Unusual Magnetic Properties in Interfacial Phase-change Memory

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ABSTRACT

Interfacial phase-change memory (iPCM) films composing of a crystalline-multilayered $[(GeTe)_x/Sb_2Te_3)_y]_z$ (x, y, and z are integer) structure emerge unusual magnetic properties, such as more than 2000% magnetoresistance even at room temperature. In this paper, we discuss about the characteristics from the point of view of topological insulators.

Key words: superlattice, iPCM, topological insulator

1. INTRODUCTION

Phase-change memory (*PCM*) is one of the leading candidates of the next generation non-volatile memory (*NVM*). However, it has a drawback on switching energy (especially, current in *Reset*) larger than the other *NVMs*. This is because a phase-transition through a melting process accompanies a large energy loss as entropy, which reaches more than 95% of total input energy [1]. Even the device size becomes smaller and a phase-change material is surrounded with low thermal conductive materials, the ratio remains high. The fundamental principle on the 1st phase-transition does not allow an exception. In order to suppress the ratio and to reduce the entropic energy loss, it is to remove a melting process from the phase-change cycle. That is, a crystal-crystal phase-transition (2nd phase-transition) is suitable. Based on a switching model of a Ge-Sb-Te system, in which an electrical resistance is changed by the bonding state of Ge to Te: tetrahedral or trigonal (octahedral), the 2nd phase-transition may be realized in the system. Interfacial phase-change memory (*iPCM*) was first designed on the model of the 2nd phase-transition for saving the energy ratio, in which a Ge-Sb-Te film was separated into two components: GeTe and Sb_2Te_3 sub-layers stacked alternately. In addition, the two sub-layers have a same crystalline growth direction towards *<111>* as an *fcc* lattice. A phase-transition only occurs in the GeTe sub-layers and the Ge motions are locked along <111> direction to change the bonding states, while the Sb_2Te_3 sub-layers play no role in the phase-transition but just hold the whole crystal state. It was found in our two different calculations using *Boltzmann's law* and *ab-initio* simulation, that *iPCM* device can theoretically save the entropy loss by ~90% [2]. In simpler discussion, a *PCM* device performance depends on Ge atoms that transit at the slowest speed, but not on the atoms with an average speed of the Boltzmann distribution. That is, a coherent motion of all Ge atoms, which go back and forth in one-dimension, requires the minimum energy for switching in thermodynamics. *iPCM* is therefore the most suitable *PCM* to save the energy.

Spintronics has long been studied at low temperature for future nanoelectronics and quantum computing applying quantum entanglement. Quantum behaviors of spins at room temperature have been reported, for example, as quantum Hall effect or quantum spin Hall effect, which emerge only under a special conservation of physical parameters. The discovery of topological insulator (*TI*) may realize and exhibit quantum behavior under time inversion symmetry; the surface state is robustly preserved as a conductor while the inside is an insulator [3]. Candidate materials as *TIs* are usually alloys or binary compounds composed of heavy elements (non magnetic). Up-to-now, Bi_2Se_3, Bi_2Te_3, Sb_2Te_3 and several other chalcogenides have theoretically been predicted, and later experimentally been confirmed to be a three-dimensional *TI* using angle-resolved photo-emission spectroscopy (*ARPES*) [4,5]. More recently, Kim *et al*.

and Sun *et al*. reported by *ab-initio* simulations that a single crystal of $Ge_2Sb_2Te_5$ may indicate TI characteristics under some stress conditions [6,7].

2. SIMULATION

From the point of view of *TI*, it is very interesting to confirm whether *iPCM* is related with a *TI* or not. As we discussed about *Rashba effect* and *magneto-reflection* change of *iPCM* films in the last E\PCOS2011 in Switzerland [8], the important factor to generate *TI* characteristics is a strength of spin-orbit coupling (*SOC*) in *iPCM* films. If an *iPCM* film is related with a *TI*, the band structure has a single or multiple *Dirac cones* in the reciprocal lattice.

