Magnetic Properties and Band Structures in Superlattice Phase-change Memory

Junji Tominaga*[1], Alexander V. Kolobov [1] and Paul Fons [1]

[1]Green Nanoelectronics Center, Nanoelectronics Research Institute, National Institute of Advanced Industrial Science & Technology (AIST), Tsukuba Central 4, 1-1-1 Higashi, Tsukuba, 305-8562, Japan

*j-tominaga@aist.go.jp

ABSTRACT

Supelattice phase-change memory 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 at room temperature. In this paper, we discuss the characteristics from the point of view of topological insulators.

Key words: superlattice, iPCM, topological insulator

1. Introduction

Chalcogenides, especially, Ge-Sb-Te ternary alloys, have long been used as a recoding material in rewritable optical discs. The recording and erasing mechanism is simple and based on 1st phase transition between amorphous and crystal because the alloys have a large change in optical constant (refractive index), which reflects two reflection levels (high and low) corresponding to 1 and 0 digit. On the other hand, a large difference in electrical resistance has been applied to the nonvolatile electrical phase-change memory (PCM). All these physical properties in optics and electronics are emerged from the bonding states (covalent or metallic) of Ge atoms. Recently, it has been reported that the amorphous state have a shorter bond length with the nearest Te atoms exist in the amorphous while three longer and three shorter bond lengths are included in the crystals [1]. That is, energetically optimization of the generation and elimination of the longer bonds is a key factor to suppress the switching energy in PCM. Interfacial phase-change memory (iPCM) using superlattice composing of GeTe and Sb_2Te_3 sub-layer stacks provides an ideal solution for the objective [2, 3]. In iPCM, the exchange of the bonding between covalent and metallic states can be performed without moving the atomic positions in the Sb_2Te_3 sub-layers. An energy loss accompanied with the phase-transition is greatly suppressed as a result [4].

A unique property of magnetoresistance induced by electrical field was recently discovered in iPCM in addition to the low power switching [5]. The phenomenon is highly unusual because no magnetic sensitivity has been observed in the Ge-Sb-Te alloys at room temperature until now. Since E*PCOS2011 and PCOS2011, our group has focused on topological insulator to explain the interesting phenomenon coming out from the superlattice structures. In this PCOS 2012, we discuss the unique property on the point of view of topological insulator.

2. Topological Insulator

Topological insulator (TI) is an electrical insulator in a bulk state [6]. In normal insulators, there is a rigid band gap between the top of the valence bands and the bottom of the conduction bands, while in TIs there is a band gap which is made of the inversion between the top valence band and the bottom conduction band. Therefore, the property (topological phase) of a band gap is different. The interface between a normal insulator and vacuum for example can be connected smoothly. On the other hand, to connect a TI to vacuum, there must exist a point somewhere to recover the inversion bands of the TI to the normal insulating band state of vacuum. To realize this connection, there is no way except for a route through a gapless (Dirac point) or a conductive edge. As a result, the surface of TI must be conductive. The surface band structure is a specially unique because the dispersion is approximately linear near the Dirac point, where an electron has no mass. It means high mobility without scattering. These features result in the conservation of time reversal symmetry in TI. At the surface, spin-up and spin-down electrons flow oppositely as spin current to keep the conservation. How such a special band structure is realized? This is performed using heavy elements with a strong spin-orbit coupling (SOC). Zn Ga, Ge, As, Se, In, Sn, Sb, Te, Hg, Tl, Pb, Bi, and Po are candidates for generating such a bang gap. Among them, Bi_2Se_3, Bi_2Te_3, Sb_2Te_3 are suitable crystals and were already identified to be a TI experimentally [7]. It has been predicted theoretically that one unique crystal structure of Ge-Sb-Te may become a TI, but which is called the Kooi's sequence [8, 9]. Unfortunately, no one has observed the TI property until now. On the other hand, the superlattices made of $GeTe/Sb_2Te_3$ in iPCM has been more promising to observe the TI properties because both GeTe and Sb_2Te_3 crystalline sub-layers have a same growth orientation towards <111> with a highly spatial-inversion symmetry. In addition, a GeTe is a normal insulator [10, 11].

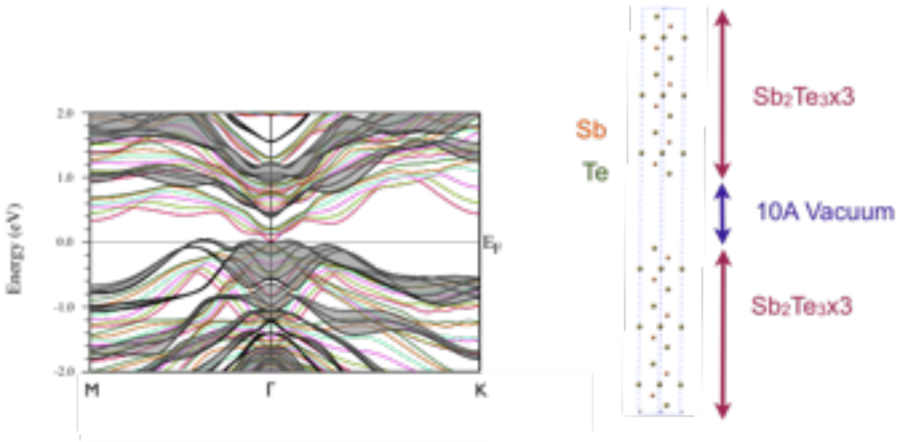

Figure 1 Electronic band structure of Sb_2Te_3 with a vacuum slab (left) and the structure of the model in *P3m-1* (right). In the band structure, grey shadow regions are of the bulk without the vacuum slab. The bulk Sb_2Te_3 has a ~0.5 eV band gap, while at the surface band with the vacuum slab the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

