Size-dependent random-telegraph noise in phase-change memories

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ABSTRACT

Current noise is among the major concerns for nonvolatile memories, as it affects the read speed and the capability to distinguish among different programmed levels in the memory cell. The memory size reduction usually enhances noise, due to current localization and variability effects in nanoscale electronic devices. Phase change memory (PCM) devices display noise, mostly due to fluctuations of the subthreshold current in the amorphous chalcogenide phase. Understanding the current noise and its physical nature may allow for physics-based predictions of its scaling dependence in future PCM generations. This work addresses random telegraph noise (RTN) in PCM devices. Experiments at variable temperature indicate that the fluctuation kinetic is controlled by an Arrhenius law, while the temperature-dependent amplitude reveals that the current fluctuation is driven by a change in activation energy for conduction. Based on these evidences, we develop a model for RTN based on bistable fluctuations of defects along the percolation path. Simulation results account for the temperature and size dependence of noise observed in PCM devices. The model allows to explain the noise spectrum in PCM devices as the convolution of many RTN component, each associated to bistable fluctuations with a different characteristic frequency. Scaling projections of noise are finally provided based on model simulations.

Key words: random telegraph noise, phase change memory, Poole-Frenkel conduction, physical modeling.

1. INTRODUCTION

Phase change memory (PCM) devices are approaching the market level thanks to impressive improvements in the integration, scaling and reliability during the past decade [1]. The development of high performance devices has been accompanied by a continuous progress in the understanding of transport and phase transition phenomena in chalcogenide materials [2,3]. Among the open challenges, resistance instabilities such as current noise, resistance drift and threshold switching play an important role in achieving stable and tight distributions of resistance in large arrays. Current noise, in particular, is known to strongly depend on the size of the active device in several memory technologies, including Flash [4], resistive switching memories [5] and conductive bridge RAM [6]. Current noise in PCM has been already addressed from experimental and theoretical viewpoints [7, 8, 9,10]. Here, we focus on the physics-based understanding and modeling of the scaling dependence of RTN and 1/f noise contributions in PCM devices [11,12]. Based on temperature-dependent experiments, RTN is interpreted as a two-level fluctuation of resistance due to a bistable defect affecting the localized current path in the amorphous chalcogenide. RTN studies evidence that the two levels in the fluctuations correspond to two different activation energies of conduction, thus unveiling the nature of noise as a local conductivity fluctuation in the thermally-activate hopping process. Based on this novel understanding, a Monte Carlo model for RTN is developed, accounting for the combined 1/f and $1/f^2$ nature of PCM noise and its size dependence. Size dependence of noise is attributed to (i) size-dependent activation energy of conduction, similar to the interpretation of size-dependent drift [13], and (ii) averaging effects along the conduction paths [11]. Finally, simulation results are used to provide noise projections in future PCM generations.

2. EXPERIMENTS

Noise measurements were conducted on PCM cells with $Ge_2Sb_2Te_5$ (GST) as active chalcogenide material, fabricated by Numonyx/Micron [14, 15]. Devices were first reset by applying a high voltage pulse of 100 ns width, then a short high-temperature annealing was applied to quench thermally-activated drift in order to keep the resistance to a stable

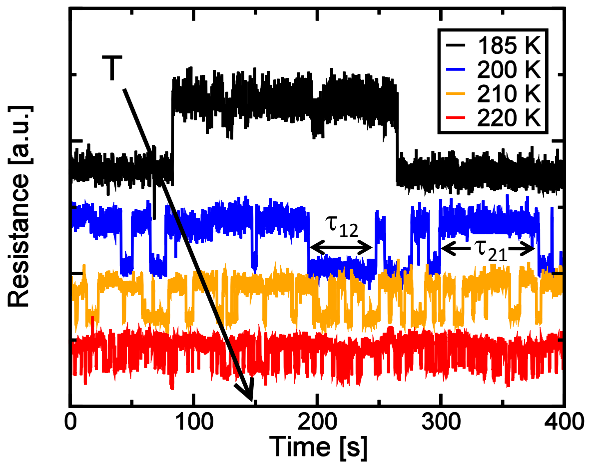

Fig. 1 Measured R as a function of time for increasing T. The measured resistance clearly displays RTN with increasing amplitude and transition times for decreasing T [12].

