In situ TEM investigation of electrically-driven phase change behavior in $Ge_2Sb_2Te_5$ nanowire memory devices

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Phase change memory (PCM) is regarded as a promising alternative to conventional memory devices such as DRAM or FLASH owing to its nonvolatility, scalability and fast switching speed. However, the fundamental origin of the fast switching process in PCM has been hard to be achieved, which mostly comes from the difficulties to separate the electric field effect from the high temperature processes. The unique geometry of one-dimensional nanowires (NW) serves as a good platform to investigate the atomic structures during electrically-driven phase change process via in situ transmission electron microscopy (TEM) observation. In NW PCM, the compositions and the grain formations can be easily monitored during the switching process, which offers a great opportunity to explore the underlying mechanism of the electrically-driven phase change behavior.

Our study is focused on the direct observations of the electrically-driven phase change behavior through TEM. We utilized an electron transparent SiN membrane on which we assemble vapor-liquid-solid (VLS) grown $Ge_2Sb_2Te_5$ NWs in Figure 1. We carried out both current-voltage (I-V) sweeping and programming operations of $Ge_2Sb_2Te_5$ NW devices and obtained reliable threshold switching and excellent phase switching behavior between crystalline and amorphous states as shown in Figure 2. TEM observation clearly shows that the hot spots region defined in the nanowire devices localize the heat and act as active phase change region. Very clear signatures of amorphous RESET and polycrystalline SET states are observed with HRTEM. We show direct evidence of nucleation dominant recrystallization mechanism in $Ge_2Sb_2Te_5$ nanowire devices with electrical switching, consistent with thermally induced process. What is more interesting is the structure of the device just above threshold switching; we have observed the evidence of electric-field assisted nucleation process which guides the crystalline nuclei formation in a correlated manner with the applied electric field, and unlike the random nucleation and percolation behavior typically observed for thermally induced recrystallization. Similarly, during RESET (amorphization) operation, the recrystallized region next to the amorphous phase has aligned grains attributed to the directional grain growth during melting process. It is believed that the uniform current path in near-melting state may allow the grains to be aligned in the direction of the electric current. Our observations suggest that the electric field plays a unique role during electrically-driven phase change process and may explain the fast switching process observed in these materials. The role of filament formation by electric field during switching will be discussed and the implications of these findings for modeling the electrical properties of phase change materials will be presented.

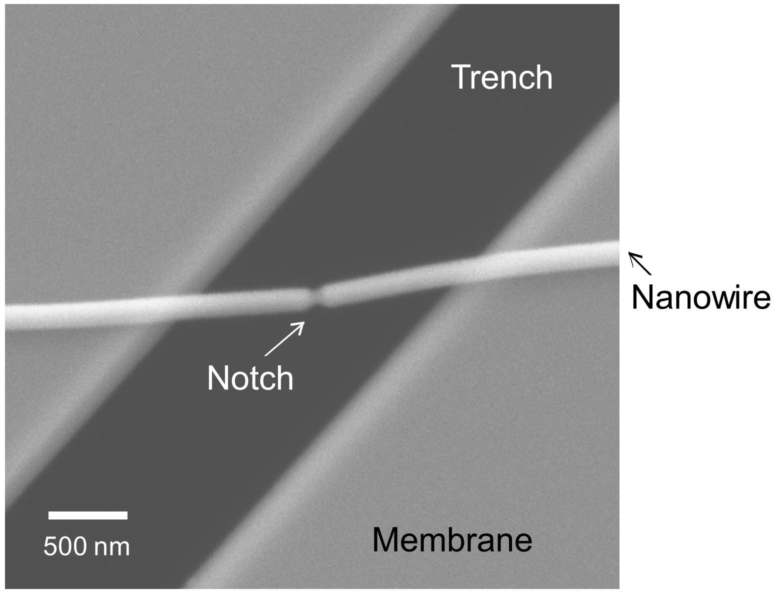

Figure 1. Free-standing $Ge_2Sb_2Te_5$ nanowire across the trench structure on membrane for in situ TEM observation

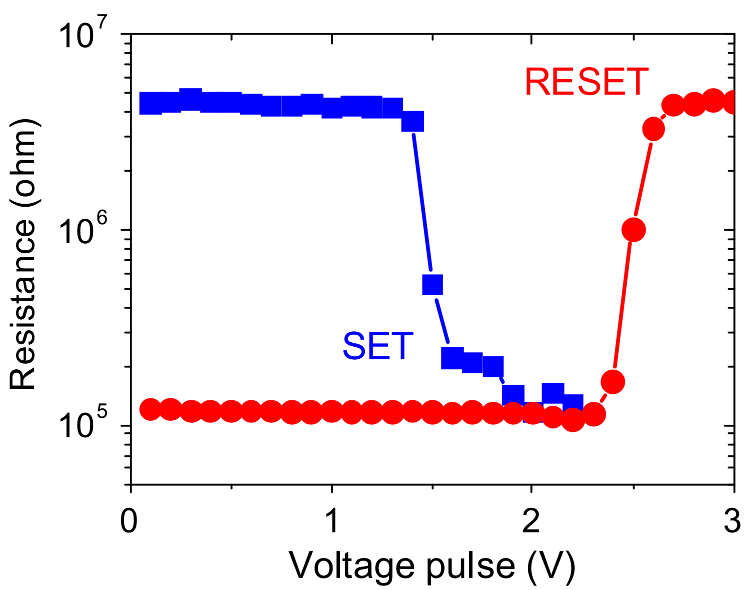

Figure 2. Programming of SET (crystallization) and RESET (amorphization) operations of $Ge_2Sb_2Te_5$ nanowire: For SET operation, we applied relatively long electric pulse (200 nsec) for crystallization process, which drops the electric resistance through amorphous-to-crystalline phase change. On the other hand, for RESET operation, we applied short electric pulse (50 nsec) for melt-quench amorphization process.