Ab-initio computer simulations were carried out for *iPCM* models of $[(GeTe)_2(Sb_2Te_3)_4]$ and $[(Sb_2Te_3)_3$/(10A vacuum slab)/$(Sb_2Te_3)_3]$ as a reference of a *TI*, combining *LDA-CASTEP* and *WIEN2K* calculation with a *LAPW* method including *SOC*. Figure 1 shows the electronic band structure of $[(Sb_2Te_3)_3$/(10A vacuum slab)/$(Sb_2Te_3)_3]$ model. The grey regions are of the bulk Sb_2Te_3 without the vacuum slab, while color bands are of the surfaces contributed from Sb_2Te_3 with the vacuum. It is found that the bulk Sb_2Te_3 has a band gap of 0.5 eV, while the surface band is gapless accompanied by a *Dirac con*e at *Γ* point in the *k-space*. That is, Sb_2Te_3 is a *TI* in *nontrivial* and *strong TI* as already reported [9].

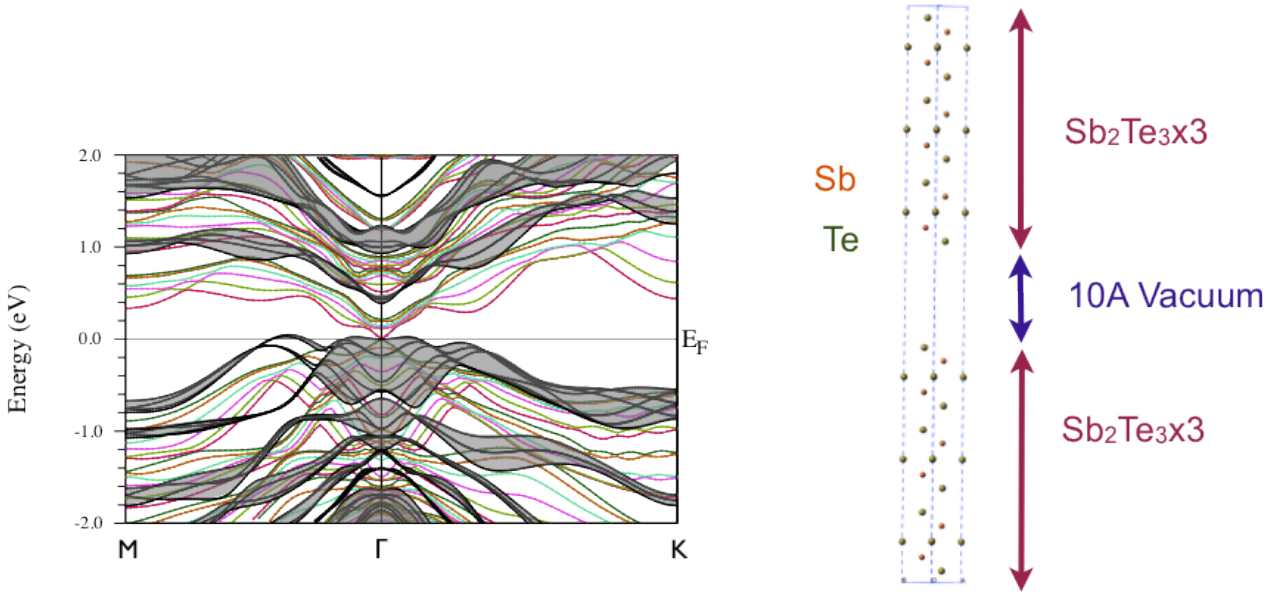

Figure 1 Electronic band structure of Sb_2Te_3 with a vacuum slab (left) and the structure of the model in *P3m-1* (right). In the band structure, grey shadow regions are of the bulk without the vacuum slab. The bulk Sb_2Te_3 has a ~0.5 eV band gap, while at the surface band with the vacuum slab the gap closes to become a *TI*.

Although to elucidate the *TI* properties of Sb_2Te_3 itself is also interesting in the future *PCM* study of course, manipulation of the surface with vacuum is impractical for device applications. Instead, *TI* properties at an interface with other solid surfaces are more friendly and suitable. Our research objective is to fill the vacuum slab in the model with a solid layer, which corresponds to a (-Te-Ge Ge-Te-) block in *iPCM*. It is addressed that the terminal atoms with the two surfaces of the Sb_2Te_3 block must be Te because of the requirement of van der Waals force [10]. The configuration exactly agrees with the *iPCM* model with tetrahedral bonding states of Ge atoms [2]. Figure 2 shows the band structure of *iPCM* $[(GeTe)_2(Sb_2Te_3)_4]$. The calculation without *SOC* has a 50 meV gap at *Γ* point, while the gap closes when *SOC* is included in the calculation. It is found that the Dirac cone is quadruply degenerated: top-interface of the Sb_2Te_3 block, top-interface of the $(GeTe)_2$ block, bottom-interface of the Sb_2Te_3 block, and bottom-interface of the $(GeTe)_2$ block, respectively. As Jhi *et al*. and our group reported at *MRS spring meeting* in 2012, the band structure of *iPCM* $[(GeTe)_2(Sb_2Te_3)_4]$ can be explained in terms of the surface states of the three-dimensional topological insulator Sb_2Te_3, realized on heterogeneous solid-solid interfaces.

