

Properties of Low-Power Phase-Change Device with GeTe/Sb₂Te₃ Superlattice Material

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ABSTRACT

The properties of the device using the superlattice phase-change material or interfacial phase-change memory (iPCM) proposed at EPCOS 2011 were introduced. Firstly the film deposition conditions, which are important for low-power phase-change according to the entropic theory, are explained. Then the consumed electric current when recording the data in iPCM device is shown to be reduced to about 1/20 compared to the device with the conventional phase-change material.

Key words: phase-change memory, superlattice, interfacial phase-change memory, low-power, green nanoelectronics

1. INTRODUCTION

The reduction of power or energy consumption in storage devices, as well as the data capacity, is strongly required because of vast increase of the digital data used throughout the world. In this situation, the solid-state drives (SSDs) are paid attention to since SSDs consumes less power and energy than other storage devices such as hard disk drives. One of the attractive non-volatile memories is a phase-change memory (PCM) because of some advantages, one of which is the excellent scalability¹⁾²⁾³⁾ that leads to the prospect for high-data-density storage devices. There are, however, some problems that a PCM has to solve. One of them is the power or energy consumption in recording. Basically, phase-change devices take advantage of Joule's heat generated by electric current in phase-change materials. The temperature in the phase-change material in RESET operation should be higher than the melting point. This thermal energy is quite high and it can cross-erase the data recorded in the neighboring cells (thermal disturb).

Recently, the new mechanism of phase change was proposed where the electric resistivity and the optical indices are greatly modified only by the switching of the Ge atoms in GeSbTe⁴⁾. Furthermore, using this model, the superlattice phase-change (interfacial phase-change memory; iPCM) was proposed, where the consumed power in recording was demonstrated to be dramatically reduced⁵⁾⁶⁾. This method utilizes the periodical thin film layers (superlattice) GeTe/Sb₂Te₃.

This paper describes the deposition conditions for the superlattice and the measurement results on an iPCM device.

2. EXPERIMENTS

The deposition conditions for superlattice were examined from the two points of view: the crystal orientation and the surface roughness. The crystal orientation is important for reducing entropy required in recording. According to reference 5, the key point for low-power recording is the reduction of the entropy consumed for Ge atoms movement. From this point of view, we can expect that the highly-oriented Sb₂Te₃ crystal will enable the low-power recording because the direction of Ge atoms movement, which is guided by Sb₂Te₃, will be highly oriented. The surface roughness is important to form the highly periodic superlattice.

All the films were deposited by sputtering.

We paid attention mainly to two conditions: the substrate temperature during the sputtering (T_{sub}) and the underlayer on which the film was deposited. Figure 1 shows the schematic of the cross section of our device. According to this device structure, the underlayers we should consider are W, SiO₂, GeTe (for Sb₂Te₃ on it) and Sb₂Te₃ (for GeTe on it). We also considered TiN. The crystal orientation was observed by X-ray diffraction. The surface roughness was observed by a scanning electron microscope (SEM). The thickness of the deposited films and the substrate used for pursuing the film deposition conditions was 100 nm and Si wafer if not mentioned.

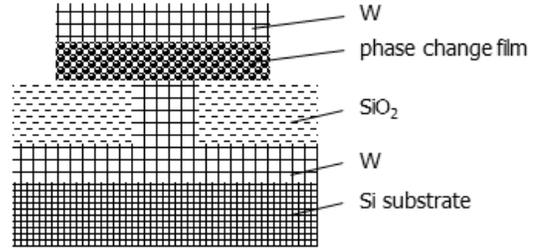


Fig. 1 Cross section of the device

The device structure as shown in Fig. 1 was fabricated with the above-mentioned conditions. The substrate used was Si with the bottom electrode pattern (W plug surrounded by SiO₂). After the deposition of the superlattice and W films on the substrate, the photoresist was spin-coated on the sample surface. The resist pattern was formed by photo lithography. The superlattice and W films was etched away by RIE to form the cells and the electrode pad for contact of the probe for electric measurement. The device with the conventional Ge₂Sb₂Te₅ film was also fabricated for comparison.

