Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp761-762

Crystal Growth and Characterization of Topological Insulator BiSb Thin Films by Sputtering Deposition for SOT-MRAM Applications

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Abstract

We characterize BiSb thin films grown on sapphire substrates by sputtering deposition with Ar and Kr plasma. By optimizing the growth conditions, we are able to obtain quasi-single-crystal BiSb(001) thin films with equivalent twin crystals. The conductivity of BiSb at the studied thicknesses exceed 10^5 Ω^{-1}m^{-1}, reaching a maximum of 1.8×10^5 Ω^{-1}m^{-1} at 10 nm. From the temperature dependence of the electrical resistivity, we confirm the existence of metallic surface states. Our results demonstrate that it is possible to obtain sputtered BiSb thin films with quality approaching that of epitaxial BiSb grown by molecular beam epitaxy.

1. Introduction

Topological insulators (TI) are exotic materials with insulating bulk states but metallic surface states [1]. The giant spin Hall effect has been observed in several topological insulators [2], making them very promising for spin-orbit-torque (SOT) magnetoresistive random access memory (MRAM) [3]. Among TIs, BiSb is particularly promising because it shows both a giant spin Hall angle (θ_{SH}~ 52 for the BiSb(012) surface) and high electrical conductivity (σ ~ 2.5×10^5 Ω^{-1}m^{-1}) [4]. Furthermore, SOT switching with ultralow current density was demonstrated in MnGa/BiSb bilayers [4]. However, BiSb thin films are usually deposited by molecular beam epitaxy (MBE), which is not suitable for mass production of realistic spintronic devices. Thus, physical deposition of high-quality topological insulators is strongly required.

Here we report on the crystal growth and characterization of high-quality BiSb thin films deposited on sapphire substrates by the sputtering technique. By optimizing the growth conditions, we were able to grow high-quality quasi-single-crystal BiSb thin films with σ exceeding 1×10^5 Ω^{-1}m^{-1}. Electrical measurements indicate dominant surface conduction when the thickness is reduced to 10 nm. Our results demonstrate the probability to grow BiSb thin films by sputtering deposition with quality approaching those grown by MBE.

2. Crystal growth

In this work, we deposit BiSb thin films with various thicknesses on sapphire c-plane (0001) substrates by radio-frequency magnetron sputtering from a single $Bi_{0.85}Sb_{0.15}$ target. Before deposition, the sapphire substrates were processed by acid solution and thermal cleaning. Table I shows the list of samples and their deposition condition used in this work. There are two series of samples, deposited using Ar plasma and Kr plasma respectively. The substrate temperature was either kept constant (one-step) or changed (two-step) during the deposition, as discussed below. The Ar/Kr gas pressure was kept at 0.2 Pa, and the typical sputtering power was 0.9 W/cm^2. For samples deposited by the one-step method, the best substrate temperature varies according to the thickness of BiSb film. To further improve the crystal quality, we employed a two-step technique for thick films. First, we deposited a BiSb layer thinner than 10 nm at 50 °C. Then, we increased T_S to 150 °C, and annealed the layer for 10 minutes. Finally, we deposited the rest at 150 °C. We found that this two-step technique can improve the crystal quality and the electrical conductivity of BiSb thin films thicker than 10 nm.

Table I List of samples in this work

Sample	Substrate temperature	Thickness (nm)	Gas
A1-1	50 °C	10	Ar
A1-2	150 °C	14	Ar
A1-3	150 °C	28	Ar
A1-4	150 °C	40	Ar
A2-1	50 °C → 150 °C	14	Ar
A2-2	50 °C → 150 °C	24	Ar
A2-3	50 °C → 150 °C	40	Ar
K1-1	50 °C	10	Kr
K1-2	150 °C	30	Kr
K1-3	150 °C	50	Kr
K2-1	50 °C → 150 °C	17	Kr
K2-2	50 °C → 150 °C	25	Kr
K2-3	50 °C → 150 °C	43	Kr

3. Results

Fig. 1 shows the θ - 2θ X-ray diffraction of 10-nm BiSb thin films. The patterns show strong BiSb(003), (006) and (009) peaks, indicating the dominant BiSb(001) phase. At 10 nm, there is no other phase than BiSb(001), demonstrating that it is possible to obtain a single-phase BiSb thin film by sputtering deposition. As the thickness increases, extra phases such as BiSb(012) and BiSb(014) start to appear. Meanwhile, the two-step deposition can significantly suppress these extra phases. Indeed, the BiSb(001) single phase was observed up to at least 24 nm by the two-step deposition. The surface morphology observed by atomic force microscopy shows that the 10-nm-thick BiSb films have smoother surfaces than thicker films. The roughness of 10 nm-thick BiSb thin films is about 0.9 nm for sample A1-1, and about 0.8 nm for sample K1-1. However, the surface smoothness deteriorated rapidly as the thickness increased from 10 nm, which is consistent with the emergence of other phases as revealed by the XRD spectra.

