Over-programming induced effects in the amorphous state of Phase Change Memories

A. Calderoni[1], M. Ferro[1], E. Varesi[1], D. Ielmini[2] and P. Fantini[1]

1) Micron, R&D – Technology development, via Olivetti2, 20041 Agrate Brianza, Italy E-mail address(es)
2) Politecnico di Milano-IU.NET, Dip. Elettronica e Informazione, Piazza L. da Vinci 32, 20133 Milano, Italy

ABSTRACT

Ge2Sb2Te5 (GST) chalcogenide alloys have been demonstrated to be a suitable and reliable material in the memory market for many years: used as optical mass-storage (CD/DVD) first, recently it has became the first choice in phase change memory (PCM) enabling novel applications [1, 2]. In this work, we have electrically and physically investigated material changes due to the programming pulse. In particular, a detailed characterization of the over-reset state, occurring when high programming pulses for reset are applied, is presented. Amorphous volume thickness, activation energy for conduction, time drift exponent, 1/f noise intensity, threshold switching and stoichiomety changes are investigated to address the physical understanding of the over-reset state.

Key words: Phase Change Memory, Over-Reset, Electrical Characterization, Physical Analysis

Over-reset definition. A typical programming characteristic reporting the readout resistance as a function of increasing reset pulse is shown in Fig. 1. Starting from the set state, the resistance suddenly jumps at higher values as a consequence of the phase transition. A further increase in the programming current leads to a reproducible resistance roll-off: the *over-reset* effect. This effect has been explained by heat accumulation at high programming currents, leading to a re-cristallization effect along the quenching edge [3], or by the shallower energy and/or higher density of traps contributing to the hopping conduction [4]. The sub-threshold *I-V* curves, showed in Fig. 2, are in a good agreement with a Poole-Frenkel-like conduction [5], for all programming pulses. Nevertheless, the curve corresponding to the OR state shows a higher low-field conductance with respect to the full-reset one despite having a lower sub-threshold slope (STS) in the exponential region. According to the Poole-Frenkel transport model the STS lowering is a signature of the amorphous thickness (u_a) increasing for $u_a = q^3/(kT)^2\bullet(\pi\varepsilon_{GST})^{-1}\bullet(STS)^{-2}\bullet(1-T/T_{MN})^2$, being q the electron charge, k the Boltzmann constant, T the temperature, ε_{GST} is the dielectric constant of amorphous GST and T_{MN} is the Meyer-Neldel iso-kinetic temperature. Fig. 3 shows the TEM images of the amorphous dome of cells programmed with increasing pulses (A through D) up to the FR and OR states, providing the physical proof of the higher amorphous thickness consequently to the higher (OR) pulse. Furthermore, the shape of the dome becomes more hemi-elliptic in comparison to that of the FR state that is more hemispheric.

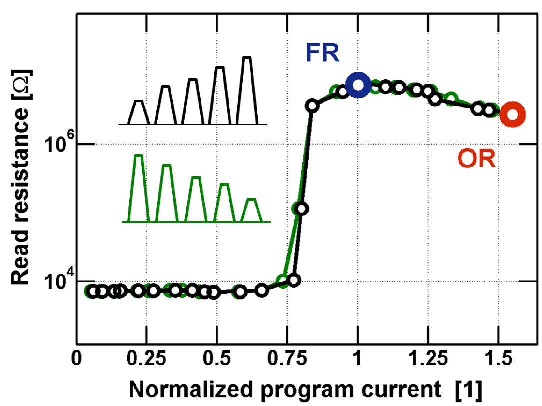

Fig. 1 Programming characteristics of a PCM for a stair-case up/down pulses (black/green). Full-reset (FR) and Over-reset(OR) are highlighted on both the overlapping curves.

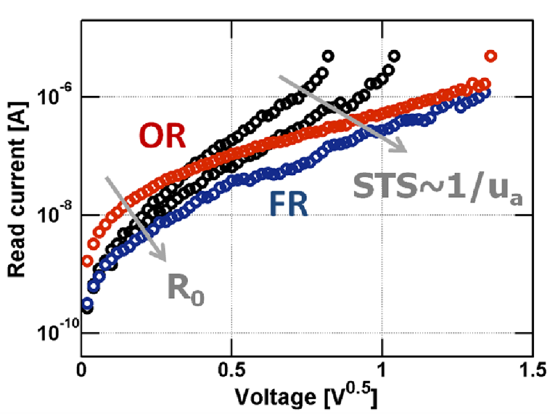

Fig. 2 Current vs Voltage cell curves for increasing programming pulses. The low-field resistance of the OR state is clearly decreasing while its STS is still increasing

