Novel Applications Possibilities for Phase-Change Materials and Devices

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ABSTRACT

Phase-change materials and devices are most widely known for their use in optical and electrical non-volatile memory applications. Recently however the potential has been demonstrated for using phase-change materials and devices for a range of novel applications, including the provision of electronic 'mimics' of biological synapses and neurons (and their associated use in neuromorphic computing) and the provision of arithmetic and logic functionality. Furthermore, such neuromorphic, arithmetic and logic capabilities of phase-change materials and devices are accessible in both the optical (photonic) and the electrical (electronic) domains, or indeed via a 'mixed-mode' approach in which excitation is in the optical domain and detection is electrical, or vice-versa. This versatility of operation opens up the route towards various intriguing possibilities, such as 'all-optical' memory and computing devices, or the development of an optical analogue of the memristor, the so-called 'memflector'. In this paper we discuss such novel applications possibilities for phase-change materials and devices and present proof-of-principle of some of the underlying concepts.

Key words: phase-change processors, neuromorphic, memflector

1. INTRODUCTION

Electrical phase-change memories (PCMs) have been the subject of intense research in recent years due to their possible use as a replacement for CMOS 'Flash' memory and/or for DRAM memory, and also as a route for the provision of so-called 'storage class memory' [1]. Optical phase-change memories, such as re-writable DVDs, have been with us even longer. In these 'conventional' phase-change memories binary data is stored as crystal or amorphous regions, with the two phases having very different electrical and optical properties (resistivity and refractive index) and for binary storage the aim is to ensure complete crystallization (and re-amorphization) with a single (electrical or optical) excitation. However, as pointed out many times by Stan Ovshinsky and his co-workers (see for example [2-5]), simply using phase-change materials for binary storage barely begins to exploit their potential functionality which extends, quite remarkably, to arithmetic processing, logic and even bio-inspired or neuromorphic (or as Ovshinsky termed it, 'cognitive') computing.

The origins of this advanced functionality of phase-change devices is best illustrated using one of Stan Ovshinsky's diagrams from his EPCOS2004 keynote, reproduced here in **Fig. 1a**. Here the two fundamental operating regimes of phase-change devices are shown, the *accumulation-regime* (LHS in Fig. 1a) and the *multi-state regime* (RHS in Fig. 1a). It is by clever exploitation and manipulation of these phase-change accumulation and multi-state regimes that we can provide the advanced arithmetic and neuromorphic ('brain-like') processing capabilities using phase-change devices. Specifically, the accumulation regime is best suited to arithmetic processing and the provision of neuronal mimics [6,7], while the multi-level resistance regime is suited to the provision of synaptic mimics [8-10]. Both the accumulation and multi-state regime can be used for the provision of multi-level memories, with the multi-state regime (where multi-level resistance states are obtained by increasing the size of the amorphized region) usually proving to be the most controllable and more suited to practical implementation of multi-level phase-change memories.

It should be noted that the fact that phase-change devices can 'remember' their previous excitation history means that, in the electrical domain, phase-change devices may be thought of as a form of 'memristor', the so-called missing circuit element linking charge and flux and expounded by Chua in the early 1970s [11, 12] and observed in TiO_2 devices by Williams et al. in 2008 [13]. The fact that phase-change devices are a form of memristor (and Chua recently stated that all 2-terminal non-volatile resistive memories are a form of memristor [14]) also means that it should also be possible for phase-change devices to provide all the functionality that more conventional (i.e. transition-metal oxide or perovskite oxide type) memristors can provide, such as Boolean logic and logic by implication (see e.g. [15]). However, a notable difference, and perhaps an advantage, of phase-change memristors over their conventional oxide-based counterparts is that phase-change devices are simultaneously optically and electrically active. We can switch them optically and measure their response optically, or we can switch them electrically and measure their response electrically; alternatively we can switch them optically and measure their response electrically (or vice-versa). This versatility of operation (of phase-change devices) opens up the possibility of some novel operating modes with potentially interesting applications, some of which we describe below.

