Kinetic of resistance drift in PCM by structural relaxation of the amorphous chalcogenide phase

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ABSTRACT

Amorphous materials are known to undergo temperature-accelerated structural relaxation (SR), affecting the electrical and optical properties. Due to SR, phase change memory (PCM) displays a drift of resistance after programming. Our study of SR in PCMs demonstrates that drift is controlled by the activation energy for conduction, allowing for the optimization of programming algorithms and active material for minimum drift. Statistical analysis reveals the defect-related nature of resistance drift. The possible physical processes responsible for resistance drift are finally discussed.

Key words: phase change materials, phase change memory, structural relaxation, resistance drift, reliability modeling.

1. INTRODUCTION

The ability to understand and model physical phenomena in the active materials of phase change memory (PCM) is essential for the development and scaling of a robust device technology. Conduction and switching mechanisms in the amorphous phase, thermally-activated crystallization and current fluctuations need to be carefully modeled to allow for physics-based prediction of memory reliability and scaling. This work addresses the resistance drift, that is the spontaneous increase of resistance with time which is commonly observed in PCM cells containing an amount of amorphous phase [1-9]. Although there is a general consensus in attributing resistance drift to structural relaxation (SR), the detailed mechanisms for the resistance change as a result of SR are not clear. Here we show new experimental results for SR revealing that drift kinetics is controlled by activation energy for conduction. The possible physical mechanisms affecting the electrical properties of the memory cell are discussed.

2. RESULTS AND DISCUSSION

Fig. 1 shows the measured resistance R as a function of time, for PCM states with different R, obtained by different amplitudes of the programming pulses. The cell was first programmed at room temperature (RT), than subjected to annealing at elevated temperature in the range 80-160°C, finally measured at RT. All data are shown as a function of annealing time normalized to 120°C as discussed in [6]. R increases with annealing time according to a power law $R \propto t^{\nu}$, with ν varying between about 0 for the set state (low R) to about 0.12 for the reset state(high R, see the inset).

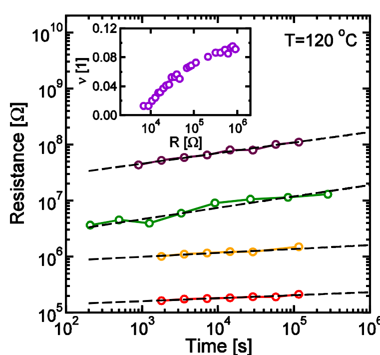

Fig. 1 Measured R as a function of annealing time normalized at 120°C. The inset shows the time exponent ν as a function of resistance.

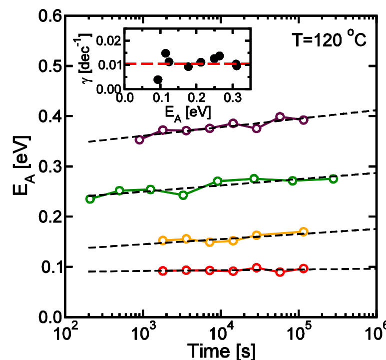

Fig. 2 Measured E_A as a function of time for the same devices in Fig. 1. The inset shows γ in $E_A = E_{A0}(1+\gamma\log(t/t_0))$.

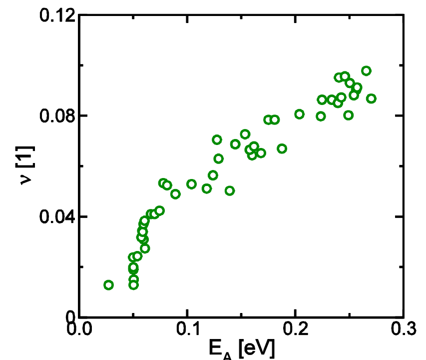

Fig. 3 Measured ν as a function of R [7].

To highlight the main mechanism controlling resistance drift, Fig. 2 shows the measured activation energy E_A for conduction as a function of annealing time, for the same devices shown in Fig. 1. E_A increases with time, thus leading

to the measured resistance increase as a result of the exponential dependence $R = R_0\exp(E_A/kT)$ [5]. Note that the pre-exponential constant R_0 remained virtually constant during annealing (not shown). The increase of E_A can be empirically modeled as $E_A = E_{A0}(1+\gamma\log(t/t_0))$, where $\gamma \approx 0.01$ is a constant irrespective of the initial value of E_A, as shown in the inset. This indicates that E_A is the controlling parameter for resistance drift, namely a slow drift rate can be achieved by reducing E_A, by e.g. engineering the active material or optimizing the programming operation.