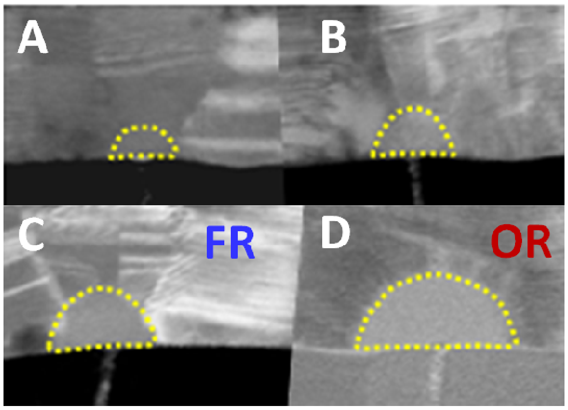

Fig. 3 TEM images of the amorphized dome for cells programmed with increasing pulses (A trough D). OR has a higher and wider amorphous region, according to the electrical extrapolations of u_a from STS.

Electrical characterization. A thorough electrical investigation of the OR state has been performed on 10k cells to account for cell-to-cell variability. The activation energy for conduction, E_A, was thus extracted for good reset cells and both a FR and OR states (Fig. 4 - left axis of upper panel). Again a slight roll-off in the E_A trend is observed for the OR state, although u_a increases. Since E_A is found to correlate with the value of the time drift exponent (ν) of the *power-law*, $R = R_0(t/t_0)^{\nu}$, we have also characterized the drift of the over-reset state (Fig. 4 - right axis of upper panel). We also performed *1/f* noise measurements, which is a sensitive technique to investigate the quality of the material. Middle panel of Fig. 4 shows a factor 3 higher normalized current noise intensity corresponding to the FR state with respect to OR that cannot be explained considering the ratio of the amorphous volume in between. Thus, a higher N_T and lower E_A for the OR state might be supposed, accordingly to our model [6]. Lower panel of Fig. 4 reports the switching threshold as a function of the amorphous thickness, as determined by *STS* parameter calibrated using TEM data, statistically collected from array level measurements for three different reset pulses intensity. The correlation in between indicates a field-induced switching mechanism (E_{TH}) in agreement with literature data for the two lower pulses [7], while it is lost for the over-reset cells (higher programming pulse). In agreement with the gain and loss model for switching [8], the V_{TH} pinning of OR cells can be well reproduced assuming, simultaneously, the slight E_A decreasing and u_a increasing. Fig. 4 (lower panel) also reports the good agreement between simulation and the experimental trend.

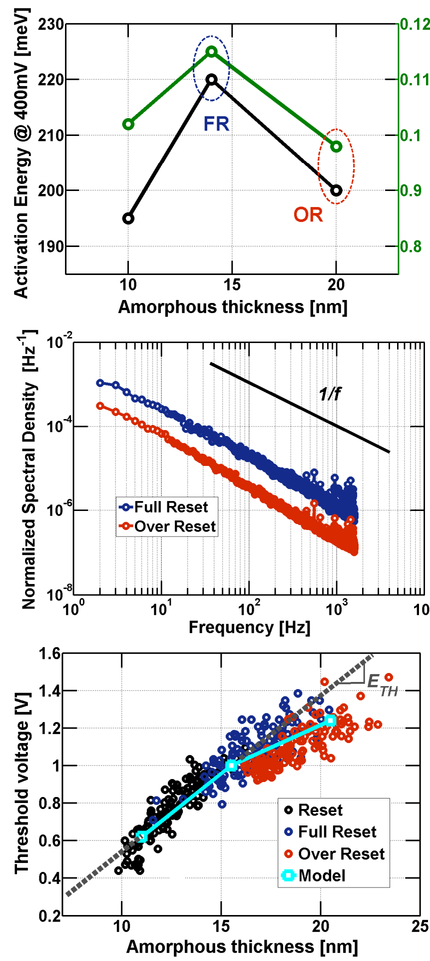

Fig. 4 From top to down. i) Average (10k cells) activation energy and drift exponent as a function of u_a. ii) Normalize current noise spectral density: a 3.5x lower noise intensity in the 1/f-like spectra of the OR state is ascribed to both higher u_a and lower E_A. iii) Threshold voltage vs extracted amorphous thickness foe increasing programming pulses. The switching field saturates in the OR.

Physical characterization. All these experimental findings strongly suggest that different amorphous state/material is realized as a consequence of the high programming pulse. In fact, a high programming pulse could promote atoms displacement changing the active area stoichiometry [9]. Indeed, it has been verified by means of STEM-EDX (not reported here) that FR and OR bits have a modified local composition as a consequence of the program operation.

Conclusions. A detailed electrical and physical characterization of the amorphous state as a function of the programming pulse in the 45 nm PCM cell is presented. This allowed the physical understanding of the over-reset state in terms of pulse induced compositional change, decreasing the conduction activation energy of the melt-quenched amorphous GST.

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