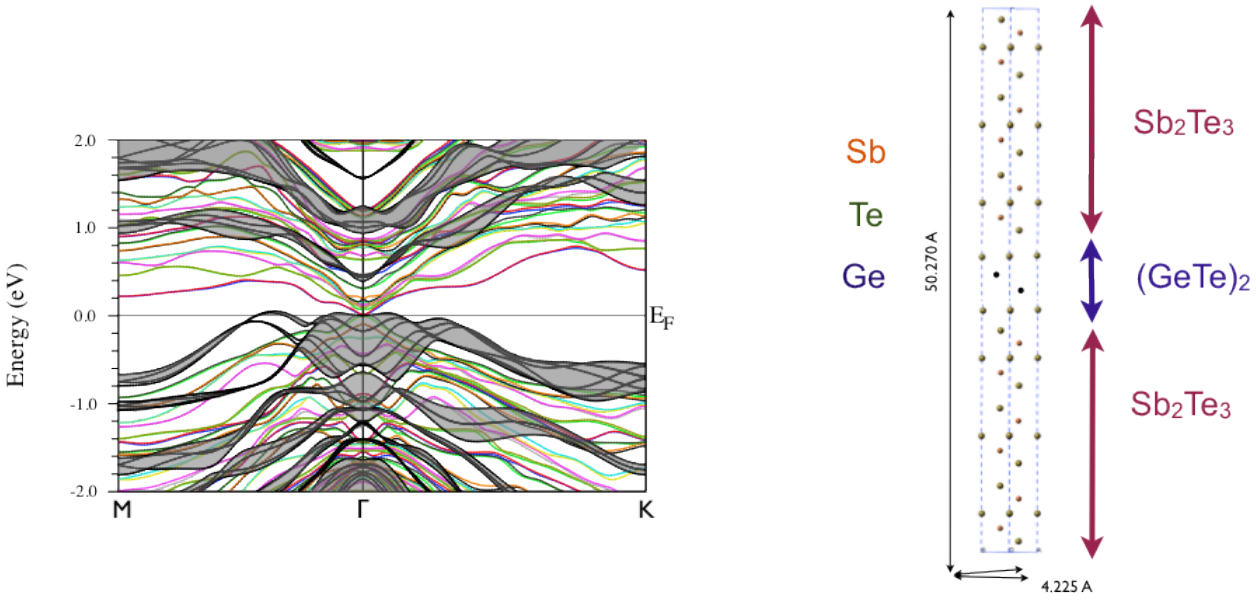

Figure 2 Electronic band structure of *iPCM* $[(GeTe)_2(Sb_2Te_3)_4]$ and the structure of the model in *P3m-1* (right). In the band structure, grey shadow regions are of the balk Sb_2Te_3. The band structure without SOC has a 50 meV band gap, while the gap closes to become a *TI* when SOC is included.

3. EXPERIMENTAL RESULTS

An *iPCM* of $[(GeTe)_2(Sb_2Te_3)_4]_8$ was fabricated using the same device as that already reported [1, 2]. The film was deposited using two-inch targets: GeTe and Sb_2Te_3, by a helicon-wave sputtering system at 250°C. Therefore, all the layers were grown in crystal. It is well known that phase-change materials, Ge-Sb-Te or Ag-In-Sb-Te, are all nonmagnetic at room temperature, although they may have a weak magnetic sensitivity at very low temperature [11]. However, the *iPCM* has a completely different magnetic feature [12]. As shown in Figure 3, in *I-V* characteristics under 0.1 T magnetic field, V_{set} voltage in *iPCM* device was shifted by ~ 1.2 V higher than the original curve, while in the control *PCM I-V* curve did not change at all with and without the magnetic field. After removing the magnetic field, the *I-V* switch returned to the original. The property is reversible.

