Microprocessor and multi-state memory devices using phase-change technology

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ABSTRACT

A rate-equation approach is used to perform dynamic modeling of phase-transformation processes that define the operating regimes and performance attributes of electronic (and optical) processors and multi-state memory devices based on phase-change materials. The prediction of the so-called 'energy accumulation' and 'direct overwrite' regimes, pre-requisites for processing and memory functions respectively, emerge in detail from the model providing a theoretical framework for future device design and evaluation.

Key words: phase-change memories, multi-state memories, phase-change processors

1. INTRODUCTION

Electrical memory devices based on the reversible transition between amorphous and crystalline phases in chalcogenide alloys, such as GeSbTe, are attracting much interest, in particular as possible replacements for silicon 'Flash' memory. The development of binary memories currently predominates, but multi-state memories are also of much interest since they offer greater storage capacity. More remarkable and far-reaching potential applications of phase-change technology, recently discussed by S.R. Ovshinsky and co-workers [1,2], include the provision of non-Von-Neumann (micro) processing devices capable of both general-purpose computation and 'cognitive' function. The origins of such possibilities lie in the detail of the phase-transformation event itself. In conventional phase-change memories crystallization relies on both electronic and thermal effects; applying a voltage above a certain value induces a conducting on-state in the previously high-resistance amorphous material, allowing current to flow which in turn generates heat to drive crystallization. The electrical resistance during switching changes abruptly at the 'percolation threshold', where growing (nano)cystallites merge to form the first conducting pathways between device electrodes. It is the pre-threshold region that offers the potential to perform general-purpose computation and provide artificial neuron-like capabilities. This may be explained by considering pre-percolation behaviour to involve energy-accumulation; energy is accumulated and crystal clusters grow as each input pulse is applied and when enough energy has been accumulated to reach the percolation threshold the cell resistance changes abruptly. This energy accumulation property has the potential to implement basic mathematical operations such as addition, subtraction, multiplication and division, as well as more complex functions such as factoring, encryption and logic [1,2]. The accumulation property, the presence of a distinct threshold, and a non-linear (output) transition (between resistance states) mimic the basic action of a biological neuron. Furthermore, the (synaptic) weighting of inputs might be provided by another phase-change cell operating in the multi-level storage regime. Thus, an artificial neuron might be achieved using only phase-change cells. In this paper we investigate some of these novel concepts for the use of phase-change materials using a theoretical approach based on rate-equation models [3] for understanding the phase-transformation process.

Two basic arrangements for using phase-change cells to provide processing and cognitive-like functions are shown in Fig 1.

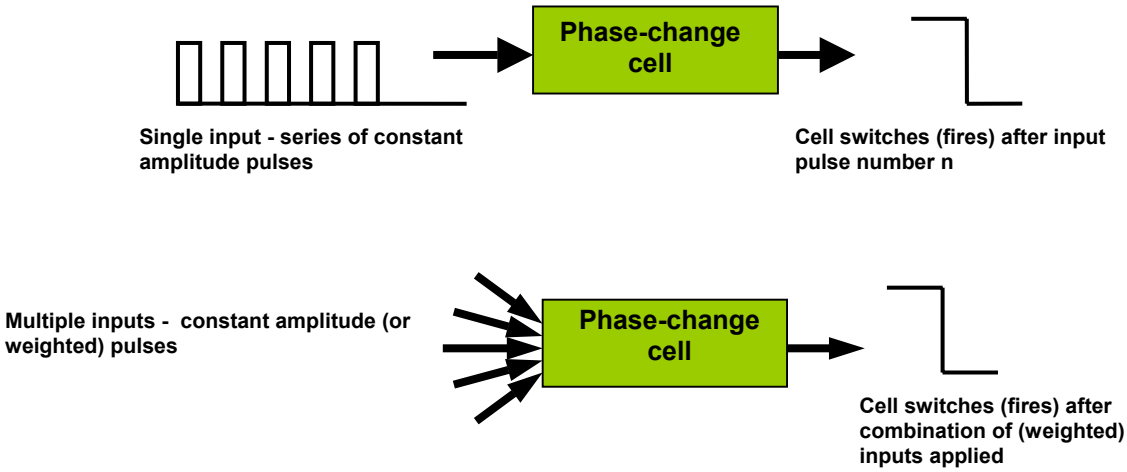

Figure 1: The basic arrangements for providing processing (top) and cognitive-like (bottom) functions using phase-change technology