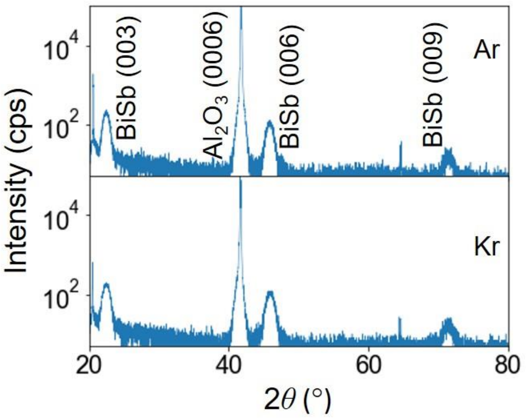

Fig.1 XRD spectra of 10-nm-thick samples sputtered by Ar (top) and Kr (bottom) plasma.

Fig.2 shows the polar mapping for XRD χ (tilting angle) - φ (azimuth angle) scan to investigate the in-plane texture of the 10 nm-thick samples. The θ angle was set at 13.6° for the (012) plane. The polar maps show 6 strong peaks located at χ = 55°. It indicates that there are equivalent twin crystals in samples A1-1 and K1-1 [5]. However, there is no other plane in the polar maps besides BiSb(012), indicating the high crystal ordering of sputtered BiSb films despite the large lattice mismatch of -4.8% between the BiSb films and the sapphire substrates.

Fig. 3 shows the electrical conductivity, σ, of the BiSb thin films as a function of the film thickness, measured at 300 K. We notice that the thin samples have higher conductivity than that of the thick samples. This feature can be explained by the existence of the topological surface states. The conductivity of a topological insulator is given by

$$\sigma = \sigma_S t_S / t + \sigma_B,$$

where σ_S and σ_B are the conductivity of the surface states and bulk states, and t_S and t are the thickness of the surface and the whole film, respectively. When the bulk conduction is dominant (i.e. $t >> t_S$), σ approaches σ_B. However, when t is reduced, the contribution of surface conduction becomes much more important, and σ becomes larger than σ_B. The highest σ of $1.8\times10^5\ \Omega^{-1}m^{-1}$ is obtained for the 10-nm-thick A1-1 and K1-1 samples, which is close to that of high quality MBE-grown 10 nm-thick BiSb films on GaAs(111)A substrates ($2.5\times10^5\ \Omega^{-1}m^{-1}$).

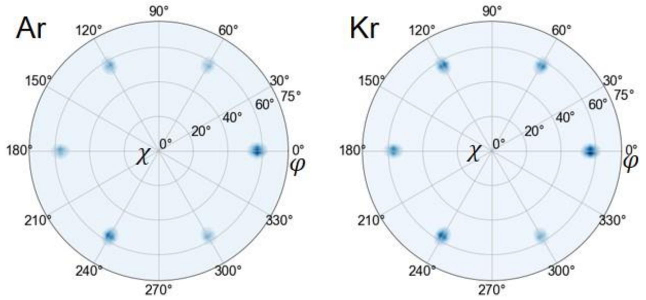

Fig. 2 Polar mapping for XRD χ - φ scan of 10-nm-thick samples sputtered by Ar (left) and Kr (right) plasma.

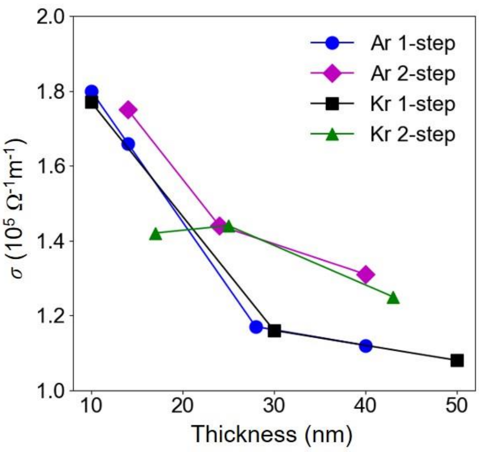

Fig. 3 Electrical conductivities of BiSb at various thicknesses.

4. Conclusion

We have characterized BiSb thin films deposited on sapphire substrates by sputtering deposition. We show that it is possible to deposit high quality quasi-single-crystal BiSb thin films by sputtering deposition with quality approaching that of MBE-grown epitaxial thin films. We confirmed the existence of surface states from the thickness-dependence and temperature-dependence of the electrical conductivity/resistivity. Our results are promising for future integration of BiSb in spintronic devices, such as SOT-MRAM or spin Hall oscillators.

Acknowledgements

This work is supported by JST-CREST (JPMJCR18T5). We sincerely thank the Material Analysis Division and the technician H. Iida at Titech, for their help in XRD measurement.

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