

Crystallographic Analysis of $\text{Sn}_x\text{Te}_{100-x}/\text{Sb}_2\text{Te}_3$ Superlattice and Proposal of its Low Switching Power Mechanism

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We performed XRD measurements on previously discovered $\text{Sn}_x\text{Te}_{100-x}/\text{Sb}_2\text{Te}_3$ superlattice (SL) with ultra-low switching power ($X=10, 20, 35,$ and 50 at.%), and then analyzed its crystalline structure for proposal of the ultra-low switching power mechanism. XRD showed that only a little $\text{SnTe}/\text{Sb}_2\text{Te}_3$ SL and major NaCl-type SnSbTe phases coexist for $X=50$, and that only a little $\text{SnTe}/\text{Sb}_2\text{Te}_3$ SL, major Bi_2Te_3 -type SnSbTe , and Te phases coexist for $X=10, 20,$ and 35 . The detailed crystallographic analysis showed as follows. There was a high possibility that both the NaCl-type and Bi_2Te_3 -type SnSbTe -alloy phases have SL structures themselves: “Self-assembly SL”, with the vacancy layer in the specific (Sn, Sb) and Te layer, and that something new phenomenon such as Sn switching in the SnSbTe self-assembly SL leads to the ultra-low switching power.

I. INTRODUCTION

Recently, our group discovered $\text{Sn}_x\text{Te}_{100-x}/\text{Sb}_2\text{Te}_3$ diluted SL device which showed the ultra-low switching power.¹⁻³ The consumed power was approximately 1/2250th ($X=10$ at.%) \sim 1/15th ($X=50$ at.%) that of the GST225 device.¹⁻³ The XRD results showed that only a little $\text{SnTe}/\text{Sb}_2\text{Te}_3$ SL and major NaCl-type SnSbTe -alloy (only a little $\text{SnTe}/\text{Sb}_2\text{Te}_3$ SL, major Bi_2Te_3 -type SnSbTe -alloy, and Te) phases coexist for $X=50$ ($X=10, 20,$ and 35) (later Figs. 1 and 3 references). Since the $\text{SnTe}/\text{Sb}_2\text{Te}_3$ SL phase was only a little, the cause of the ultra-low switching power may be so-called Sn switching in the SL phase¹ seemed to be unreasonable.

The purpose of this current study is, therefore, to carry out the crystallographic analysis of the SnSbTe phase, and afterward to propose the ultra-low switching power mechanism.

II. EXPERIMENTAL

Sb_2Te_3 (10 nm)/ $[\text{Sn}_x\text{Te}_{100-x}$ (1 nm)/ Sb_2Te_3 (4 nm)]₉ SL film ($X=10, 20, 35,$ and 50 at.%) was deposited at substrate temperature of 200°C by using a dc magnetron sputtering apparatus. XRD measurement (Cu $K\alpha$) was carried out to analyze the crystalline structure of the SnSbTe phase.

The structure of the SnSbTe phase with NaCl-type for $X=50$ (Bi_2Te_3 -type for $X=10, 20,$ and 35) was examined by using the following procedure (a)–(d):⁶

- (a) Experimental integral peak-intensity ratio of $(I_{111}/I_{222})_{\text{Obs.}}$ ($(I_{006}/I_{009})_{\text{Obs.}}$) was estimated from the $\text{SnSbTe}(111)$ and (222) peaks ($\text{SnSbTe}(006)$ and (009) peaks) obtained in the XRD experiments. (I_{111} and I_{222} (I_{006} and I_{009}): integral peak-intensity of $\text{SnSbTe}(111)$ and (222) peaks ($\text{SnSbTe}(006)$ and (009) peaks)).
- (b) Conceivable vacancies were taken in the SnSbTe structure, and modeled.
- (c) Theoretical integral peak-intensity ratios of $(I_{111}/I_{222})_{\text{Cal.}}$ ($(I_{006}/I_{009})_{\text{Cal.}}$) were estimated for all the modeled SnSbTe structures by using Eqs. (1) and (2).

$$I_{hkl} \approx |F_{hkl}|^2 \times LZ \times P = |F_{hkl}|^2 \times \frac{1 + \cos^2 2\theta}{\sin^2 \theta \cos \theta} \times P \quad (1).$$

$$F_{hkl} = \sum_n f_n e^{2\pi i(hx(n)+ky(n)+lz(n))} \quad (2).$$

F_{hkl} , P , and LZ are the structure factor, multiplicity factor, Lorenz polarization factor, respectively. θ is the Bragg angle, f_n is the atomic scattering factor for atomic sort n , and hkl and xyz are the mirror index and the fractional coordinates, respectively.⁴