3. RESULTS AND DISCUSSIONS

Firstly, the T_{sub} dependency was examined. Figure 2 shows the X-ray diffraction data of Sb₂Te₃ and GeTe deposited on SiO₂ with various T_{sub} 's. These figures indicate the following facts; 1) Sb₂Te₃ forms c-axis orientation at $T_{sub} > 140^\circ\text{C}$ while the deposited film was not observed at $T_{sub} > 240^\circ\text{C}$ because of evaporation from the substrate, 2) GeTe forms c-axis orientation at $T_{sub} > 190^\circ\text{C}$ or 210°C . When GeTe was deposited on 200-mm-diameter Si wafer at $T_{sub} = 240^\circ\text{C}$, the deposition rate was much slower on the circumference of the wafer. This is considered due to evaporation of the deposited film. Thus, $190^\circ\text{C} < T_{sub} < 240^\circ\text{C}$ must be fulfilled. Though this value might depend on some conditions such as the sputtering machines, it is qualitatively reasonable that too low and too high T_{sub} is inadequate to

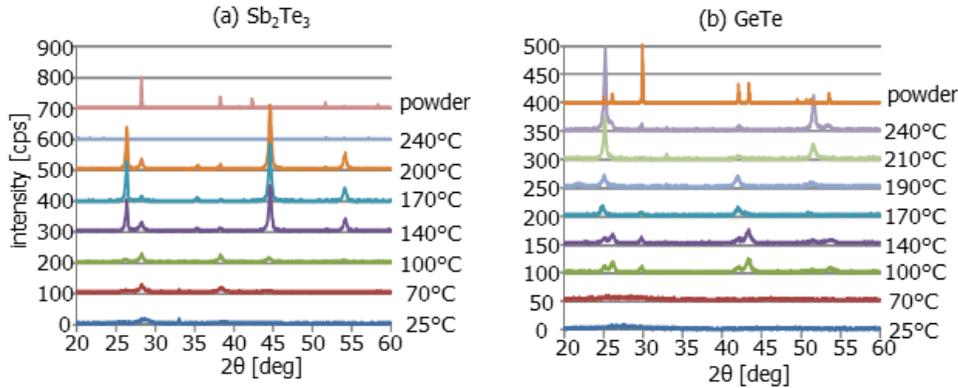


Fig. 2 X-ray diffraction data for (a) Sb₂Te₃ and (b) GeTe sputtered at various substrate temperatures. The digits on the right of each diffraction pattern show the substrate temperatures during sputtering. The substrate was Si with SiO₂ on its surface for all the cases. The powder patterns shown are the simulation results.

form superlattice. The underlayer dependency of Sb_2Te_3 properties was examined. Figure 3 shows the scanning electron microscope (SEM) images of Sb_2Te_3 and GeTe sputtered on SiO_2 . These figures show that Sb_2Te_3 surface was rough while GeTe surface was smooth. Figure 4 shows the SEM images and X-ray diffraction data of Sb_2Te_3 sputtered on SiO_2 and GeTe. Figures 4 (a) and (b) show that the roughness is more suppressed on GeTe while the crystal orientation is higher on SiO_2 . Figures 4 (c) and (d), however, show that the roughness and the crystal orientation are desirable on W and TiN.

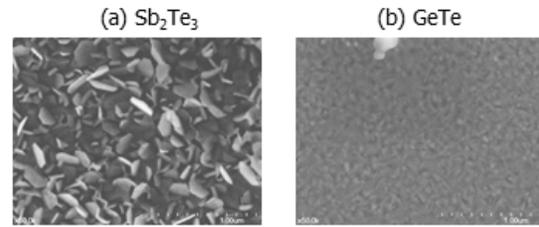


Fig. 3 SEM images of (a) Sb_2Te_3 and (b) GeTe sputtered on SiO_2 .