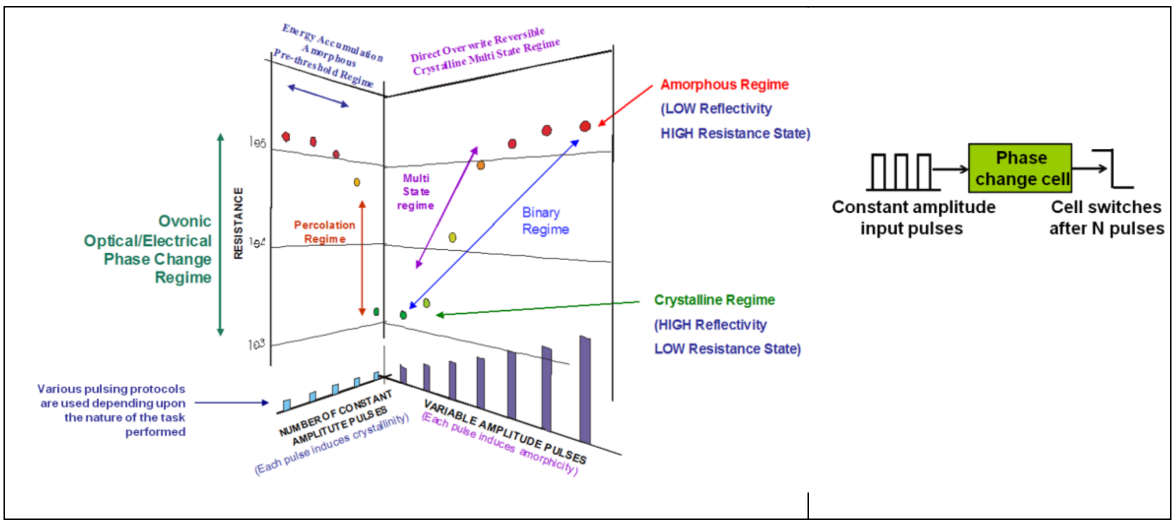

Fig. 1: (a) The accumulation and multi-state phase-change regimes (left), taken from [5] and (b) schematic operation of a phase-change accumulator, where the cell switches from the RESET to the SET state only after the receipt of N pulses (right).

2. PHASE-CHANGE ACCUMULATORS AND PHASE-CHANGE NEURONS

We have, based upon Stan Ovshinsky's original suggestion, previously demonstrated how the accumulation regime can be used to perform arithmetic computations (addition, subtraction, multiplication, division, factoring) in both the optical [6] and electrical [7] domains. The basic operating mechanism is shown schematically in **Fig. 1b** where a single (potentially nanometric in size) phase-change cell accumulates energy from each input pulse, gradually transforming it from the amorphous to the crystalline phase. This provides a form of electronic abacus which both simultaneously calculates and stores the result (so providing a form of non Von-Neumann computing architecture). The amplitude of the input excitations, and/or their duration, determines the number of input pulses needed to ultimately switch the cell (i.e. to force it into the crystalline or SET state). In

Fig. 2a, for example, we show phase-change accumulator responses for performing arithmetic in bases 6, 4 and 2, obtained using $Ge_2Sb_2Te_5$ cells of 100 nm in diameter and switched using the C-AFM-based system shown in **Fig. 2b**. We also implemented a base-10 accumulator in the same way, and with such accumulators demonstrated base-10 addition, base-6 subtraction and 'parallel' factorization (see [7]). Such accumulator responses are of course also available in the optical domain (see [6]).