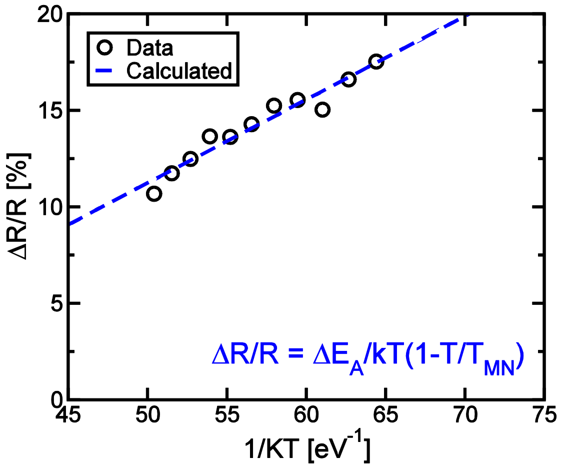

Fig. 2 Measured ΔR/R from Fig. 1, as a function of 1/kT. The linear behavior indicates a change of activation energy for conduction E_A as the root cause for the two-level conductance fluctuation [12].

level during the noise measurement. After these preparation stages, the current noise was measured through a band-pass filter, a trans-conductance amplifiers and a spectrum analyzer. Fig. 1 shows the measured resistance as a function of time, under an applied voltage of 0.1 V and for increasing temperature T. A clear RTN effect is shown, where the resistance displays a fluctuation between two levels, namely a low resistance R_1 and a high resistance R_2. Correspondingly, characteristic times τ_{12} and τ_{21} can be measured for the transitions from low to high resistance and vice versa, respectively. Both transitions become faster for increasing T, which indicates a temperature-activation of RTN. More insight into the bistable fluctuation at the basis of RTN can be obtained from Fig. 2, showing the relative change in resistance ΔR/R, where $\Delta R = R_1 - R_2$ and R is the average between the two levels, as a function of 1/kT. ΔR/R decreases linearly for increasing T, showing an intercept at $1/kT_{MN}$ with T_{MN} = 483 K.
To interpret the observed T-dependence of RTN, we use the Arrhenius law for conduction due to thermally-activated hopping [16]:

$$R = R_0 \exp(E_A / kT) \tag{1}$$

where E_A is the activation energy for conduction and R_0 is a pre-exponential factors given by the Meyer-Neldel (MN) rule [12,17], namely:

$$R_0 = R_{00} \exp(-E_A / kT_{MN}) \tag{2}$$

where R_{00} is another pre-exponential factor and T_{MN} is the isokinetic temperature, namely the temperature for the crossing of all exponential extrapolations of resistance in the Arrhenius plot [8]. Differentiating Eqs. (1) and (2), one can evaluate the resistance change induced by a fluctuation in the pre-exponential factor R_{00} or of the activation energy E_A. In the latter case, using the approximation for the resistance change given by $\Delta R = dR/dE_A\ \Delta E_A$, one obtains [12]:

$$\Delta R / R = \Delta E_A / kT (1 - T / T_{MN}) \tag{3}$$

which evidences that a linear increase of ΔR/R for increasing 1/kT should be expected in correspondence of a change in E_A. This is the behavior observed in Fig. 2, thus strongly suggesting that RTN origins from a fluctuation of the effective activation energy in the conduction path through the amorphous phase [12]. Note that this interpretation is similar to the one developed for the resistance drift, where size dependent experiments and theoretical studies have shown that resistance increases with time due to a change in the activation energy for conduction [13]. From the slope of data in the figure, Eq. (3) yields ΔE_A = 4 meV, corresponding to the change in E_A at the basis of the observed RTN.

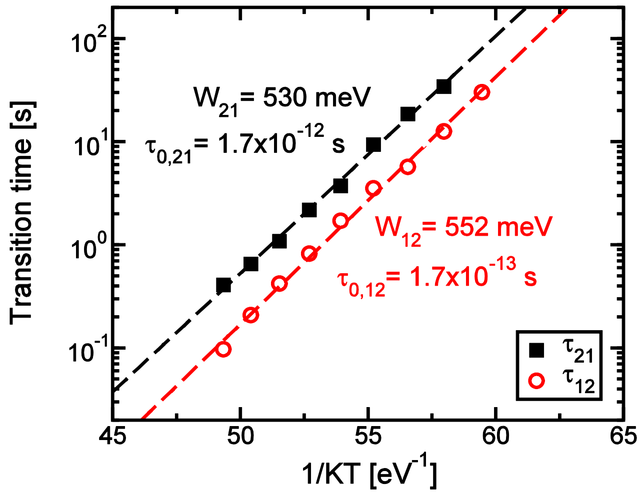

Fig. 3 Measured transition times τ_{12} and τ_{21} in the Arrhenius plot. Times were obtained from the time-domain analysis of data in Fig. 1. Arrhenius fitting from Eq. (4) is also shown [12].