(d) From the obtained $(I_{111}/I_{222})_{Obs.}$ and $(I_{111}/I_{222})_{Cal.}$ ($(I_{006}/I_{009})_{Obs.}$ and $(I_{006}/I_{009})_{Cal.}$), the order parameter S was estimated using the following equation.⁵

$$S^2 = \frac{[I_{111}/I_{222}]_{Obs.}}{[I_{111}/I_{222}]_{Cal.}} \quad \text{for } X=50 \quad (3).$$

$$\left(S^2 = \frac{[I_{006}/I_{009}]_{Obs.}}{[I_{006}/I_{009}]_{Cal.}} \right) \quad \left[\text{for } X=10, 20, \text{ and } 35 \quad (4). \right]$$

The vacancy layer and/or site which satisfy $0.7 (\pm 0.1) \leq S \leq 1.0 (\pm 0.1)$ “as a judgment whether the SnSbTe phase is ordered or not” were searched.⁶ The resultant vacancy configuration is judged to be the most likely.⁶

III. RESULTS

A. Crystalline structure of X=50 at.%

Figure 1 shows an XRD profile for the SnTe/Sb₂Te₃ SL film. Only a little SnTe(111)/Sb₂Te₃(001) SL phase and a major SnSbTe phase with the NaCl-type structure coexisted.

The theoretical relatively integral peak-intensity ($I_{111, Cal.}$) of the SnSbTe phase is expressed as follows:⁴

$$\begin{aligned} I_{111, Cal.} &\approx |4f_{(Sn, Sb)} - 4f_{Te}|^2 \times LZ \times P \\ f_{Sn} &\approx f_{Sb} \approx f_{Te} \\ \therefore I_{111} &\approx 0 \end{aligned} \quad (5).$$

So, the SnSbTe(111) peak of Fig. 1 should not be observed. The structure that can allow this peak was thus searched according to the aforementioned procedure (a)–(d).

The resultant configuration: crystalline structure, was shown in Fig. 2 (a). In Fig. 2 (b), that of GeTe layer in GeTe(111)/Sb₂Te₃(001) SL film was also shown for comparison.^{6–9} The -(Sn, Sb) (layer)-Te-Vacancy-Te-(Sn, Sb)- stacks in order along the SnSbTe[111] for Fig. 2 (a) well corresponded to the -Ge-Te-Vacancy-Te-Ge- stacks for Fig. 2 (b). The structure of the SnSbTe phase was all the same as the GeTe layer in the GeTe(111)/Sb₂Te₃(001) SL film.

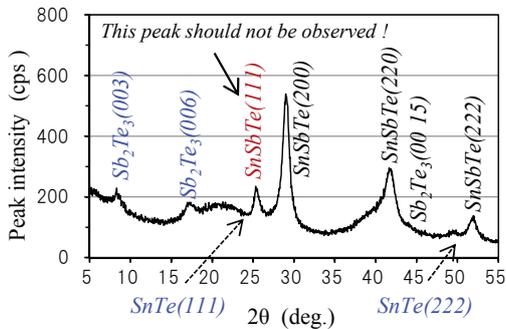


Fig.1 XRD profile of SnTe/Sb₂Te₃ SL film.

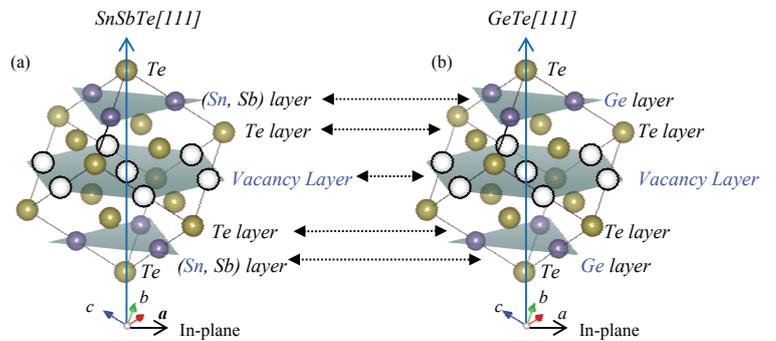


Fig.2 The most likely structure for (a) the SnSbTe-alloy phase in the SnTe/Sb₂Te₃ SL film and (b) the GeTe layer in the GeTe/Sb₂Te₃ SL film.

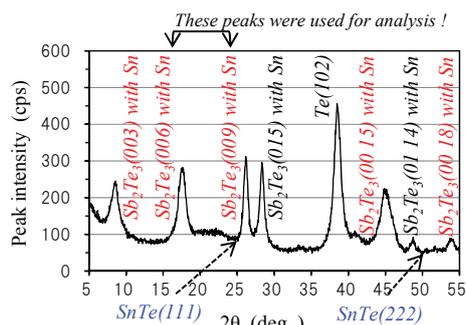


Fig. 3 XRD profile of $\text{Sn}_x\text{Te}_{100-x}/\text{Sb}_2\text{Te}_3$ SL film when $X=10$ at.%, representatively.