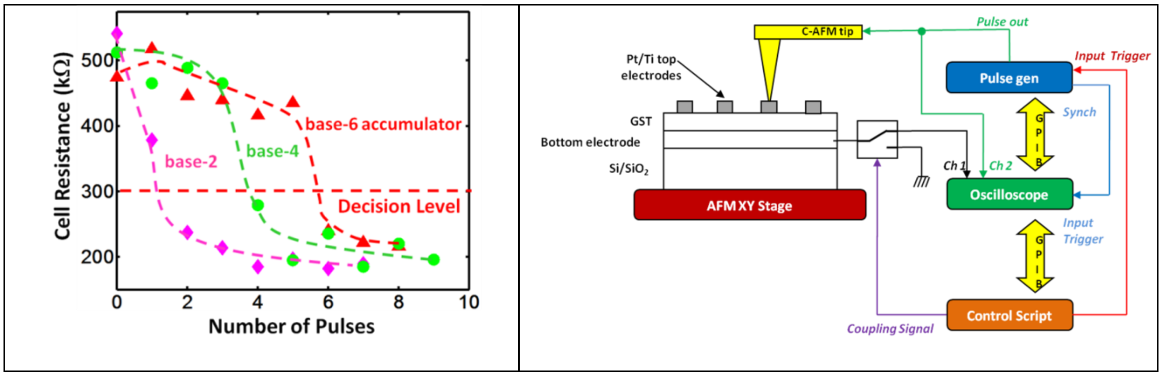

Fig 2: (a) Experimental realization of phase-change accumulators working in bases 2, 4 and 6 (left) and (b) C-AFM arrangement (see [7])used to access and switch the ~100 nm diameter $Ge_2Sb_2Te_5$ cells (right).

The natural accumulation process inherent to phase-change materials and devices can also be used to provide a simple form of phase-change integrate-and-fire neuronal 'mimic', as pointed out by Stan Ovshinsky at numerous PCOS and E/PCOS meetings going back as far as 1997 [16]. Indeed, a simple phase-change based neuron circuit can be realized using only one active device (the phase-change cell itself), as shown in **Fig. 3a**; here the 'neuron' accumulates excitations from incoming pulses and 'fires' (i.e. switches to a low resistance state), causing the comparator to switch, only after the receipt of a certain number of pulses. Indeed, by feeding back the output of the comparator to the phase-change cell (after a small delay) it is possible to 'self-reset' the phase-change cell and comparator so that the circuit can begin accumulating once more, ready for the next firing event. This is illustrated in **Fig. 3b** where the input to the phase-change cell and the output of the comparator are shown from a SPICE simulation of the circuit of Fig. 3a connected to a MOS transistor comparator.

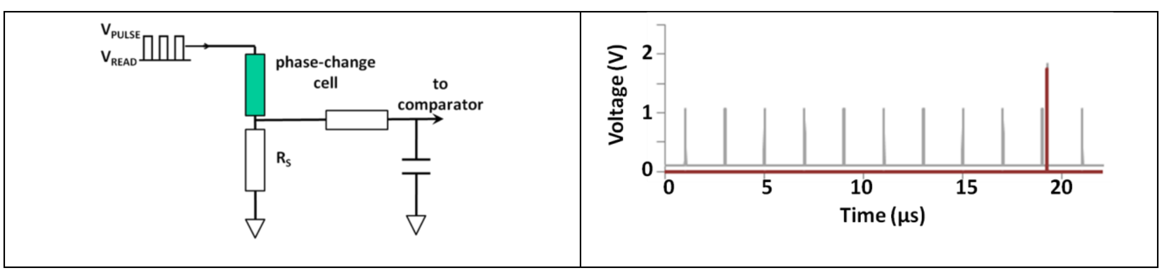

Fig. 3: (a) A phase-change neuron circuit exploiting the accumulation regime (left) and (b) the operation of a 'self-resetting' version of the neuron circuit in which the output of the comparator is fed back to the input of the phase-change cell (right; grey pulses input to phase-change cell, red pulse output of comparator).