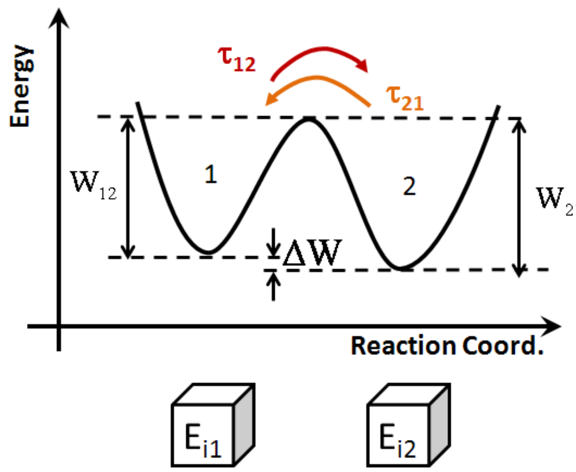

Fig. 4 Schematic energy diagram for bistable fluctuation at the basis of RTN. The small ΔW leads to slightly different transition rates between the metastable states [12].

The isokinetic temperature T_{MN} = 483 K is in agreement with results from T-dependent measurements of resistance [12]. It should be noted that a change of R_{00} in Eq. (2) would have led to a T-independent $\Delta R/R = \Delta R_{00}/R_{00}$, thus further supporting our interpretation of RTN as an activation energy driven phenomenon. From these results, we can describe RTN as due to a bistable structural fluctuation in the disordered amorphous phase, leading to a fluctuation of the energy barrier for hopping at a critical hopping site along the conduction path.

From the T-dependence of RTN transition times in Fig. 1, one can gain information about the kinetic of the structural fluctuation at the basis of the RTN phenomenon. Fig. 3 shows the Arrhenius plot of characteristic times τ_{12} and τ_{21}, obtained from the analysis of resistance waveforms in Fig. 1. The transition times τ_{12} and τ_{21} show an Arrhenius temperature dependence according to:

$$\tau_{nm} = \tau_0 e^{W_{nm}/kT} \qquad (4)$$

where τ_0 is the attempt-to-escape time and W_{nm} is the energy barrier for the transition from state n = 1 to state m = 2 or vice versa. Analysis of τ_{12} and τ_{21} through Eq. (4) yields the energy barrier W_{12} = 0.446 eV and W_{21}= 0.467 eV, respectively, while the pre-exponential time τ_0 is in the range 10^{-13}-10^{-12} s for both transition times. A small energy difference $\Delta W = W_{12} - W_{21} \approx 22$ meV is extracted between the two apparent activation energies: This corresponds to the energy misalignment between the two states of the fluctuating defect. The small ΔW is responsible for the bistable behavior of the fluctuation, since there will be no strong 'preference' of the system for one metastable state or the other. On the other hand, crystallization and structural relaxation are described as irreversible transitions from a metastable state (amorphous phase) to a relatively stable state (amorphous state in the SR case, crystalline state for the crystallization transition), as a result of ΔW being considerably larger than kT at the experimental temperature [18,19]. Note that, in the studied case of Figs 1-3, state 1 (high resistance state) is slightly more stable than state 2 (low resistance state), thus yielding activation energy barriers $W_{12} > W_{21}$. This can be seen in Fig. 1 as a longer time spent, on average, by the system in the high resistance R_1 with respect to the low resistance R_2.

3. NOISE MODEL

The Arrhenius behavior of RTN and the similarity between bistable RTN and metastable states annealing in structural relaxation at the basis of the resistance drift [18,19], we propose a physical model according to the two-level fluctuating system in Fig. 4. This shows the schematic energy diagram of a 'defect', e.g. a weakly-bonded atom or group of atoms, affected by distorted/dangling bonds or close to a vacancy or a microvoid. The defect can fluctuate between two energy minima corresponding to state 1 and state 2, having almost the same energy. The transition takes place by thermally-activated excitation over energy barriers W_{12} (from state 1 to state 2) or W_{21} (opposite transition). The transition times are thus clearly obtained from Eq. (4). The energy diagram in Fig. 4 is similar to the typical metastable picture used for structural relaxation in resistance drift [18, 19, 20]: RTN may thus be viewed as a peculiar case of resistance drift, where the similar energy of the initial and final states results in a reversible sequence of transitions between the two resistance states, as opposed to the irreversible transition to higher hopping barrier, hence higher resistance, of resistance drift [18,19].

