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Unified physical modeling of reliability mechanisms and scaling perspective of phase change memory

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ABSTRACT

Phase change memory (PCM) is attracting an increasing interest as next generation stand-alone and embedded memory technology. Quantitative predictions of PCM scaling require a thorough understanding of physical reliability mechanisms, such as current fluctuation, structural relaxation and crystallization in the amorphous phase. This work describes recent advances in the physical modeling of structure fluctuation, relaxation and crystallization for the amorphous chalcogenide in PCM cells, showing a unified interpretation of relaxation/crystallization kinetic. The statistical variability of crystallization in PCM arrays and potential limitations in memory downscaling are discussed.

1. Introduction

Nonvolatile memory (NVM) has grown tremendously during the last 20 years as the enabling technology for portable devices, such as cell phones, multimedia players and memory sticks. The continuing downscaling of size and cost of NVM has been achieved by Flash memories, which are based on charge storage into a floating gate of a MOS transistor. Future Flash scaling beyond the 20 nm node is however made difficult by increasing capacitive coupling between floating gates and few electron effects [1,2]. Among the several options for NVM downscaling, phase-change memory (PCM) is considered one of the most attractive technology for both stand-alone and embedded applications. However, PCM scaling will ultimately be limited by size-dependent and statistical reliability mechanisms, which are still not fully understood today [3].

This paper describes recent progress in the understanding of reliability in PCM cells, which are mostly affected by the metastable nature of the amorphous chalcogenide material. Physical models for structural relaxation and crystallization will be discussed and a unified interpretation of their thermally-activated kinetics will be presented. The array statistics of crystallization will be addressed and the potential scaling limitations will be pointed out and discussed.

2. PCM concept and reliability

The PCM relies on the electrically-operated phase transition in the active chalcogenide material, that is a compound or alloy including at least one element from the sixth group of the periodic table (most typically S, Se and Te). If heated above the melting point and suddenly quenched to room temperature, the chalcogenide material can be frozen into an amorphous phase, with no long range atomic order. The crystalline phase can be recovered by heating the amorphous region at sufficiently high temperature, enabling recrystallization at the solid state [4,5]. The two phases can be discriminated by their electrical resistance, as schematically described by the band structure shown in Fig. 1. The crystalline chalcogenide is characterized by a doped-semiconductor behavior with a relatively small band gap and Fermi level lying close to the valence band. The amorphous phase is instead described by a mobility gap with large density of *localized states*, originating from disorder and point defects (e.g. dangling bonds, vacancies, etc.) [6–10]. The Fermi level is generally located around the middle of the mobility gap, resulting in the lower portion of the mobility gap being filled by localized electrons. These electrons can only contribute to the electrical current by substantial thermal excitation to the conduction band edge, while localized holes must be similarly excited to the valence band edge. This generally results in a large resistance with relatively large activation energy, in the 0.25–0.4 eV range for $Ge_2Sb_2Te_5$ (GST) [11]. Reliability issues stems from (i) the well-known metastable nature of the amorphous state as compared to the stable crystalline state, and (ii) the intimate relationship between atomic structure in the amorphous phase and

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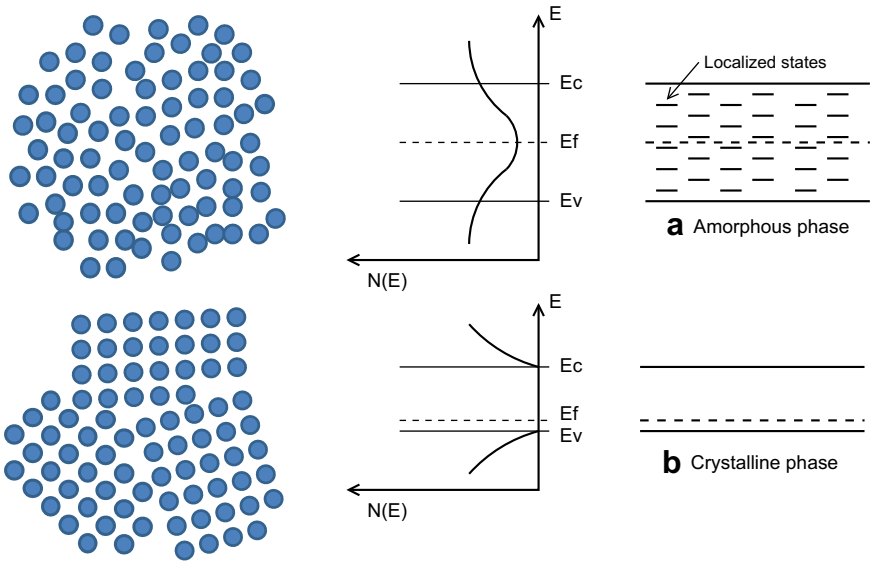

