An *in situ* phase-change memory cell study using nanometer scale x-ray optics

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We present for the first time an x-ray absorption spectroscopy study focusing on individual phase change material ($Ge_2Sb_2Te_5$) memory cells in fully integrated PC-RAM structures. Devices were investigated employing an x-ray nanobeam of only about 300 nm diameter, which could be fully contained within the spatial extent of the heater element within a single cell and enabled us to investigate individual devices without interference from non-switching material surrounding the area of interest. By monitoring the fluorescence signals of tungsten and germanium at a photon energy corresponding to the Ge K-edge absorption edge white line position, we were successful in producing 2D area maps of the active cell region clearly showing the imbedded tungsten heater element and the switched region of the phase change material. Additionally, position dependent changes in the phase change material could be traced by taking an array of XAFS spectra of the Ge K-edge on and in the vicinity of individual devices.

Due to the continuous development in consumer electronics towards increased performance and smaller device sizes, Si technology will soon reach its physical limit as a memory material. The unsatiated demand for higher density memory material will ultimately lead to the emergence of new types of memory storage systems from novel materials. Phase change materials are a promising candidate for fulfilling this role^[1] and have already successfully been used for years in optical storage medium (DVD and Blu-ray) technology. Phase change random access memory (PCRAM) utilizes a different data storage mechanism from Si technology with inherent scaling ability to a much lower ultimate scaling limit[2, 3]. In PCRAM materials information is stored in the local crystal structure of the material as opposed to charge trapping in Si based technology[4]. Phase change materials can be reversibly and stably switched between an amorphous and a crystalline phase on a timescale less than 50ns[5, 6] by injecting energy into the system, which is usually achieved through either laser or electrical pulses. Originating from the atomic scale structural differences the two phases display large optical and electrical differences [7], with the crystalline phase usually possessing higher refractive index, optical absorption and electrical conductivity. For phase change material scaling down, reduces the power input demand as the active volume decreases[8]. Once set the material will reliably remain in its current state for decades, which makes it suitable for long term data storage, but is also interesting from a different perspective. This means PCRAM would retain information even if the driving device was turned off unlike Si based technology, where the information needs to be constantly recycled and is immediately lost upon turning off.

The pseudobinary $(GeTe)_x(Sb_2Te_3)_{1-x}$ system has been intensively studied due to its current application in optical data storage technology, particularly $Ge_2Sb_2Te_5$ is widely used in DVD technology. Despite its tried and tested usage and extensive research being carried out, the basic switching mechanism is still not so well understood with the umbrella flip model[9] currently being the best model to simulate the dynamics of phase change. In order to gain a more complete understanding of the switching process it would be most instructive to perform *in situ* real time measurements of single devices on fully device integrated phase change memory materials as the phase change takes place. In this work we present x-ray spectroscopy based measurements on single devices employing a nano beam of only about 300nm dimensions, which in the future will enable us to perform these real time *in situ* measurements of the switching process on individual devices.



FIG. 1: Schematic drawing of lance cell type device

The $Ge_2Sb_2Te_5$ phase change layer was deposited on a sample chip of about 10mm x 10mm and fully device integrated. The chip consisted of an array of device structures of lance cell type (see fig. 1), i.e. a device consists of the $Ge_2Sb_2Te_5$ phase change layer sandwiched between tungsten counter and bottom electrodes. The bottom electrode and phase change layer are separated by a dielectric layer with only a small tungsten heater element defining the active region. A Keithley 4200 SCS semiconductor characterization system capable of sending electrical pulses ranging from nanoseconds to milliseconds pulse duration and amplitudes up to 10V was used for the preparation of the initially crystalline cells performed at AIST, i.e. various cells were switched into a predetermined state (SET, RESET, as deposited).

Synchrotron radiation based x-ray spectroscopy experiments were carried out at beamline BL39XU at SPring-8, Hyogo, Japan. X-ray spectra were taken at high energies at and around the Ge-K edge (11.105keV). For rough alignment of the sample with the x-ray beam a microscope system was used that permitted viewing of the sample under incident x-rays by allowing the x-ray beam to pass though an aperture in the microscope mirror optics. The x-ray beam was focused using Kirkpatrick-Baez x-ray mirror optics into a spot of about 250nm x 350nm spot size as confirmed by a knife edge scan[10, 11], which was small enough to fully contain the extent of the x-ray spot within the dimensions of one heater element, thus enabling us to exclusively measure the active (switching) region of a single individual device with only minor interference from the surrounding matrix. Due to chip structure dependent variations in the tungsten thickness, the position of the x-ray beam on the chip could be identified by monitoring the tungsten fluorescence signal at a fixed photon energy while performing line scans, i.e. translating the sample under the x-ray beam along one of the natural sample stage directions. In more detail first line scans across the entire counter electrode were performed locating the center of the counter electrode. Subsequently more detailed scans of the central area were performed enabling us to locate the exact position of the much smaller heater device. In order to gain insight into the spatial properties of the amorphous mark created, arrays of XAFS scans were taken at various positions on and in the vicinity of the heater device. 2D maps of the contrast between amorphous and crystalline regions of the active cell area were generated using two-dimensional XY scans recording the germanium and tungsten fluorescence response at a fixed photon energy corresponding to the Ge K-edge absorption edge at about 11.105keV (Ge "white line").

