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Changes in Morphology and Local Conductance of GeTe-Sb_2Te_3 Superlattice Films on Silicon Made by Scanning Probe Microscopy in a Lithography Mode

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Abstract

Superlattice (SL) films consisting of layers of GeTe and Sb_2Te_3 have been attracting much attention as the promising candidate material for next generation of memory cells. To assess SL films as a recording media, we measured conductance state switching caused by local electric field by using scanning probe microscopy (SPM) and SPM nano-lithography. For SL films on Si(100) sudden conductance increase by ~200 fold at 2.0-2.6 V was observed and ascribed to local electronic excitation of interface atoms by energetic electrons injected from the tungsten probe. At above +3.0 V thermally-driven transformation of the SL films was observed.

1. Introduction

Development of new materials for next generation memory cells has been of great importance. In particular, interfacial phase-change memory topological materials such as (GeTe)/(Sb_2Te_3) superlattices (SL) have been studied extensively showing huge magnetoresistance and magneto-optical properties essential for memory application.[1,2] In contrast to conventional amorphous-to-crystalline phase-change transition, the SL films expected to have different mechanism of conductance switching, which involves migration of Ge atom at the interface of the constituent sub-layers. To address the conductance switching behavior of different SL films, we established WRITE-READ routines and performed local conductance switching in the lithography mode of a multimode scanning probe microscope (MSPM).[3]

2. Results and Discussion

Sample structure

SL films have the structure of $[(GeTe)_n (Sb_2Te_3)_m]_p$ (*n-m-p*), where *n, m* indicate the number of monolayers in each sub-layer, and *p* is the number of SL periods. Samples with *n*=1, 2, and *m*=1, 4 (*p*=4) were prepared on oxide-free p-Si(100) substrates by spattering in Ar at 250ºC. A Ta foil was used as a backside electrode.

STM lithography

Change in film morphology and local conductance was measured at room temperature by using a MSPM system (integrated STM/AFM) operating in a UHV chamber (<10^{-7} Pa) to avoid SL oxidation. Fig.1(a) illustrates the measurement setup, where a sharp tungsten STM probe was attached to a quartz length-extension resonator (qLER). The setup allows simultaneously acquiring both tunneling current (I_{tun}) and frequency shift (Δf) as a representative of force acting on the STM probe, it is called the dual-mode of a non-contact SPM.[3] The conductance switching was done in a SPM lithography mode, when the STM probe was driven along straight lines under a WRITE voltage (V_{WRITE}) with a speed of 0.5-1.0 nm/s while keeping the probe-sample gap constant in the constant force (AFM) mode. Resulting changes of the SL conductance was observed in tunneling current maps at a READ voltage of 1.2 V in the non-contact AFM mode.

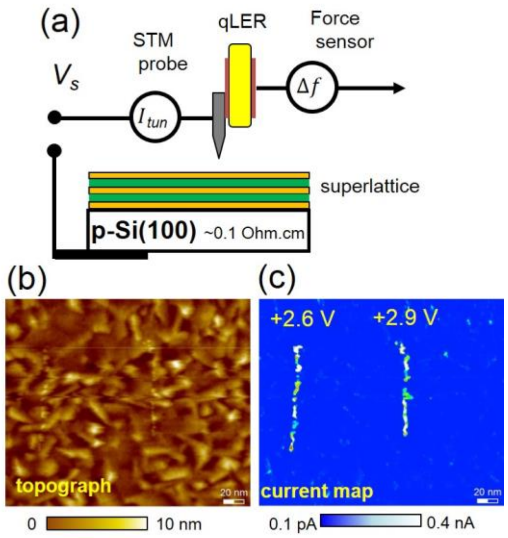

Fig. 1 (a) MSPM measurement setup. (b,c) AFM topograph and corresponding current map at a READ voltage of +1.2V after writing 2 lines for the (2-1-4) film. Numbers indicate V_{WRITE}.

Fig.1(b,c) shows a result of writing 2 lines at 2.6 and 2.9 V. Local switching from low conductance state (LCS), less than 1 pA, to high conductance state (HCS), ~400 pA is evident. An average HCS/LCS ratio was ~200 for the (2-1-4) film. There was little effect on the morphology of the SL film which composed of grains with a size of ~20 nm. Breaks of the HCS lines were seen, indicating that the switching voltage varied for grains and grain boundaries, and some grains remained in LCS at the WRITE voltage.

Conductance switching behavior

To compare the SL switching behavior, variations in the STM probe position (Z) and WRITE current were recorded during the WRITE session as shown in Fig.2. There two distinct conductance switching events(CSE): (1) a *gradual* increase of the WRITE current from ~0.1 pA to 5-9 pA at about 195 s and 210 s, and (2) *sudden* switching ON when the WRITE current reached ~2 nA in less than 20 ms, maintained the value for ~4 s, and switched back to LCS. We confirmed that the CSE occurrences coincided with high current spots observed in the READ current map in Fig.1(c).

