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On the electrical variability of resistive-switching memory devices based on NiO oxide

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Resistive-switching memories (so-called RRAM) are increasingly investigated since they gather low cost, high integration capabilities together with good performances [1]. RRAM memories based on transition metal oxide are promising candidate because of a simple metal/oxide/metal stack allowing the integration of memory elements into the back end of line [2]. Before substituting conventional Flash memories, RRAM devices must fulfill reliability requirements and the variability of their electrical characteristics has to be properly apprehended. *In this paper the variability on forming and reset characteristics are reproduced by 1D modeling. By using this approach, this paper aims at identifying the key physical parameters that may explain the intrinsic spread of electrical characteristics.*

As depicted in Fig.1, RRAM devices consist of a NiO active layer (25 nm thick) sandwiched between two platinum electrodes (25 nm thick). Such devices exhibit unipolar resistive switching effect between two conductivity states, *i.e.* a low resistance state (LRS) and a high resistance state (HRS) [3]. To identify the conduction mechanism in the pristine state, current-voltage characteristics were accurately measured at various temperatures. Below the forming voltage (zone III in Fig. 2a), the current does not show evident thermal activation that may be in agreement with a trap-assisted tunneling (TAT) mechanism described here in terms of barrier height (ϕ_B) and average distance between traps (w) [6]. Figure 3 shows the max/min and median dc IV characteristics measured on several RRAM either during the forming stage (Fig. 3a) or during the reset operation (Fig. 3b). Finally in Fig. 4 forming and reset voltages are monitored with respect to enviroining temperature (these are first data ever shown in the literature, to our knowledge, on this aspect). To apprehend the impact of physical parameters on the intrinsic variability of electrical characteristics, a self-consistent physical model accounting for both forming and reset operations was used [4]. This model takes into account two distinct mechanisms: a redox reaction (*i.e.* electrochemical oxidation/reduction processes) during forming, and thermal diffusion and dissolution of conductive filaments (CFs) during reset [5]. In Table 1, the impact on electrical characteristics is evidenced for each physical parameters. Microscopical parameters related to TAT conduction (ϕ_B and w) and the free energy of the reduction reaction at equilibrium (E_{red}) mainly affect the forming voltage. In contrast, the activation energy of the LRS (E_a) involved in the dissolution of CFs and retention characteristic, together with electrical parameters related to the CFs (resistivity ρ_{CF0} , thermal conduction K_{thCF} , thermal coefficient α_T) largely affect the reset voltage and the reset current. Another important parameter is the current compliance during forming I_{comp} that strongly influences reset current and resistance in LRS [7]. Indeed I_{comp} must be controlled to avoid larger spread of electrical characteristics [8]. Provided these elements, the mean values (*ie* μ) of different parameters were calibrated on the median IV, for forming and RESET (Fig 3); then slight variation (*ie* σ) on each of them allowed a good fit on min/max characteristics, as evidenced in Fig. 3 and Fig. 5 on large set of data: in Table II the set of μ and σ are highlighted. Note that in Table II a quantitative view of the impact of each microscopical parameters is provided in the last column. Eventually in Fig. 4 we compare modeling result on random set of physical parameters (with μ and σ from Table 2) with data. We obtain a fine agreement with data, that could be improved enlarging the statistical ensemble of data.

To summarize, the present work enables apprehending the impact of physical parameters on the variability of NiO-based RRAM. The important variability of current in pristine state may be linked on variation of NiO layer during fabrication process which impacts the barrier height (ϕ_B) and average distance between traps (w). And the modification of filament structure could impact the electrical

parameters (ρ_{CF0} and K_{thCF}) and can explain the variability in LRS for current and reset voltage. Also the impact of each microscopical parameter has been quantitatively put in relation with the macroscopical electrical counter-part.

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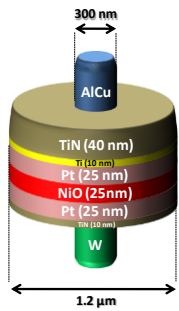


Figure 1: Schematic description of the NiO-based RRAM memory elements.