Beside describing the fluctuation kinetic, the RTN model has to couple to an appropriate conduction model, implementing thermally-activated hopping conduction in presence of energy-barrier disorder due to the amorphous structure. To describe conduction and resistance calculation, we used the distributed Poole-Frenkel (DPF) model where the amorphous chalcogenide is composed of hopping sites with distributed hopping energy barriers E_i [8, 11]. Each hopping site was assumed to fluctuate according to the energy diagram in Fig. 4, where the two minima states correspond to two different activation energies E_{i1} and E_{i2} with difference ΔE_i. Energy barriers were randomly extracted by Monte Carlo approach between 0 and 1.35 eV leading to a wide range of local resistances within the amorphous volume, according to the Arrhenius formula [8, 12]:

$$R_{in} = R_{0i} \exp(E_{in} / kT) = R_{00,site} \exp(E_{in} / kT(1 - T / T_{MN})), \quad (5)$$

where R_{0i} and $R_{00,site}$ are local pre-exponential factors, n is an index with n = 1 or 2, and R_{0i} is given by a MN rule similar to Eq. (2). The change of energy barrier ΔE_i was assumed to be a fraction of up to 10% of the local E_i. The change of activation energy between E_{i1} and E_{i2} led to a corresponding change in resistance, leading to the two-level local fluctuation of resistance. The energy barriers W_{12} and W_{21} were also assigned randomly between 0 and 1 eV, with an energy barrier change ΔW of a few kT [21,22]. Monte Carlo simulations of defect fluctuation with a time step Δt were performed to obtain time-dependent activation energies and resistances within the discretized amorphous volume. The resulting resistance network was finally solved to yield the global resistance R(t) [8, 12].

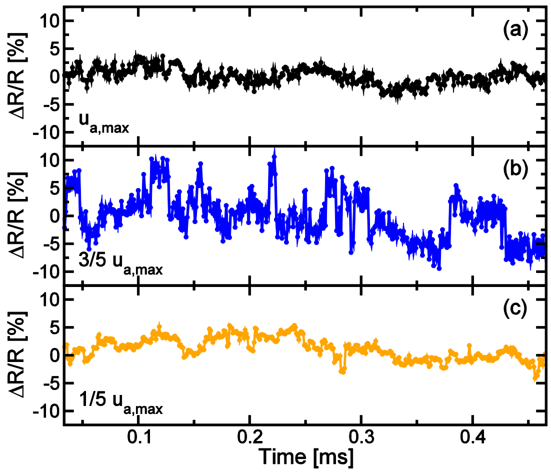

Fig. 5 Calculated R as a function of time for amorphous thickness $u_a = u_{a,max}$ (a), 3/5 $u_{a,max}$ (b) and 1/5 $u_{a,max}$ (c) [12].

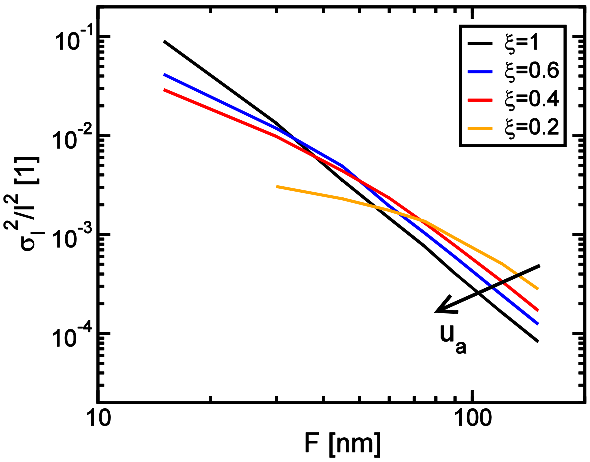

Fig. 6 Calculated average ΔR/R as a function of F for various aspect ratios $\xi = u_a/\sqrt{A}$ of the amorphous volume. Isotropic scaling approach was assumed in the calculations [12].