2. THE RATE-EQUATION MODEL

Several methods have been used over the years to model the process of crystallization in phase-change alloys, such as the Johnson-Mehl-Avrami-Kolmogorov model (JMAK). Unfortunately many of the assumptions on which JMAK is based are violated in real switching events in phase-change devices. Furthermore JMAK cannot distinguish materials with the same crystallized fraction but different crystallite size distributions, and this is important to predict the dynamical progress of the complex anneals necessary for multi-state memories and phase-change processors. Another common approach is based on separable nucleation and growth models, often used to examine optical phase-change recording [4]. However, such approaches deal only with crystal clusters at or above the critical (stable) size, whereas sub-critical clusters are also likely to play a significant role in the nanoscale dynamic behavior of future devices. An attractive, physically plausible, alternative to these more established methods is the master-equation approach that models the evolution of the crystal cluster size distribution during the entire phase-transformation process [3,5]. Using rate equations, the frequencies of attachment and detachment of material 'monomers' representing unit changes in crystal cluster sizes can be determined.

The basis of the rate-equation approach is determination of the distribution function, Z(n, t), representing the density of crystal clusters of size n (monomers) at moment t. Changes in the crystal cluster sizes occur when 'monomers' are attached to or detached from existing clusters. In all the simulations presented here a discrete version of the master-equation has been used for which the temporal evolution of the cluster density Z is given by [3]

$$\frac{\partial Z(n,t)}{\partial t} = g(n-1,t,T)Z(n-1,t) + d(n+1,t,T)Z(n+1,t) - g(n,t,T)Z(n,t) - d(n,t,T)Z(n,t) \quad (1)$$

where g(n, t,T) and d(n, t,T) are, respectively, the rates of attachment to and detachment from a crystal cluster of size n units (monomers) and depend strongly on temperature (primarily via (i) Boltzmann factors defined in terms of Gibbs free energy differences between cluster sizes *n* and *n+1* and (ii) a jump frequency at the crystal/amorphous interface). More complete details of the model can be found elsewhere [3,5], and a diagrammatic representation of the processes modelled by the rate-equation approach can be seen in Fig. 2