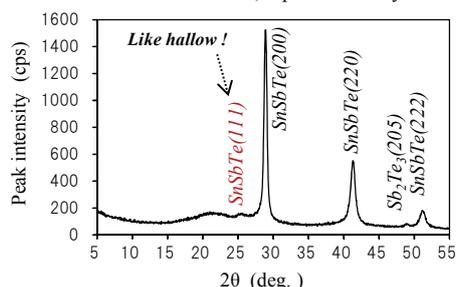


Fig. 6 XRD profile of SnSbTe-alloy film prepared by co-sputtering.

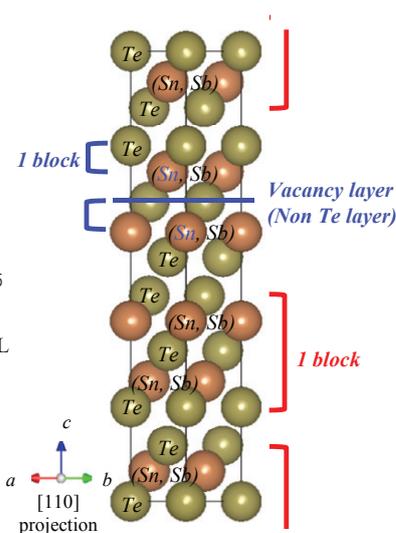


Fig. 4 The most likely structure for the SnSbTe-alloy phase in the $\text{Sn}_x\text{Te}_{100-x}/\text{Sb}_2\text{Te}_3$ SL film. ($X=10, 20, \text{ and } 35$ at.%)

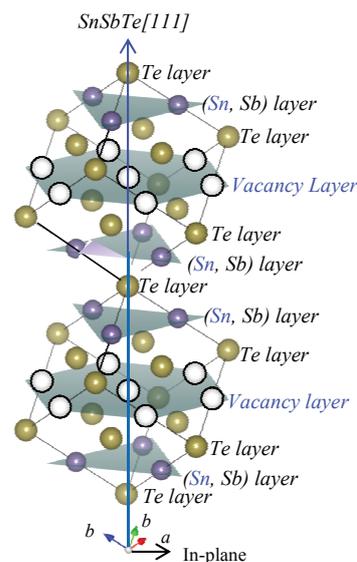


Fig. 5 Two stacked SnSbTe-lattices of Fig.2 (a).

B. Crystalline structure of $X=10, 20, \text{ and } 35$ at.%

Figure 3 shows an XRD profile of $\text{Sn}_x\text{Te}_{100-x}/\text{Sb}_2\text{Te}_3$ SL film when $X=10$, representatively. Only a little SnTe(111)/ $\text{Sb}_2\text{Te}_3(00l)$ SL phase, a major Sb_2Te_3 phase with Sn: Bi_2Te_3 -type SnSbTe phase, and a Te phase coexisted. The strong SnSbTe(00l) peaks mean that this phase mainly exists in the SL film.

The structure of SnSbTe phase was thus searched according to the aforementioned procedure (a)–(d). The resultant configuration: crystalline structure, was shown in Fig. 4. The configuration was as follows: -Te-(Sn, Sb)-Te-Te-(Sn, Sb)-Te-(Sn, Sb)-Te-Te-(Sn, Sb)-Vacancy-(Sn, Sb)-Te-Te-(Sn, Sb)-Te- stacks, in order along the SnSbTe[001] per its one lattice.

IV. DISCUSSION

A. Switching mechanism in case of $X=50$ at.%

The mechanism on the low switching power was still unclear.¹ But, figure 2 (a) offered the key to consider it.

We stacked up two SnSbTe lattices of Fig. 2 (a) in its [111] (Fig. 5). Figuratively speaking, it was possible that the upper (lower) lattice corresponds to the GeTe (Sb_2Te_3) layer in the GeTe(111)/ $\text{Sb}_2\text{Te}_3(001)$ SL. And that the vacancy layer of the upper (lower) lattice corresponds to a vacancy layer (a Te–Te weak bond layer) of the GeTe (Sb_2Te_3) layer.^{7–9} Therefore, it was possible that the SnSbTe phase has a SL structure itself, i.e., “self-assembly SL structure”. And that something new phenomenon such as Sn switching occurs in such a self-assembly SL phase, which leads to the low switching power.¹ (Consumed power: $\sim 1/15$ th that of GST225 device.)