4. SIMULATION RESULTS

Fig. 5 shows the calculated R for amorphous regions of increasing thicknesses u_a, namely 20% (a), 60% (b) and 100% (c) of the maximum thickness $u_{a,max}$ = 36 nm. Both RTN and 1/f components can be seen in the calculated R, where the 1/f contribution comes from the envelope of a large amount of individual RTN contribution [21]. The presence of a *dominant* RTN component is due to fluctuating defects with particularly large difference in activation energy ΔE_i along the localized conduction path, thus resulting in a strong change in the global resistance. In addition, for a fluctuating defect to be dominant, it must serve as one of the critical bottlenecks for conduction. According to Fig. 10, thin amorphous regions show a relatively small noise with no visible RTN. This is due to averaging effects, where the

fluctuations coming from many parallel conduction paths is averaged out. Also, the activation energy is small in thin amorphous caps, as a result of DPF conduction and percolation effects: As a result, the relative change ΔE_i of the controlling hopping site is also small, resulting in a small $\Delta R_i/R_i$ according to Eq. (3). As u_a increases, $\Delta R/R$ increases due to the increase of activation energy for conduction. This is similar to the thickness dependence of the drift exponent in PCM devices, where the time exponent of drift increases for increasing thickness [13]. The RTN contributions also increase for increasing u_a (see Fig. 5b, $u_a = 3u_{a,max}/5$), as the effective E_A controlling the critical path increases. The noise amplitude and the RTN relative contribution finally decrease for relatively thick samples, due averaging effects, this time taking place due to multiple fluctuating defects acting in series along the relatively long hopping conduction path.
Fig. 6 shows the calculated $\Delta R/R$ as a function of the minimum feature size of lithography F, assuming an isotropic scaling of all dimensions of the amorphous volume according to a single scaling factor [12]. A reference cubic volume with aspect ratio $\xi = u_a/(A)^{1/2} = 1$, where A is the cross-section area of the amorphous volume, was used. The relative resistance change was also calculated for smaller aspect ratios ξ = 0.2, 0.4 and 0.6, corresponding to amorphous regions with shallower shape than the cubic case. For relatively large u_a, $\Delta R/R$ decreases for decreasing F, which is due to the decreasing number of hopping sites in the amorphous volume. This leads, on the one hand, to an increase of the global E_A, as a result of a limited probability to find lucky paths with small E_A, hence to an enhanced noise according to Eq. (2). On the other hand, the decreasing number of fluctuating hopping sites causes less averaging and more relative fluctuation, as already observed in resistance drift experiments [23] and calculations [12]. As ξ decreases, E_A increases less with downscaling, thus resulting in a partial compensation of the noise increase with respect to $\xi = 1$ [8]. Averaging effects and the activation energy appear thus as the main parameters controlling size-dependent noise and dictating the scaling behavior of RTN in future PCM generations.

6. CONCLUSION

A noise model based on bistable fluctuating defects in PCM is presented. T-dependent RTN evidences the origin of RTN as a fluctuation of energy barrier for conduction in thermally-activated hopping transport. This evidence serve as the physical basis of the RTN model, where conduction is described by a DPF model and bistable fluctuation introduces noise via time-dependent activation energy of hopping sites. The model can describe the size-dependence of noise in PCM, thus allowing for scaling predictions of noise amplitude in future PCM technology nodes.

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Biographies

Daniele Ielmini received the Laurea (cum laude) and Ph.D. in Nuclear Engineering from Politecnico di Milano in 1995 e 2000, respectively. In 1999, he joined the Dipartimento di Elettronica e Informazione, Politecnico di Milano, where he became an Assistant Professor in 2002 and Associate Professor in 2010. He held visiting positions at Intel Corporation and Stanford University (2006). His most recent research interests include the modeling and the characterization of emerging non volatile memories, such as phase change memory (PCM) and resistive switching memory (RRAM). He authored/coauthored two book chapters, more than 160 papers published in international journals and presented at international conferences, and three patents. He has served in several Technical Subcommittees of international conferences such as IEEE-International Reliability Physics Symposium (IRPS, 2006-2008), Semiconductor Interface Specialist Conference (SISC, 2008-2010), International Electron Device Meeting (IEDM, 2008-2009) and Insulating Films on Semiconductors (INFOS, 2011).

Davide Fugazza was born in 1981. He received the M.S. degree (cum laude) in Electronic Engineering from Politecnico di Milano, Italy, in 2006. In 2006-07 he worked as a digital hardware engineer, developing base band processing algorithms for PtP microwave radio systems. Then, in January 2008, he joined the non-volatile memory research group within the Dipartimento di Elettronica e Informazione, Politecnico di Milano, Italy, working toward his Ph.D. in Information Technology, that he attained in first quarter of 2011. His primary research interests are in the area of microelectronics devices and his research activity is mainly focused on the experimental characterization and analytical/numerical modeling of switching and reliability characteristics for phase change non volatile memories (PCMs). He also cooperates with Politecnico di Milano as a teacher assistant and he supports public/private organizations for the initiation and submission of R&D project proposals within different European Commission’s funding schemes.