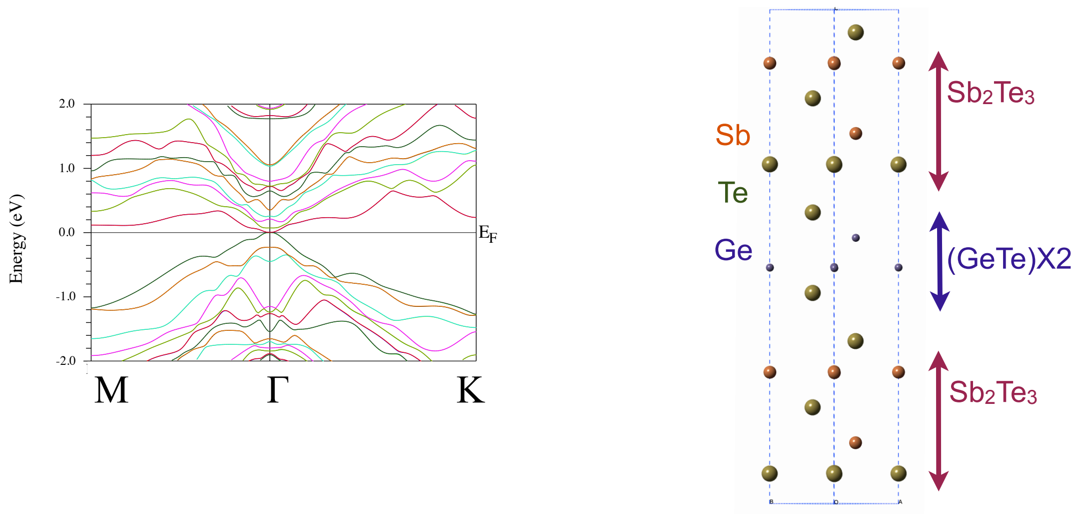

Figure 2 Electronic band structure of *iPCM* $[(GeTe)_2(Sb_2Te_3)_2]$ and the structure of the model in *P3m-1* (right). In the band structure, grey shadow regions are of the balk Sb_2Te_3. The band structure without SOC has a 50 meV band gap, while the gap closes to become a *TI* when SOC is included.

3. Confirmation of TI property in iPCM

As mentioned, the band structure near the Dirac point in TI has a time reversal symmetry E(-k, spin-up) = E(+k, spin-down). A external magnetic field normal to the surface may break the symmetry, and the degeneration of the band is lifted, resulting in a Rashba-type band splitting. If the splitting energy is very large against thermal perturbation, TI may show a magnetic property. As we reported, iPCM showed a large magnetoresistance under an external magnetic field of 0.1 T, while a PCM with the same composition Ge-Sb-Te alloy did not. This is one of the strong evidences that iPCM is a TI [5].

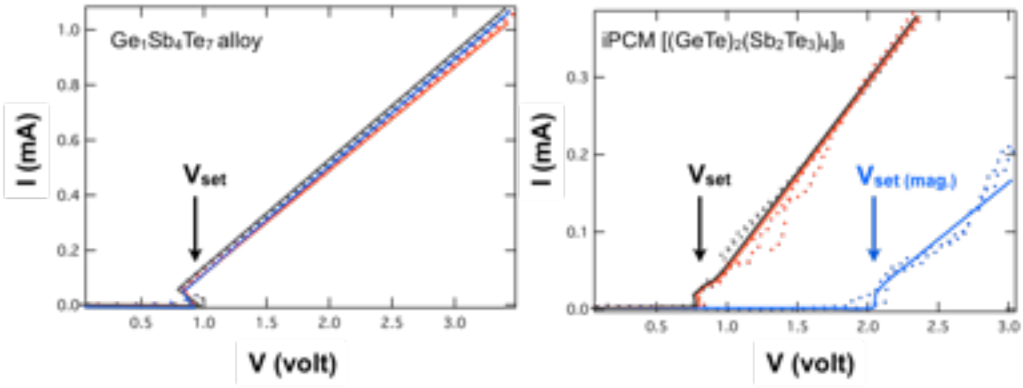

Figure 3 I-V comparison between *PCM* and *iPCM* under a magnetic field. Red and black curves are the original scan and the scan after removing the field, respectively, and blue curves are scans under 0.1 T in-plane magnetic field [5].

ACKNOWLEDGEMENT

A part of the work was supported by *FIRST* program initiated by the Council for Science and Technology Policy (*CSTP*).

References:

[1] Kolobov *et al*., *Nature Mater*, **3**, 703 (2004).
[2] J. Tominaga *et al*. *in Proceedings of the European Symposium on Phase Change and Ovonic Science (E \PCOS)*, Milan, Italy, 2010, pp. 54-59.
[3] R. Simpson, P. Fons, A. V. Kolobov, and J. Tominaga, *Nature Nano*. **6**, 501 (2011).
[4] J. Tominaga *et al*., *Phys. Status Solidi* **B**, 1932 (2012).
[5] J. Tominaga *et al*., *Appl. Phys. Lett*. **99**, 152105 (2011).
[6] H. Zhang, C. Liu, X. Qi, X. Dai, Z. Fang, and S. Zhang, *Nature Phys*. **5**, 438 (2009).
[7] Y. Xia *et al. Nature Phys*. **5**, 398 (2009).
[8] J. Kim, J. Kim, and S. Jhi, *Phys. Rev.* **B82**, 201312 (2010).
[9] B. Sa *et al*. *Phys. Rev*. **B84,** 085130 (2011).
[10] B. Sa *et al*. *Phys. Rev. Lett.* **109**, 096802 (2012).
[11] J. Kim *et al*. *Phys. Rev. Lett.* **109**, 146601 (2012).