Figure 6 shows an XRD profile of SnSbTe film prepared by co-sputtering using the SnTe and Sb_2Te_3 targets. The SnSbTe(111) peak was hallow pattern, which means that the NaCl-type SnSbTe lattice has no vacancy layer. Only when the layer by layer sputtering between the SnTe and Sb_2Te_3 layers was performed, the SnSbTe can have the self-assembly SL structure.

B. Switching mechanism in case of X= 10, 20, and 35 at.%

The mechanism on the ultra-low switching power was also unclear. Figure 4, however, offered the key to consider it.

The vacancy layer of GeTe layer in the GeTe(111)/Sb₂Te₃(001) SL is the essence of Ge switching.^{7, 9} The Refs. 7 and 9 also mentioned that the Te–Te weak bond layer of Sb₂Te₃ layer in that SL is also essential. And that the following partial arrangement along the GeTe[111]/Sb₂Te₃[001] SL, for example, is also essential:^{7,9}

-Te-Sb-Te-Te-Sb-Te-Sb-Te-Ge-Te-Vacancy-Te-Ge-Te-Sb-Te-

As shown in Fig.4, the SnSbTe phase had the vacancy and the Te–Te weak bond layers. And its phase also had the following partial arrangement along the SnSbTe[001]: -Te-(Sn, Sb)-Te-Te-(Sn, Sb)-Te-(Sn, Sb)-Te-Te-(Sn, Sb)-Vacancy-(Sn, Sb)-Te-Te-Sb-Te-. The latter arrangement in the SnSbTe[001] resembles the former one in the GeTe[111]/Sb₂Te₃[001] SL.^{7, 9} Thus, there was a possibility that the vacancy layer (the Te–Te weak bond layer) of the SnSbTe plays a similar role to that of the GeTe (Sb₂Te₃) layer in the GeTe(111)/Sb₂Te₃(001) SL.^{7,9} Therefore, it was possible that the SnSbTe phase has a SL structure itself, i.e., “self-assembly SL structure”.

Something new phenomenon concerning the numbers of Sn atoms such as Sn switching¹ occurs in the its self-assembly SL, the Sn atoms ought to operate for the resistance switching is decreased with decreasing X, as it turned out, the maximum conservation of electric power, $\sim 1/2250$ th that of GST225 device (X=10 at.%), is considered to be obtained.³

In the Sn_XTe_{100-X}/Sb₂Te₃ diluted SL also, the SnSbTe can have the self-assembly SL structure only when the layer by layer sputtering between the Sn_XTe_{100-X} and Sb₂Te₃ layers was performed.

V. CONCLUSION

In summary, it was possible that the SnSbTe-alloy phase mainly existed the Sn_XTe_{100-X}/Sb₂Te₃ SL film has a self-assembly SL structure, and that something new phenomenon in its self-assembly SL leads to the ultra-low switching power.

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APPENDIX

Thinning of SnTe/Sb₂Te₃ superlattice

Figure 7 shows the electrical properties of one unit SL composed of Sb₂Te₃(4 nm)/[SnTe(1 nm)/Sb₂Te₃(4 nm)]₁. The set (reset) voltage was ~ 0.2 V (0.39 V), and the set (reset) current was ~ 1.0 μ A (~ 2.27 μ A). Multiplying the reset voltage by the reset current yields switching power of ~ 0.89 μ W. Since the switching power of GST225 device with the same prober was ~ 6080 μ W, this power is $\sim 1/6800$ th that of GST225. As a result of crystallographic analysis by using the aforementioned procedure (a)–(d), the one unit SL also had the self-assembly SL structure shown in Fig. 5. Therefore, thinning down to 5nm might thus be possible.

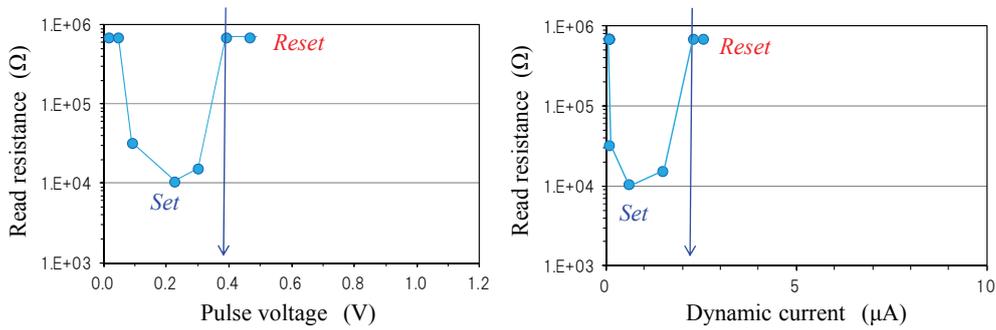


Figure 7 Electrical properties of one unit SL composed of Sb₂Te₃(4 nm)/[SnTe(1 nm)/Sb₂Te₃(4 nm)]₁.