WATCHING NANOSCALE PHASE CHANGE MEMORY WORK IN REAL TIME VIA *IN SITU* ELECTRON MICROSCOPY

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Different alternative memory concepts have been explored in the last decade, aiming to overcome the major limitations of existing electronic memories, i.e. the volatility of dynamic random access memory (DRAM) and the slow programming speed and limited endurance of FLASH memory. The ultimate goal is a universal memory, a high density memory that can be written and accessed at high speeds for a virtually unlimited number of cycles with data nonvolatility. The major efforts have been broadly focused on four concepts: ferroelectric, magnetic, resistive and phase change memory. In ferroelectric memory, the polarization states of a ferroelectric material are used to store information, while in magnetic memory, the magnetization states of the material store the information. Ferroelectric memory requires less power, but is quite difficult to scale-down. Magnetic memory can be switched rapidly, but requires large current for programming. Resistive memories (RRAMs) rely on the formation of ionic or filament paths between the two terminals and offer small form factor, low power operation and high speed, but questions regarding the reliability and mechanism still remain. Phase change memory (PCM) is promising as it is fundamentally scalable, and can be operated at very high speed, with data nonvolatility and random accessing capability.

Chalcogenide-based (Ge-Sb-Te system) PCM referred to as Ovonic memory are fundamentally different from other semiconductor memories; information storage is achieved through changes in electrical resistivity/optical reflectivity via structural transformations rather than through manipulation of vanishingly small amounts of charge. The reversible crystalline to amorphous phase transition in Ge-Sb-Te alloys has always been believed to be obtained by heating and subsequent cooling of the material. PCM utilizing Ge-Sb-Te materials have attracted great attention due to their non-volatile memory properties and fast write/read speeds, and low manufacturing costs. Phase change-based thin-film technology is currently being used in optical disk storage and is being widely studied for electrical memory applications owing to their reversible switching behavior between crystalline and amorphous states. However, phase change memory devices are still limited due to the requirements of high scalability, low power consumption, non-volatility and most significantly, the lack of understanding of the physical mechanisms that lead to such rapid changes in the material's structure. Despite many efforts, intrinsic properties of nanostructured phase-change materials have remained largely unexplored.

Motivated by the challenges, we have successfully synthesized a variety of phase-change nanowires by vapor phase transport method with diameters ranging from 20 – 200 nm. Devices assembled from single NWs showed reversible memory switching behavior with extremely low writing currents. Remarkably, the size-dependent memory switching behavior of $Ge_2Sb_2Te_5$ NWs shows that amorphization current decreases systematically by scaling-down the NW diameter. Size-dependent recrystallization studies of phase-change NWs is critical to determine the minimum device size that can be used for non-volatile memory combined with the benefits of low-power consumption and ultrahigh device density. Size-dependent nanowire resistance-change reveals that rapid recrystallization occurs for thinner nanowires, but a 20 nm device can still retain data at 80 degrees for 10 years.

However, in spite of extensive investigations of the phase-change and electronic switching in PCM, the underlying mechanisms involved in the relationship between structural and electrical properties in phase change materials is quite complex and remains poorly understood. Despite some success in theoretical approaches to explain the atomic motions involved at the atomic-scale, direct visualization of electrically-driven structural transition has been experimentally challenging. This is mainly because the active phase-change material in thin-film PCM devices are embedded within multiple layers, which prohibits direct probing of structural transformations on a working device with high spatial resolution while under electrical biasing. Detailed understanding of electrically-driven switching process in phase change materials is essential to achieve their successful integration into memory devices.

We studied the effect of electrical pulses on the crystalline-to-amorphous phase change in a single-crystalline nanowire nonvolatile memory device via *in situ* transmission electron microscopy (TEM). The crystalline-to-amorphous phase-change in GST has always been believed to occur via melt-quench process; however, we showed that electrical pulses produce dislocations in crystalline GST, which become mobile and glide in the direction of hole-carrier wind force. The continuous increase in the density of dislocations moving unidirectionally in the material leads to a dislocation jamming transition, which eventually induces the crystalline-to-amorphous phase change. The amorphous phase always appears at the dislocation jamming region, where the degree of disorder is extremely high. The observation of the hole-carrier wind force assisted amorphization due to dislocation nucleation, directional motion and jamming provides new insights into the origin of fast switching behavior in phase change materials, and will assist in the design of low-power nonvolatile memory devices.