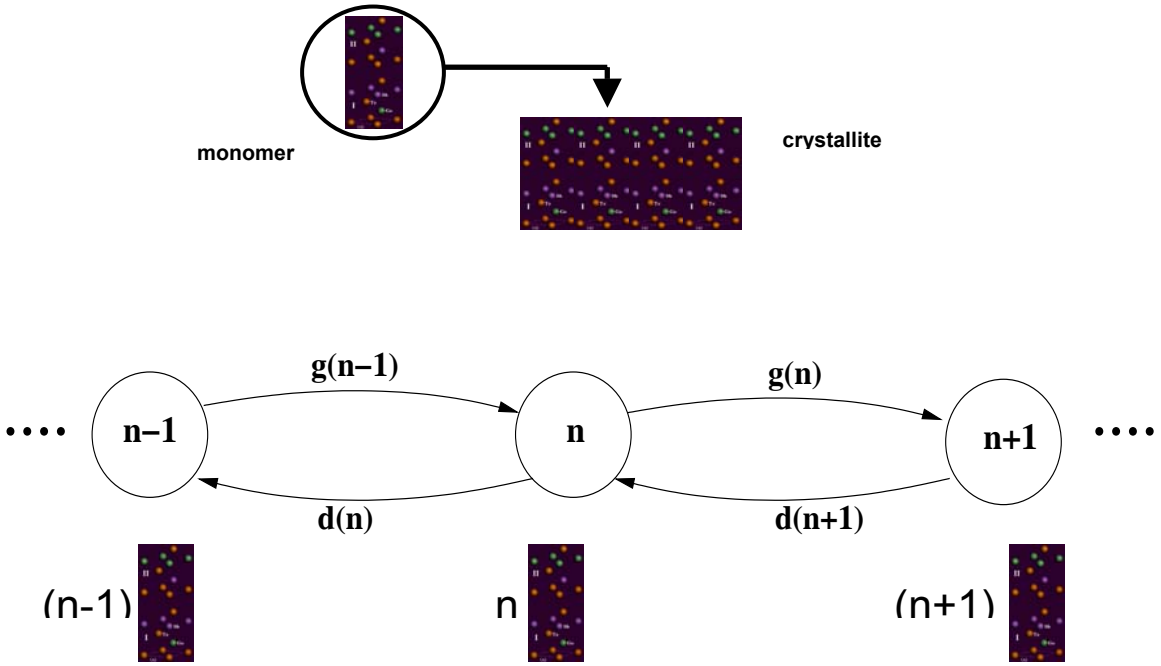

Figure 2: Schematic of the rate-equation approach. Monomers, or unit-cells, of $Ge_2Sb_2Te_5$ in this case, can add together to form crystallites. Monomers may attach or detach from crystal units of size n to form crystal units of size (n+1) or (n-1). In this way crystals may grow or shrink. The rate equation approach model contains nucleation, growth and dissociation as inherent processes.

3. RESULTS & DISCUSSION

We have used the rate-equation model to investigate the use of a phase-change cell as both a processor and a multi-state memory [6]. Figure 3 shows the case for an initially amorphous $Ge_2Sb_2Te_5$ cell (all monomers) subject to successive heat pulses (each pulse set the temperature in the cell to 350^0C for 50 ns with pulses 1μs apart). The cell was reset by the tenth pulse into the amorphous state. The figure reveals a monotonically increasing crystallized fraction with increasing number of pulses. The number of monomers (not shown) decreases monotonically while the number of dimers (n=2) and multimers ($n = n_{max}$) increases monotonically. The phase-change cell is effectively accumulating energy with each pulse and crystal clusters grow in size and number as the anneal progresses. Each particular crystallized fraction in the annealing cycle corresponds to a particular cell resistance in a real device and so by monitoring the cell resistance a decimal counter/adder, or more general purpose processor, could easily be obtained.

Next, we explore the so-called 'direct overwrite' or 'multi-state' storage regime. Figure 4 shows the results of simulations together with details of temperature variation during the anneal. For relatively low temperature anneals the crystalline fraction is 'remembered' from the previous step and we are in the energy accumulation regime, while for higher temperatures the crystalline fraction moves repeatably within the space of one pulse directly to a given state. In this latter so-called multi-state or direct-overwrite regime, the final crystallized fraction is independent of the initial state and depends only on the annealing pulse duration and amplitude (temperature), yielding a controllable multi-state memory.

Simulations of cognitive-like behaviour are currently being conducted, and results will be presented soon.