Fig. 1. Schematic for the amorphous (top) and the crystalline phase of the chalcogenide material in a PCM device (bottom): atomic (left) and band structure (right) [7]. ((c) 2009 IEEE).

its band structure. For instance, a reduction of localized states due to short-range ordering during structural relaxation will result in an increase of the mobility gap, hence in a drift of resistivity and of its activation energy [7,12]. The change of the electrical properties of the chalcogenide material will possibly affect the cell status, thus possibly raising a reliability concern.

The amorphous phase stability can be described by the diagram in Fig. 2, schematically showing the free-energy profile as a function of a generalized reaction coordinate [13]. Energy minima represent stable/metastable states of the material system. Three types of transitions between energy states are possible, depending on the relative position of the energy minima and on the energy barrier height between minima. First, the transition between equal-energy minima separated by a relatively low-energy barrier E'_A will result in a fluctuation of resistance, or current noise. The transition may describe for instance the flipping of a weak bond between two metastable states or the fluctuation of a weakly-bonded atom between two positions [14]. A single structural transition will give rise to a typical two-level fluctuation of the current, leading to a random telegraph noise (RTN) [15]. However, due to the large number of atoms and defects contained in the cell active volume, many pairs of metastable states with distributed transition barriers E'_A, hence exponentially distributed frequencies, simultaneously fluctuate in a PCM cell. The superposition of several RTN effects with distributed frequencies will give rise to a $1/f$ noise, as generally observed in PCM devices [16,17]. The typical time behavior of resistance affected by $1/f$ noise is illustrated in Fig. 3, showing the reset-state PCM resistance as a function of time after the reset responsible for the formation of the amorphous volume within the cell. Cell downscaling results in a decrease of the number of fluctuating pairs contributing to noise, leading to an increase of the noise-signal ratio and a larger probability for RTN. Giant RTN effects in PCM have indeed been recently demonstrated in scaled PCM devices [15].

3. Structural relaxation

In addition to $1/f$ noise, Fig. 3 also shows that the PCM resistance R steadily increases with time. This is the so-called resistance drift, which is generally observed for full or partial reset states and is described by a power law with time given by:

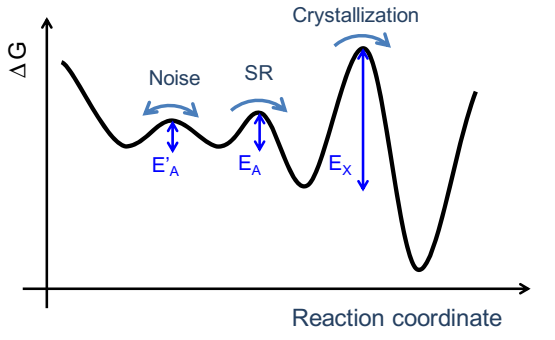

Fig. 2. Schematic picture for the free energy as a function of a generalized reaction coordinate, highlighting three types of possible transition from metastable states in the amorphous phase: (i) fluctuation between two amorphous-phase metastable states at similar energy level (left), (ii) structural relaxation (SR) from an amorphous metastable state to a higher-stability amorphous state with a lower energy (center) and (iii) crystallization from a metastable amorphous state to a crystalline state. The corresponding energy barriers E'_A, E_A and E_x, acting as activation energies for the fluctuation, SR and crystallization, respectively, are also shown.

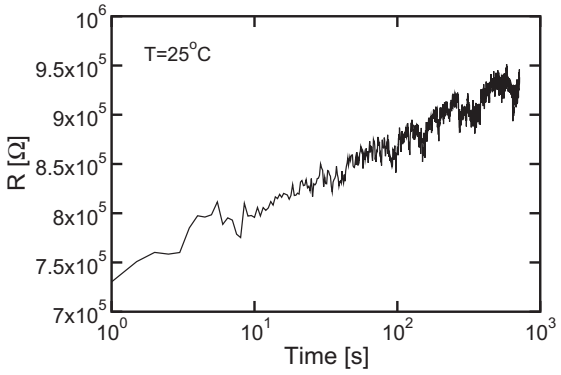

Fig. 3. Measured resistance for a PCM cell at room temperature as a function of time after the application of the reset pulse responsible for the formation of the amorphous phase. The resistance behavior displays $1/f$ fluctuation and a power-law increase with time due to SR [7]. ((c) 2009 IEEE).