3. PHASE-CHANGE MEMRISTORS AND MEMFLECTORS

The operation of a memristor is often described using the so-called moving conductive-front model. Here the application of a voltage across the device terminals causes the interface between doped (i.e. low resistivity) and un-doped (i.e. high resistivity) portions of the active region to move either left or right depending on the polarity of the voltage applied, resulting in a change in device resistance. A seemingly equivalent situation to this exists for phase-change devices, where we might imagine the un-doped and doped regions being replaced with amorphous and crystal phases, and the moving conductive-front becomes the amorphous-crystalline boundary. Furthermore, in phase-change devices we can also excite and/or measure the state of a device optically, leading, as we discuss below, to a optical analogue of the memristor that we term the *memflector* (memory-reflector).

A schematic of a phase-change device suitable for optical, electrical or mixed-mode operation is shown in **Fig. 4a**. We have simulated the switching behaviour of such a device for both optical and electrical simulations (of the form also shown in Fig. 4a), while also monitoring the response in both domains. In **Fig. 4b**, for example, we show the I-V curve for the device during each of five up/down ramped electrical excitation cycles of the form often used to characterize memristor device. Inspection of Fig. 4b shows that the 'up' curve of one cycle of the I-V response does not follow the 'down' curve of the preceding cycle; this is different to the behavior seen in many memristive devices (such as the 'classical' TiO_2 device [13,15]) and arises due to the field-dependent conductivity of the amorphous phase leading to significantly different temperatures to be experienced by the phase-change layer during the down and up curves of successive cycles. Since, in this simulation, we also have optical access to our phase-change device, we can also measure the reflectivity of the $Ge_2Sb_2Te_5$ layer during each of the electrical excitations. This is shown in **Fig. 4c**, where it can be seen that the 'up' curve for one cycle does now follow the 'down' curve of the previous cycle; this is because we are monitoring reflectivity rather than resistance, so the electrical field dependence of conductivity is no longer playing a dominant role [17]. Operating in this mode (of Fig. 4c) the phase-change device provides a form of mixed-mode memristor (electrical excitation, optical output). If however we apply both optical stimulation and take an optical output, we have an 'all-optical' equivalent of the memristor, which, as already mentioned above, we have termed the *memflector* [6]. The response of such a memflector is shown in **Fig. 4d** for the optical excitation shown in Fig. 4a.