Next, the underlayer dependency of GeTe properties was examined. Figure 5 shows the X-ray diffraction data of GeTe sputtered on various underlayers. These figures show that the crystal orientation is the highest on TiN. Figure 5 (b) shows that the crystal orientation on Sb_2Te_3 on SiO_2 is not very high, which will be a problem in forming highly functional superlattice. The reason for this low crystal orientation is speculated to be due to relatively low crystal orientation of Sb_2Te_3 on SiO_2 . If the crystal of Sb_2Te_3 is highly oriented, it can be the seed for GeTe crystal orientation. We paid less attention to GeTe surface roughness on Sb_2Te_3 because GeTe layers can be thinner than Sb_2Te_3 layers. According to the theory in reference 5, GeTe is necessary only to supply Ge atoms on the interfaces of the superlattice while Sb_2Te_3 is necessary to guide Ge atoms. Thus, GeTe can be sufficiently thin that the GeTe surface roughness is almost determined by the surface roughness of Sb_2Te_3 .

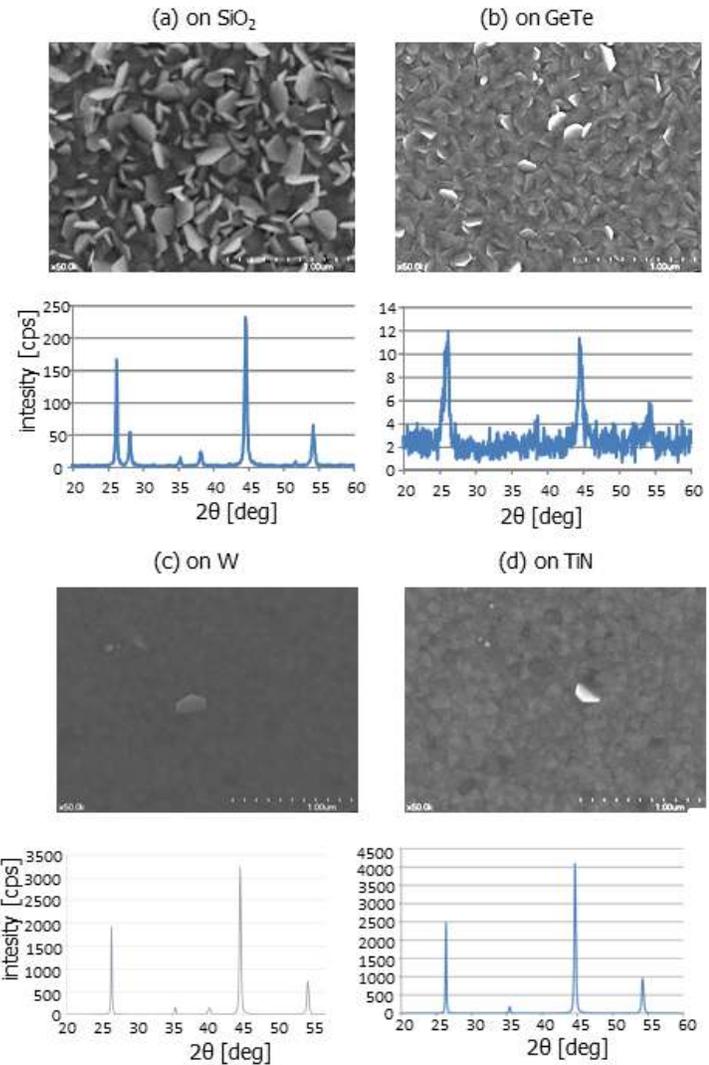


Fig. 4 SEM images and X-ray diffraction data of Sb_2Te_3 sputtered on (a) SiO_2 , (b) GeTe on SiO_2 , (c) W and (d) TiN.