In this work it was attempted to gain insight into the switching properties of phase change memory materials by focusing on the changes occurring in single cells of fully device integrated phase change memory material. We generated 2D maps of the individual cells identifying the tungsten device structures, such as the position and dimension of the heater element, while simultaneously gaining information on the state of the contained phase change material. In order to gain a more complete understanding of the switched area spatially overlapping EXAFS scans along a line crossing the switched area were performed. The data presented here was acquired from an amorphized memory cell with heater element dimension of 290 nm x 290 nm and from a crystalline cell with dimensions of 2 microns x 2 microns.



FIG. 2: Ge K-edge XAS spectra; red (a), blue (b) and black (c) colours represent spectra taken directly on, partly on and far away from the heater element respectively.

Figure 2 shows XAS spectra of the Ge K-edge recorded on a cell containing an amorphous region in an otherwise crystalline background. The three different spectra correspond to data collected directly on the heater element (red trace), partly on the heater element (blue trace) and significantly separated form the heater element (black trace). We should thus expect to find evidence for the amorphous phase in the first, a superposition of crystalline and amorphous features in the second and a purely crystalline spectra in the third spectra. In $Ge_2Sb_2Te_5$ we expect to find a reduction of about 10% in fluorescence intensity response from germanium for the amorphous phase as compared to the crystalline phase at a photon energy corresponding to the Ge Kedge white line at about 11.105keV[9]. A slight change in the spectral shape of the Ge K-edge spectra is also expected in the form of an more pronounced shoulder at photon energies just above the main absorption feature (approximately 11.108keV to 11.116keV). In figure 2 we can clearly observe the expected differences. The spectral shape for traces (a) and (b) contains amorphous contributions, while trace (c) is indicative of the crystalline structure. This is supported by the decrease in white line intensity from the spectra recorded in the crystalline background over the one taken partially on the heater element to the one fully contained in the heater element. This indicates we have successfully managed to spatially trace the change of phase with trace (c) showing the crystalline background and trace (a) showing the amorphous region upon the heater element. Trace (b) originates from a superposition of the two different phases.

In the following 2D maps of the active region of the

device and the surrounding area are presented. To this end the germanium and tungsten fluorescence intensity response at a fixed photon energy of 11.105keV was recorded in an array of 30x30 data points.



FIG. 3: 2D tungsten map of an amorphous cell (290 nm heater element): Tungsten x-ray fluorescence intensity as a function of position recorded at a photon energy of 11.105keV. The heater element is visible as an area of elevated intensity in the bottom left corner of the map.



FIG. 4: 2D germanium map of an amorphous cell (290 nm heater element): Germanium x-ray fluorescence intensity as a function of position recorded at a photon energy of 11.105keV. The amorphous region of Ge₂Sb₂Te₅ is visible as reduced intensity in the bottom left area of the map.

For the amorphous cell two 800 nm x 800 nm area maps for tungsten and germanium are displayed in figures 3 and 4, respectively. Red pixels correspond to low intensity and blue pixel to high. In both figures we observe a rather uniform background surrounding an anomaly in the bottom left region of the array. In figure 3, the tungsten signal, a region of about 15% higher intensity than the average background is clearly visible in the bottom left region of the scan indicating the presence of additional tungsten. The dimension of this anomaly supports the conclusion that this elevated intensity is caused by the buried tungsten heater element. Figure 4 shows a similar anomaly however with decreased intensity rather than elevated one. As we recall we expect to find about 10% less fluorescence intensity response from germanium for the amorphous phase as compared to the crystalline phase when excited with a photon energy corresponding to the Ge K-edge absorption edge white line position. This is in good agreement with the observed decrease in this image. As the measured Ge thickness is constant over the entire chip this change of intensity must result from a change of phase of the material. It might be argued that the decrease of intensity originates from a migration and thus a decrease of $Ge_2Sb_2Te_5$ in the observed area either by lateral displacement or by destructive evaporation upon receiving the electrical pulse. This however is ruled out as a mere displacement of material upon amorphization would either lead to a wall or ring like region of enhanced intensity around the area of decreased intensity or in case of catastrophic failure of the device and mass ejection in the form of evaporation would lead to a breakdown of the tungsten counter electrode observable with our microscope optics. As both are not observed the change in intensity is attributed to a change of phase of the PCM material.



FIG. 5: 2D germanium map of a crystalline cell (2 micron heater element) : Germanium x-ray fluorescence intensity as a function of position recorded at a photon energy of 11.105keV

For comparison and validation of our technique a 10 micron x 10 micron area map of a device containing a 2 micron x 2 micron heater element with the phase change material in the crystalline state is shown in figure 5. In order to facilitate comparison between the two germa-

nium signal maps (Figs 4,5) this graph has been rescaled to match the scale of the graph containing the amorphous area. A rather featureless relatively uniform fluorescence signal is found in this graph indicating a purely crystalline state for the phase change material over the entire area. The simultaneously recorded tungsten signal (not shown here) map for this device clearly established the position of the heater element and confirmed its presence in the examined area.

In this study we have demonstrated the feasibility of investigating individual devices of fully device integrated phase change memory materials by successfully locating and measuring nanometer sized structures using an x-ray nanobeam. It has been possible to confirm the changes in the material as a function of position and identify the phase of the material (crystalline or amorphous) in the areas under investigation.

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