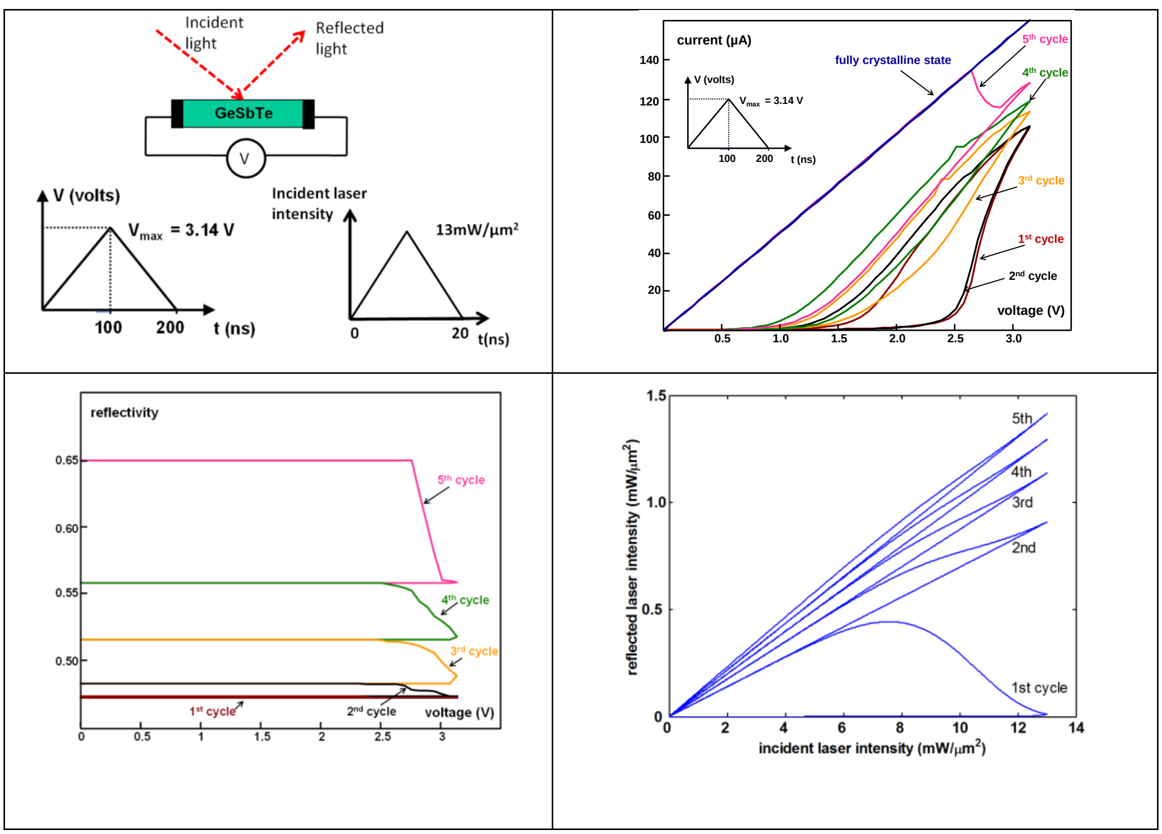

Fig 4: (a) Schematic of a mixed-mode phase-change device (top-left) and electrical and optical excitations used; (b) I-V curves during successive electrical up/down ramped excitations (top-right); (c) reflectivity-voltage curves during the same electrical up/down excitations (bottom-left); (d) the memflector response (the optical analogue of the memristor) for ramped up/down optical excitations.

We have begun to implement phase-change memflectors practically, based around $Ge_2Sb_2Te_5$ lateral-cell designs with optical access to the active region. An example of such a device is shown in **Fig. 5a**, while preliminary experimental results for mixed-mode operation of the device are shown in **Fig. 5b**.

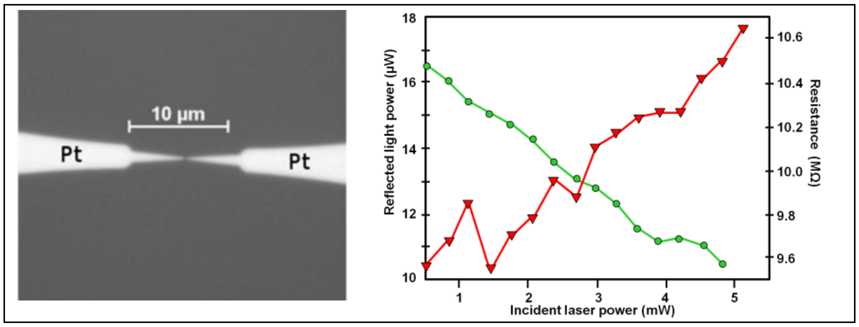

Fig. 5: (a) Lateral phase-change device configured for mixed-mode operation (left) and (b) (right) variation of resistance (circles) and reflectivity (triangles) of the cell for optical excitation pulses of increasing laser power; starting phase amorphous.

4. ALL-PHOTONIC PHASE-CHANGE MEMORIES AND PROCESSORS

The ability of phase-change devices to be configured into a form of solid-state all-optical, or photonic, arrangement raises the intriguing possibility of purely photonic phase-change devices, i.e. ones in which input, output, storage and even potentially processing are all carried out directly in the optical domain. Operating entirely in the optical domain has significant potential advantages, not least of which is the alleviation of system bandwidth and power constraints imposed by moving signals at high frequencies around electrical busses.