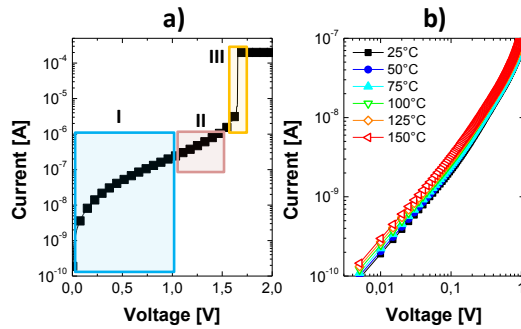


Figure 2: a) Typical current-voltage characteristic measured from the pristine state. Zone I: no resistance switching; Zone II onset resistance switching; Zone III switching event to LRS. b) Temperature-dependent evolution of current at low voltage.

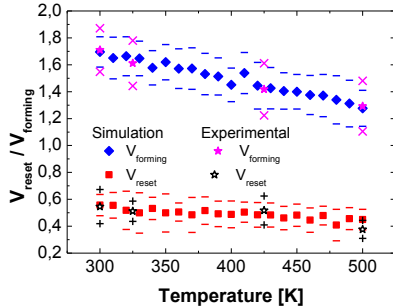


Figure 4: Forming and reset voltage behavior with respect to temperature for experimental and simulation.

	Parameters	Mean Value (μ)	Standard Deviation (σ)	Impact on electrical property of each parameter [$\mu \pm \sigma$; $\mu \pm \sigma$]
Forming impact	ϕ_B (eV)	0.390	0.045	(+ σ) $\times 3.065$ HRS current (- σ) $\times 3.065$ HRS current
	w (nm)	3.550	0.350	(+ σ) $\times 3.370$ HRS current (- σ) $\times 3.370$ HRS current
	E_{red} (eV)	3.05	0.30	$\pm 15\%$ on $V_{forming}$
Reset impact	K_{thCF} (W/K 2 m)	30	5	$\pm 5\%$ on V_{reset}
	E_a (eV)	1.10	0.11	$\pm 6\%$ on V_{reset}
	I_{comp} (mA)	5	1	$\pm 20\%$ on I_{reset} and LRS current
	α_T (1/K)	0.5e-3	0.1e-3	$\pm 7\%$ on LRS current
	ρ_{CF0} (Ω^2 m)	0.7e-5	0.2e-5	$\pm 10\%$ on V_{reset} $\pm 5.71\%$ on R_{LRS}

Table 2: Mean value (μ) and standard deviation (σ) of physical parameters used to fit experimental data (Fig 3-4). Impact on electrical characteristics due to an independent variation of each physical parameters in forming and reset operations

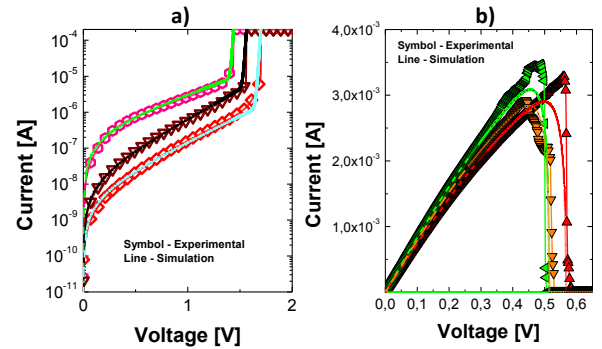


Figure 3: Extreme-value current-voltage characteristics measured either in the forming stage a) or during the reset operation b). Each experimental curve is satisfactorily fitted by the unipolar switching model.

	Parameters	Electrical impact
Forming	ϕ_B (eV)	HRS current
	w (nm)	HRS current
	E_{red} (eV)	Forming voltage
Reset	K_{thCF} (W/K 2 m)	Reset voltage
	E_a (eV)	Thermal activation of LRS retention
	I_{comp} (mA)	Resistance in LRS
	α_T (1/K)	Ohmic behavior in LRS
	ρ_{CF0} (Ω^2 m)	Reset voltage and Resistance in LRS

Table 1: Electrical impact of parameters for forming and reset operation

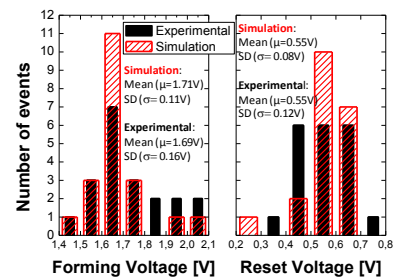


Figure 5: Experimental and simulated dispersions of forming (left) and reset (right) 20 events on each.