Table 1 summarizes the above-mentioned experimental data. The puzzle we have to solve is the material deposited firstly on the substrate to form the functional superlattice. The first layer on the substrate should be relatively thick to supply the high c-axis orientation. If GeTe is deposited first, the crystal orientation of Sb_2Te_3 to be deposited on it would not be high. If Sb_2Te_3 is deposited first, this puzzle will be well solved. Still there may be two anxieties. One is the crystal orientation of Sb_2Te_3 on GeTe. This is, however, not a problem because GeTe layers can be sufficiently thin as

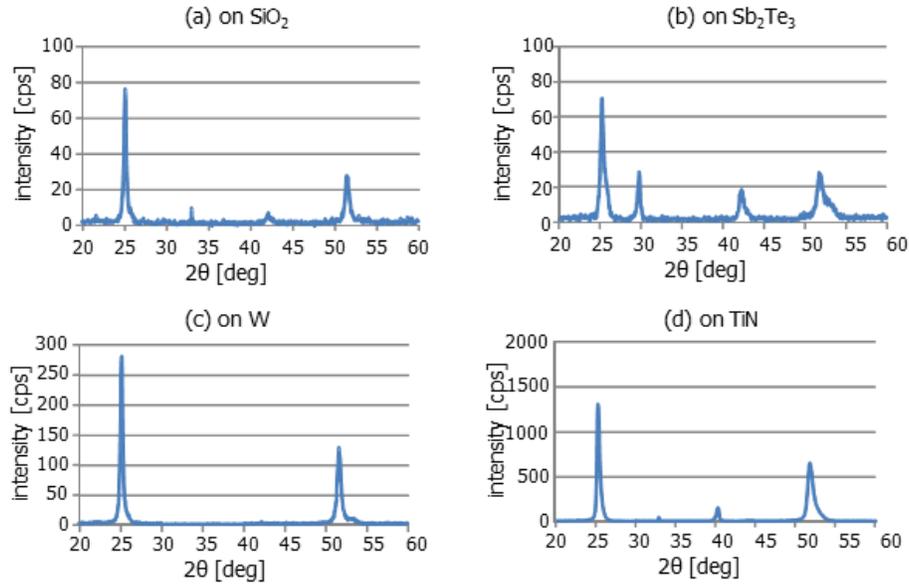


Fig. 5 X-ray diffraction data of GeTe sputtered on (a) SiO₂, (b) Sb₂Te₃ on SiO₂, (c) W and (d) TiN.

mentioned above. The other is the crystal orientation and surface roughness of Sb₂Te₃ on SiO₂ because the substrate has SiO₂ on its surface as drawn in Fig. 1. This problem was solved by controlling the thickness of Sb₂Te₃. Figure 6 shows the SEM images of thin Sb₂Te₃ sputtered on SiO₂. The surface roughness is suppressed in Fig. 6 (a) compared with 100-nm thick Sb₂Te₃ as shown in Fig. 4 (a). Though 10-nm Sb₂Te₃ still shows some roughness, this roughness might be acceptable for forming superlattice. Thus, the following film deposition condition will work; 1) about 10-nm Sb₂Te₃ deposited on the substrate, 2) thin GeTe and Sb₂Te₃ deposited periodically.

Figure 7 shows the cross sectional TEM image of the superlattice film deposited on SiO₂. The film thickness was 10

Table 1 Qualitative summary of the experimental results for film deposition conditions

Unerlayer		GeTe	Sb ₂ Te ₃
SiO ₂	crystal	OK	medium
	roughness	OK	NG
TiN, W	crystal	medium	OK
	roughness	OK if thin	OK
GeTe on SiO ₂	crystal	-	NG
	roughness	-	OK
Sb ₂ Te ₃ on SiO ₂	crystal	OK (medium)	-
	roughness	OK if thin	-

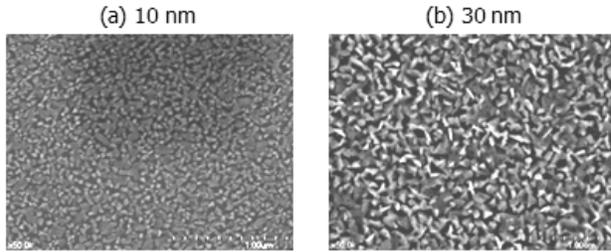


Fig. 6 SEM images of Sb_2Te_3 sputtered on SiO_2 . The thickness of Sb_2Te_3 is (a) 10 nm and (b) 30 nm.