A schematic of an all-photonic device, based on a SiN/phase-change micro-ring resonator, is shown in Fig. 6a (see [18]). Inside the ring resonator a small region of the waveguide is suspended and a thin film of $Ge_2Sb_2Te_5$ is deposited onto this suspended region. Light from the control port (shown in red) couples evanescently to this $Ge_2Sb_2Te_5$ layer, switching it between phases and significantly affecting the propagation mode in the micro-ring optical resonator. This in turn modifies the transmission via the device input/output port and, as shown in **Fig. 6b**, this modulation can be as high as 90% when the phase change material in the ring resonator undergoes a change from amorphous to crystalline phase. Such a high level of modulation means that multi-level, non-volatile storage (and arithmetic/neuromorphic processing) should be possible using this approach (here the micro-ring cavity serves as a convenient on-chip amplifier of the state of the $Ge_2Sb_2Te_5$). Via simulation we found that the power for switching was small, in the single pJ range, and the switching speed was in the hundreds of ps range, meaning that fast and low-power operation can potentially be achieved. Furthermore, using modern fabrication techniques it should be possible to realize 3-D stacks of resonators of the form shown in Fig. 6a, meaning that very high storage densities are also possible.

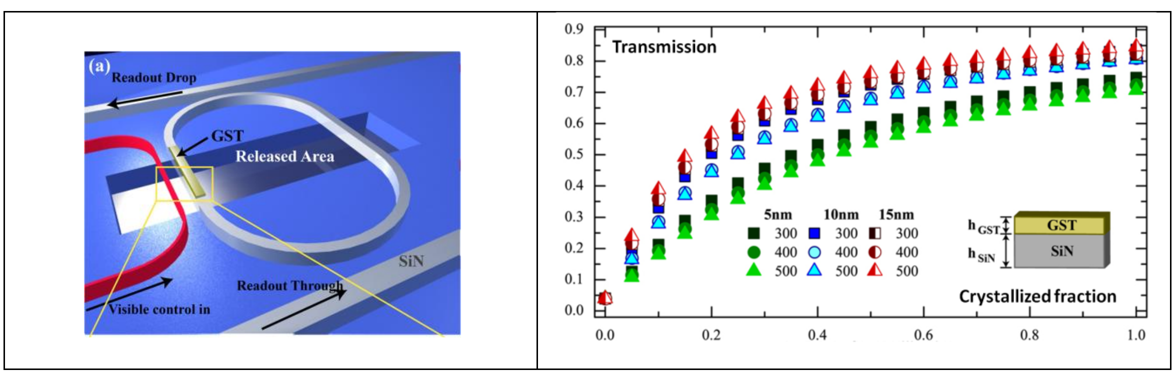

Fig. 6: (a) Schematic of an all-photonic phase-change memory based on micro-ring resonators (left) and (b) the (computationally simulated) transmission through the device as a function of the crystal fraction of the $Ge_2Sb_2Te_5$ layer (right). See Ref. [18] for further details.

5. CONCLUSION

The use of phase-change devices for simple binary storage barely begins to 'scratch the surface' of their remarkable functionality. It is, for example, also possible to configure phase-change devices to operate as electronic accumulators, performing arithmetic computations directly in high order bases and simultaneously storing the result at the same physical location (so providing an efficient form of non Von-Neumann computing). This same accumulation property can also be utilized to provide a simple form of phase-change neuron, while the multi-state regime can also be used to provide a form of phase-change synapse, leading potentially to all-phase-change neuromorphic (or 'cognitive') computing. Phase-change devices can also be considered as a form of memristor, and so can potentially provide all the advanced functionality, such as Boolean logic and logic by implication capabilities, of such devices. Furthermore, since phase-change devices can operate in both electrical and optical modes, we can imagine a number of novel device configurations, such as the mixed-mode or all-optical memflector that we have described, or indeed an all-photonic (fast, low power) non-volatile memories and processors.

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