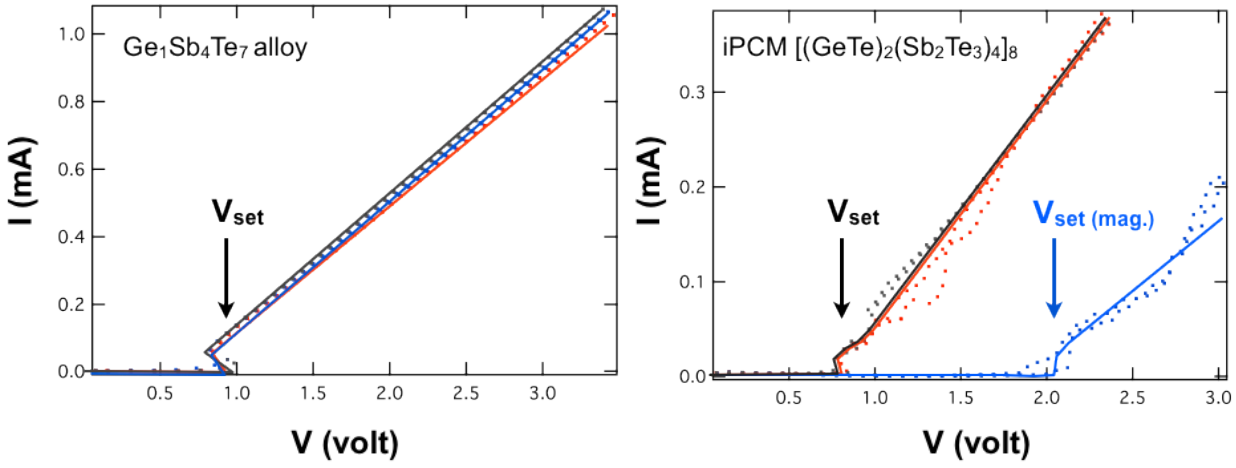

Figure 3 I-V comparison between *PCM* and *iPCM* under a magnetic field. Red and black curves are the original scan and the scan after removing the field, respectively, and blue curves are scans under 0.1 T in-plane magnetic field. [12]

4. DISCUSSION

The fact that the iPCM device is magnetically sensitive at room temperature is highly unusual because the elements in the film are all non-magnetic. However, one can explain this phenomena by taking into account the band structure of *iPCM* in terms of the *TI*. Topological properties are preserved robustly under time inversion symmetry (*TIS*), and are robust against external perturbations, which do not break *TIS*. Although external electrical pulses applied to *iPCM* for switching break the spatial symmetry, which may shift the Fermi level of the band, *TIS* is preserved. In contrast, a magnetic field breaks *TIS*, opening a band gap at the Dirac point. Once the gap is opened, current flowing or leaking through the interfaces is cut, and the resistance is suddenly increased by 2000%. Therefore, energy required to switch Ge atoms are not supplied well. As a result, the system needs a higher voltage to supply the energy for the Ge switch. If this postulation is correct, it may be possible to store spin in the *iPCM* devices when Ge bonding states are returned from trigonal (octahedral) to tetrahedral. This is because the band gap of the *iPCM* model with the trigonal (octahedral) bonding state of Ge atoms is closed and conductive, where the electrical current passing through the *iPCM* film cannot discriminate spin states, up or down. However, once a high voltage pulse is applied to the device and the bonding state is returned to the tetrahedral within a short time (ns), the electrical current must split into two currents for the respective two spin states by the recovery of the TI state. Furthermore, electrical current cannot penetrate the film. As a result, a spin state may be trapped at the interfaces due to *TIS*. *IPCM* may provide a spin memory using a reversible *TI* switch, in addition to the original phase-change memory.

SUMMARY

It is confirmed theoretically and experimentally that the novel transport properties of iPCM can be related with the interface states of the topological insulator Sb_2Te_3. The magnetic property is induced by breaking of the time inversion symmetry. Switching the difference of Ge bonding states between a TI and an insulator (high resistance state) may have a potential to store spin currents in *iPCM*.

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