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# Self-Healing of a Confined Phase Change Memory Device with a Metallic Surfactant Layer

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Phase change memories (PCMs) are non-volatile memory devices, which rely on the structural phase change of the active component for their operation: The resistance of the device is high when the active component is amorphous and it is low when the active component is crystalline. PCM is the leading memory technology to realize storage-class memory due to its non-volatility, fast switching, scalability, high endurance, and potential for multi-level cell operation [1]. Storage-class memory is expected to meet the growing memory demands stemming from the ever-growing computing power and the proliferation of data-intensive applications. In addition, an artificial neuron solely based on a PCM has recently been demonstrated, representing a breakthrough for neuromorphic computing [2].

One of the key metrics that the PCM must satisfy to realize storage-class memory is high endurance, a number of read and write cycles the device can achieve. We have recently developed a novel PCM device structure, using a metallic surfactant layer that confines the Ge-Sb-Te (GST) phase change material into a nanopillar, in contrast to the thin film of the conventional, mushroom device (Figure 1a). The novel confined PCM device achieved a record number of $2x10^{12}$ cycles [3], which was attributed to the use of the metallic surfactant layer (Figure 1b). The new device structure and added material complexity of the confined PCM device compared to the mushroom device requires a systematic investigation of the relationship between the microstructure of the GST nanopillar and corresponding electrical properties during phase change. *In situ* TEM, which allows tracking of nanoscale structural changes with simultaneous electrical measurements, is an ideal technique for this systematic investigation. Insights gained from such *in situ* TEM studies can help to establish understanding of, and possibly recovering from, the failure mechanisms of PCMs, which is critical to further improve their cycle life.

Here, we perform *in situ* TEM experiments on the confined PCM device to obtain valuable structure-property, as well as chemical, information at the nanometer resolution in order to build a fundamental understanding of the phase transformation of the GST nanopillar confined by the thin metallic layer (Figure 1c-f). We directly show self-healing of the novel confined PCM devices by controlling the electromigration of the phase change material at the nanoscale [4]. In contrast to the current mushroom PCM, the confined PCM has the metallic surfactant layer, which enables effective Joule heating to control the phase change material even in the presence of a large void. *In situ* TEM movies show that the voltage polarity controls the direction of electromigration of the phase change material, which can be used to fill nanoscale voids that form during programming. Surprisingly, a single voltage pulse can induce dramatic migration of antimony (Sb) due to high current density in the PCM device. Based on our finding, we demonstrate for the first time self-healing of a large void inside a confined PCM device with a metallic liner.

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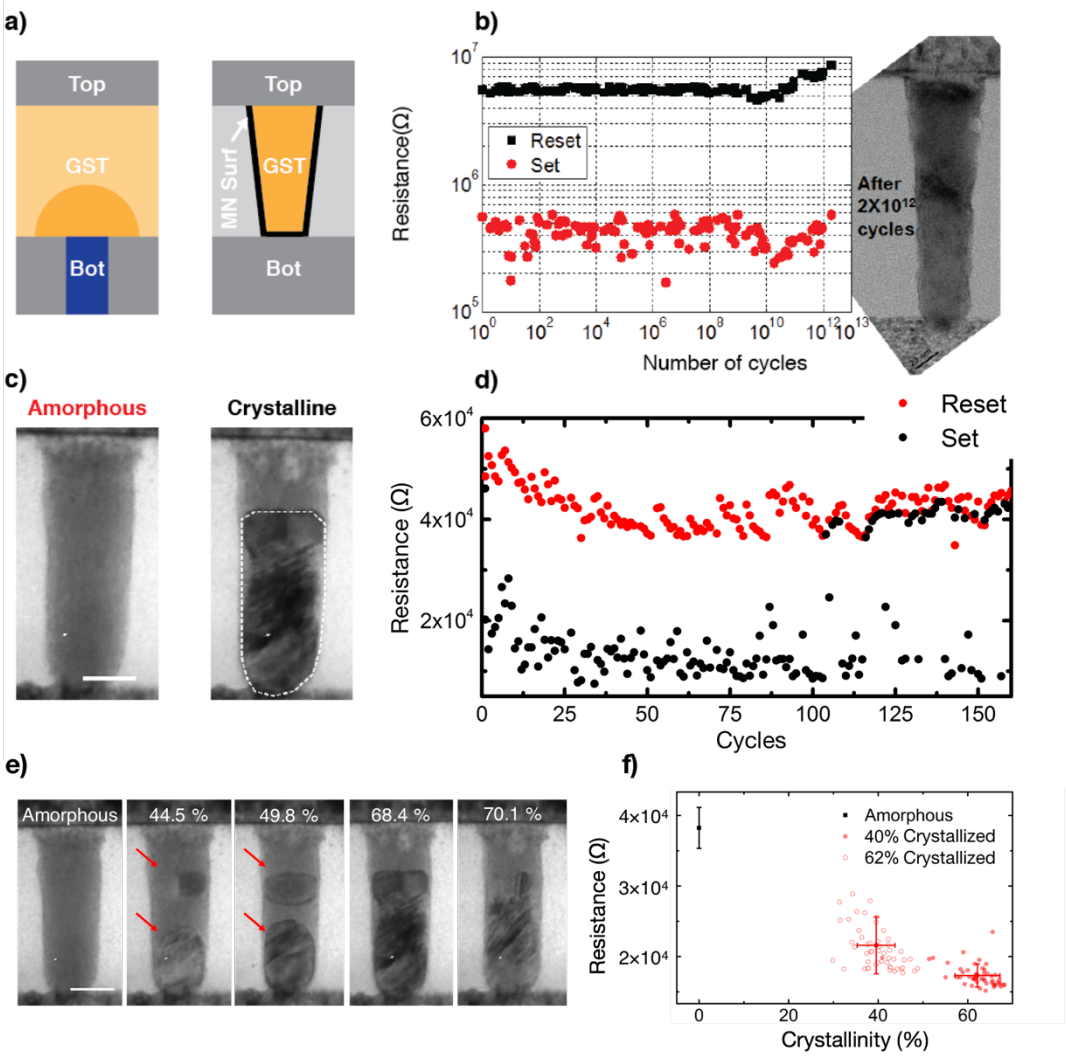


**Figure 1.** Confined PCM device with a metallic surfactant layer. (a) Schematic figures of the conventional mushroom and the confined PCM devices. (b) Endurance test of the confined PCM device with the metallic layer. The device is switched up to $2x10^{12}$ cycles. Reproduced with permission.[3] Copyright 2016, IEEE. (c) *In situ* TEM snapshot images of a confined PCM device in operation. The uniform contrast in the reset state indicates amorphous GST (left) while the intensity contrast induced by diffraction contrast in the set state indicates crystalline GST (right). Scale bar = 20 nm. (d) Resistance values of the set and reset states as a function of cycle number. Resistances were measured after each switching to correlate the electrical properties with the microstructure of the GST. This particular device failed due to formation and accumulation of voids. (e) Snapshot images of the PCM device in the amorphous and crystalline state with two switching regions indicated by the red arrows. Scale bar = 35 nm. (f) Corresponding resistance values of the PCM device as a function of the crystalline volume fraction.

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