Interestingly, the STM probe was abruptly retracted by 3-5 nm (Z-jump) on each switching ON event such as seen at 213 s, and returned to about original position on switching OFF at 217 s. It suggested expansion-contraction of the SL film upon the conductance state transitions, though, the image in Fig.1(b) was almost similar to that measured before the WRITE process. Similar SL expansion after some I/V measurements was observed for this SL (not shown). It seems that Z-jumps occurred as a response of our SPM feedback loop circuit to very abrupt current increase by few orders of magnitude upon CSE, and further details have been under investigation.

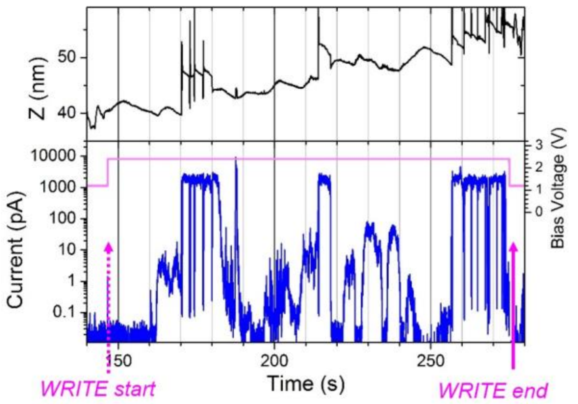

Fig. 2 STM probe position (black, top) and WRITE current (blue, bottom) at WRITE voltage (pink) for the left line in Fig.1(c).

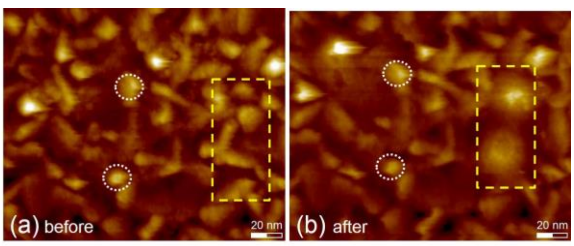

Fig. 3 AFM topographs of (2-1-4) SL before (a) and after (b) the WRITE process at +3.2 V. Dashed boxes outlined modified areas. Dotted circles indicate similar grains in (a) and (b).

After the WRITE process at a voltage of +3.2 V, two large islands appeared with a diameter of ~40 nm as seen in Fig.3. We estimated that an energy of ~50 nJ released in the events as a result of large WRITE current (>10 nA). Thus, strong heating is a plausible explanation for local regrowth of the SL.

Switching threshold voltage

Dependence of the number of CSE on the WRITE voltage is shown in Fig.4 for different measurements. A threshold voltage of +2 V, and a minimum switching energy of ~80 pJ per event at 2 V were obtained. Surprisingly, at negative WRITE voltage the CSE did not change the SL conductance state. At $V_{WRITE} > 0$, high-energy electrons were injected from the STM probe through the vacuum gap. Injection of energetic electrons seems necessary to achieve the conductance state transition. Such energetic electrons can produce electronic excitation of interfacial Ge atoms. This, in turn, causes (i) migration of the Ge atom between sites with tetrahedral/ octahedral coordination and (ii) generation of phonon. At large WRITE voltage, phonon generation prevails leading to regrowth of the SL seen in Fig.3.

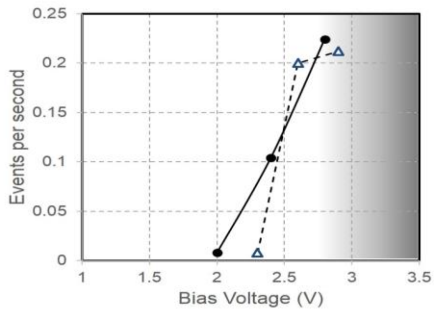

Fig. 4 The number of switching events per second vs. the WRITE bias voltage. Symbols represents different WRITE sessions.

Different layer's order

CSE showed different footprints depending on the SL layer's order, i.e. the *n* and *m* values, and growth conditions. For instance, we observed 2-5 times smaller WRITE current for (1-1-4) SL, and extended lattice destruction, i.e. creation of a trench of ~1 nm in depth at 2.6-2.8 V. The details will be discussed at the meeting.

3. Conclusions

To assess SL films as a recording media, we investigated conductance switching for SL films on Si(100) by means of local electric field employing dual-mode imaging and SPM lithography. We observed sudden increase in the local conductance by ~200 fold at 2.0-2.6 V, and ascribed it to electronic excitation of interface atoms by energetic electrons. Thermally-driven regrowth of the SL films was observed above +3.0 V.

Acknowledgements

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