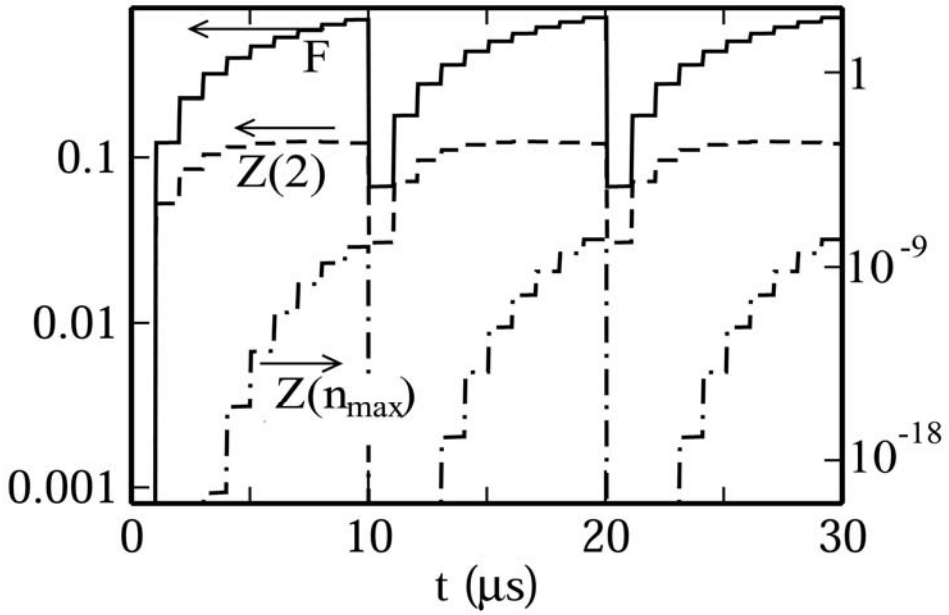

Figure 3: Crystallized fraction F (i.e. sum of Z(n) from n = 2 to n = n_{max}) (solid), density of dimers Z(2) (dashed) and density of multimers $Z(n_{max})$ (dash-dot) for an anneal cycle comprising successive 350 ^{0}C, 50ns pulses at 1μs intervals, followed by a reset pulse.

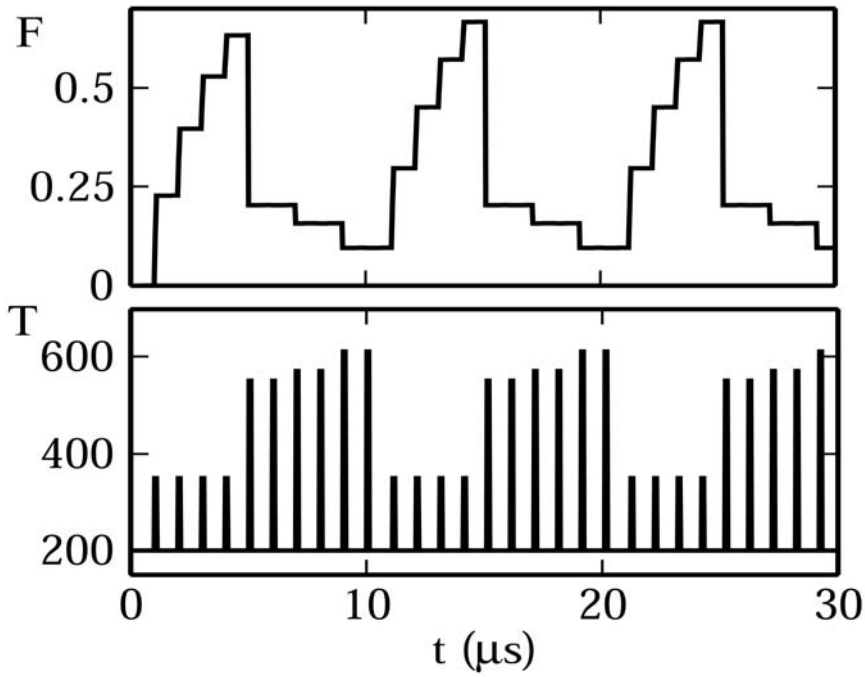

Figure 4: The crystalline fraction (top) as a function of time during an anneal comprising 100 ns pulses at 350^{0}C (4 pulses), 550^{0}C (2 pulses), 570^{0}C (2 pulses) and 610^{0}C (2 pulses).

4. CONCLUSION

Phase change technology is now well-known for its applications in optical storage and is increasingly of interest as an alternative to CMOS-based Flash memory. Phase-change technology may also have some intriguing applications beyond simple binary memories, as discussed by S.R.Ovshinsky at previous EPCOS conferences and elsewhere. Such applications include non-Von-Neumann (micro) processing, multi-state memory and even cognitive-like functions. In this paper we have presented a modelling approach to understanding some of these new and interesting uses of phase-change materials and systems.

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Biography

David Wright is Professor of Electronic and Computer Engineering at the University of Exeter in England. He took a BSc degree in Physics in 1978 at Imperial College London, and a PhD in 'Perpendicular Magnetic Recording', supervised by Professor Barry Middelton, in 1984. He also worked for Philips Electronics in Manchester, England from 1978 to 1980. Professor Wright has worked for over twenty years investigating new (at the time) types of magnetic, optical and phase-change memory materials, devices and systems. He is particularly interested in understanding and characterising the write and read-out processes in magnetic and phase-change memories.