations are also conditioned by a precision low-noise current preamplifier and recorded through a dynamic signal analyzer to acquire the averaged power spectral density, Fig. 2. This process is repeated for devices reset at different voltages (V_{RESET} = 1.1 V, 1.3 V, 1.5 V, and 1.7 V). Then, collected RTN (I–t) data are processed exploiting an FHMM analysis [11,12]. Power spectra are fitted against a Lorentzian ($1/f^2$) curve, which corresponds to a stationary 2-levels (single trap) RTN: as a result it is possible to discern whether the experimental RTN is associated with the activity of a single trap or is the result of the activity of many traps.

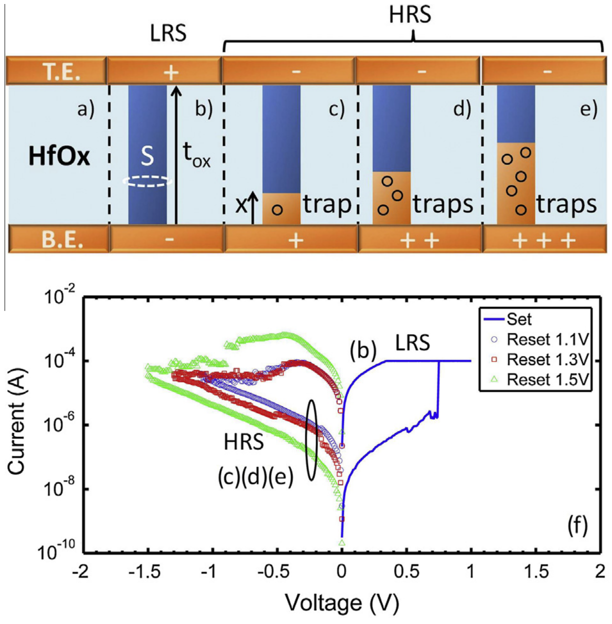

Fig. 1. (a) Schematic representation of a simplified RRAM structure at different operating conditions. (b) A conductive filament (blue cylinder) is formed by applying a positive voltage ramp. (c) Reset operation partially oxidize the conductive filament creating a barrier (orange cylinder) of length x. (d and e) The barrier length is related to the reset voltage. (f) Experimental I–V curves corresponding to the (b–e) states. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

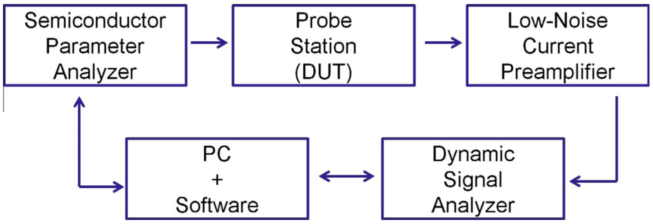

Fig. 2. Schematic of the measurement setup exploited in this work. A semiconductor parameter analyzer is used to properly bias and switch the device and to acquire both I–V and RTN I–t data. Noise data are also sent to a low-noise current preamplifier and fed to a dynamic signal analyzer which is used to acquire the RTN power spectra. The whole setup is controlled via pc through a dedicated LabVIEW-based software for automation.

3. Results

Fig. 1 shows the I–V curves measured on devices reset at different voltages along with a schematic representation of the CF state expected at the end of the reset operations. As previously reported [19], HRS resistance (measured at V_{READ} = 0.1 V) depends exponentially on the reset voltage (i.e. the maximum absolute value of the voltage during the reset sweep): this allows calculating the thickness of the dielectric barrier layer created during the reset operation. This is in agreement with the prediction of the physical model in [7] and the compact model in [19,20], both showing a linear relation between the reset voltage and the barrier thickness. Simulations show that trap-assisted tunneling through the dielectric barrier is the main conduction mechanism in HRS. Thus, we expect an increasing number of active traps with increasing barrier thickness, leading to more complex (multi-level) RTN fluctuations in HRS. Here we introduce the tools that we will exploit to investigate the relations between RTN and the dielectric barrier properties.

3.1. FHMM analysis and RTN properties

RTN is measured on devices in HRS at reading voltage (V_{READ} = 0.1 V) by recording current fluctuations. We considered devices reset at different voltages (V_{RESET} = 1.1 V, 1.3 V, 1.5 V, and 1.7 V). Raw data are processed through an FHMM technique, which we proposed as an effective tool to overcome the limitations of HMM in the analysis of multi-level RTN [11,12]. Indeed, HMM [10] models the input signal as a Markov chain with K hidden states (i.e. discrete current levels). This approach is suitable to analyze a 2-levels RTN (associated with the activity of a single trap), whereas it becomes inappropriate with the multi-level RTN, which is generated by many traps. In fact, in the standard case of a 2-levels RTN, the difference between the current levels corresponds to the amplitude of the RTN fluctuation and the HMM approach can be used to efficiently estimate the hidden states, hence the amplitude of the fluctuation. With multi-level RTN the estimation of the hidden current levels is not sufficient to univocally determine the amplitude of each 2-levels fluctuation generating the RTN. The FHMM allows overcoming the HMM limits by considering the multi-level RTN as the summation of independent 2-levels Markov chains [11,12], one for each active trap, instead of representing it as a single Markov chain with many states. This novel methodology allows to decompose the multi-level RTN into 2-levels fluctuations and to retrieve the properties of each trap contributing to the RTN. Fig. 3 schematically shows the concept of FHMM: S_T^M is the state of the M-th chain at time T, and Y_T is the current fluctuation expected at time T from the measured multi-level RTN. The number of parallel Markov chains (i.e. active traps), which is an unknown input parameter for the