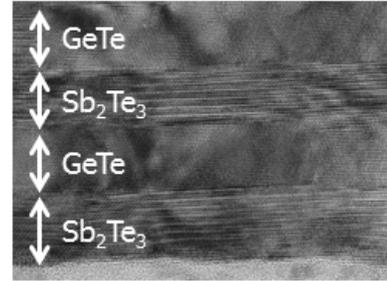


Fig. 7 TEM image of the cross section of the $\text{GeTe}/\text{Sb}_2\text{Te}_3$ superlattice sample.

nm for all the films. The second Sb_2Te_3 layer shows high crystal orientation even on GeTe .

Figure 8 shows the measurement results on the SET-RESET operation for the devices with $\text{GeTe}/\text{Sb}_2\text{Te}_3$ superlattice and $\text{Ge}_2\text{Sb}_2\text{Te}_5$. This figure shows that the dynamic current in RESET was reduced to the amount of about 1/20 compared with the $\text{Ge}_2\text{Sb}_2\text{Te}_5$ device.

4. CONCLUSION

The film deposition conditions for $\text{GeTe}/\text{Sb}_2\text{Te}_3$ superlattice for our interfacial phase-change memory (iPCM) device was pursued where it was found that Sb_2Te_3 buffer layer on the substrate is necessary from the viewpoints of crystal orientation and the surface roughness. The iPCM device was demonstrated to reduce the electric current to the amount of about 1/20 compared with the $\text{Ge}_2\text{Sb}_2\text{Te}_5$ device.

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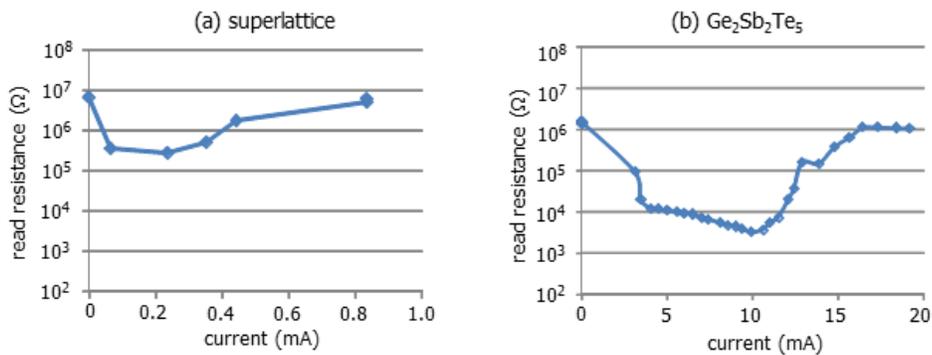


Fig. 8 Relationship between the dynamic electric current and read resistance of the devices with (a) $\text{GeTe}/\text{Sb}_2\text{Te}_3$ superlattice film and (b) conventional $\text{Ge}_2\text{Sb}_2\text{Te}_5$ film. Induced voltage was about 1.0V for both devices.

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Biographies

Toshimichi SHINTANI: Theme leader of Green Nanoelectronics Center at National Institute for Advanced Industrial Science and Technology (AIST), Japan. He received M. S. (1992) in Keio University, Japan. He joined Hitachi Central Research Laboratory in 1992. His research theme has consistently been the storage technology, mainly for large data capacity. He worked on phase-change recording with a scanning near-field optical microscope, optical disk technology such as DVD-RAM and multi-layered Blu-ray Disc, high-speed phase-change recording and super-resolution technique using transition metal oxide and phase-change materials. Meanwhile he also worked on metamaterials and phase-change etching where crystalline regions in amorphous are selectively etched. In 2010 he moved temporarily to AIST to engage in the Japanese national project "Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program)".