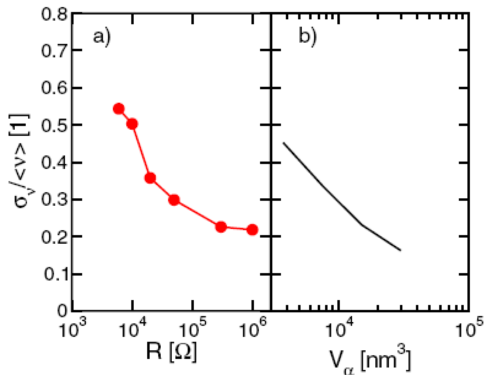

Fig. 4 Measured NSD of power-law drift exponent as a function of R (a) and calculated NSD as a function of amorphous volume (b) [7].

Further insight into the drift phenomenon can be gained from the time dependence of the measured I-V curve indicating an increase of subthreshold slope [5] and from the statistical spread of the drift exponent [5,7]. Fig. 4a shows the measured normalized standard deviation (NSD) σ_ν/ν as a function of R. Data were obtained from a sub-array of 6k cells in a 180 nm technology memory test device [7]. NSD increases for decreasing R, thus decreasing volume of the amorphous phase. This can be interpreted as the dependence of the drift spread on the length of the percolation path through the amorphous dome. In fact, the percolation path consists of localized states at structural defects (e.g. dangling/distorted/wrong bonds, vacancies, etc.). The SR of these defects changes the percolation resistance, resulting in the observed drift. Relatively short percolation paths contain a smaller number of defects, thus contributing a larger standard deviation of drift. This statistical behavior is similar to the increased spread of threshold voltage in nanoscale MOSFETs due to discrete random dopants. The physical interpretation is confirmed by numerical calculations with Monte Carlo SR model based on random defect annihilation, as shown in Fig. 4b [7].

Resistance drift has been alternatively interpreted as due to mechanical stress relaxation [3] and the smaller drift rate of intermediate states was attributed to the smaller amorphous volume suffering a lower stress by the surrounding crystalline phase [8]. However, this interpretation would imply that the observed increase of E_A with time in Fig. 2 results from the relaxation of compressive stress. This is in contrast with the observed increase of E_A for increasing amorphous volume, hence increasing compressive stress, due to the surrounding polycrystalline phase. Although a secondary role of mechanical stress on drift would be hard to rule out [9], resistance drift in PCMs seems thus to be primarily due to relaxation of the atomic structure, involving a temperature-accelerated change in the localized states responsible for electron conduction [2,4-6]. SR phenomena are indeed observed not only in stress-affected PCM devices after reset, but are rather ubiquitous in several glassy materials from metallic glasses to amorphous Si, as well as deposited chalcogenide films (e.g. see [5] and references therein).

3. CONCLUSION

The current understanding of resistance drift effect in PCMs is reviewed and discussed. The evolution of resistance and conduction activation energy for different programmed states is studied as a function of time, showing that drift is mainly controlled by the activation energy. The statistical spread of time exponent reveals the defect-related nature of the drift effect. Our results confirms that, although mechanical stress may influence the relaxation dynamics, resistance drift is mainly due to structural relaxation affecting the localized states involved in the conduction process.

REFERENCES

[1] A. Pirovano, A. L. Lacaita, A. Benvenuti, F. Pellizzer, and R. Bez, IEEE Trans. Electron Devices 51, 452, 2004.
[2] D. Ielmini, A. L. Lacaita and D. Mantegazza, IEEE Trans. Electron Devices 54, 308-315 (2007).
[3] I. V. Karpov, M. Mitra, D. Kau, G. Spadini, Y. A. Kryukov, and V. G. Karpov, J. Appl. Phys. 102, 124503 (2007).
[4] D. Ielmini and M. Boniardi, Appl. Phys. Lett. 94, 091906 (2009).
[5] D. Ielmini, D. Sharma, S. Lavizzari and A. L. Lacaita, IEEE Trans. Electron Devices 56, 1070-1077 (2009).
[6] D. Ielmini, M. Boniardi, A. L. Lacaita, A. Redaelli and A. Pirovano, Microelectron. Eng. 86, 1942-1945 (2009).
[7] M. Boniardi, D. Ielmini, S. Lavizzari, A. L. Lacaita, A. Redaelli and A. Pirovano, Proc. IRPS, 122-127 (2009).
[8] S. Braga, A. Cabrini and G. Torelli, Appl. Phys. Lett. 94, 092112 (2009).
[9] M. Mitra, Y. Jung, D. S. Gianola, and R. Agarwal, Appl. Phys. Lett. 96, 222111 (2010).