Topological heterostructure engineering toward advanced read head technologies for hard disk drives

Zhenchao Wen[1], Talluri Manoj[1], Seiji Mitani[1], Hiroaki Sukegawa[1], Brian York[1], Xiaoyong Liu[2], Maki Maeda[2], and Quang Le[2]

[1]National Institute for Materials Science (NIMS), Tsukuba 305-0047, Japan, wen.zhenchao@nims.go.jp
[2]Western Digital, San Jose, California 95119, United States

The engineering of topological heterostructures is crucial for developing next-generation spintronic devices, including advanced read heads for ultrahigh-density hard disk drives. BiSb-based topological insulator (TI) systems are promising candidates for enhancing the spin Hall effect due to their unique surface states. However, interfacial issues with ferromagnetic (FM) layers can degrade device performance. In this work, we demonstrate that the strategic insertion of titanium (Ti)-based interlayers (ILs) in BiSb/FM heterostructures significantly improves spin Hall efficiency. Studies on BiSb/NiFe structures with a Ti interlayer show that the IL protects the topological surface states and suppresses interdiffusion, exhibiting both thermal and temporal robustness. These findings highlight how interface engineering can effectively manipulate spin Hall efficiency, offering a viable pathway for integrating topological materials into future advanced read head components.

Keywords: topological insulator BiSb, interface engineering, spin Hall efficiency, titanium-based interlayers

I. Introduction

The continuous demand for higher data storage densities in hard disk drives (HDDs) necessitates innovations in read head technologies. Topological insulators (TIs), such as BiSb, have emerged as promising materials due to their giant spin-charge conversion efficiency originating from topological surface states.[1], [2], [3] This unique property is highly relevant for developing advanced spintronic devices, including potentially novel read head sensors that could utilize spin Hall and inverse spin Hall effects.[4], [5], [6] However, challenges in fabricating high-quality TI thin films and managing interfacial effects with ferromagnetic (FM) layers can suppress these crucial surface states and hinder spin transport. An effective interlayer (IL) is essential to prevent interdiffusion and preserve the structural integrity of BiSb, thereby enhancing spin-charge conversion. This research focuses on engineering BiSb-based heterostructures with Ti-based ILs to optimize spin Hall efficiency, a key parameter for such advanced reader technology for ultrahigh-density HDDs.

II. Experimental Methodology

All thin films were deposited on single-crystalline c-plane sapphire [Al_2O_3 (0001)] substrates using a room-temperature DC magnetron sputtering system. To investigate thickness-dependent transport and structural properties, the BiSb layers' total thickness varied between 4 and 12 nm. In comparison, a nominal thickness of 10 nm was selected for optimal crystallinity and surface morphology in the heterostructure studies. Titanium-based interlayers, i.e., metallic Ti, TiN_x, and TiO_x, were introduced between BiSb and ferromagnetic layers (NiFe or CoFeB). Reactive sputtering was used for TiN_x and TiO_x depositions under controlled Ar/N_2 or Ar/O_2 gas environments.

The films' crystallographic texture and phase purity were examined by X-ray diffraction (XRD) using Cu-Kα radiation, and surface morphology was analyzed by atomic force microscopy (AFM). Reflection high-energy electron diffraction (RHEED) was also employed in situ to monitor surface crystallinity in the deposition chamber. Cross-sectional scanning transmission electron microscopy (STEM) was performed to evaluate the interfacial microstructure and elemental diffusion across layers. Magnetic properties, including magnetic moment and potential dead layer formation, were characterized using a vibrating-sample magnetometer (VSM). Device fabrication for spin-orbit torque (SOT) measurements was performed using conventional UV lithography and Ar ion milling to define bar-shaped devices integrated with a coplanar waveguide structure. Spin-torque ferromagnetic resonance (ST-FMR) measurements were then conducted at various frequencies and magnetic field angles to extract spin Hall efficiencies. Measurements were performed for both as-deposited and annealed samples (400 K, 1 h), as well as samples aged at room temperature for 45 days to evaluate thermal and temporal stability.

III. Results and Discussion

A. Structural and Morphological Analysis

XRD patterns confirmed that the BiSb films exhibited strong (0001)-textured growth, particularly for thicknesses above 8 nm, which is favorable for maintaining robust topological surface states. *In-situ* RHEED patterns after the deposition of BiSb showed polycrystalline features. At the same time, it became a highly textured structure after being post-annealed at 400 K. AFM images revealed smooth surface morphology, with average roughness below 0.7 nm, indicating high surface quality suitable for spin transport measurements. Thickness-dependent resistivity measurements for the BiSb thin films illustrated the emergence of topological surface states.

Cross-sectional STEM analysis indicated that the Ti-insertion after annealing improved crystallinity and that the Ti layer acted as an effective barrier to suppress interdiffusion, which could preserve the topological properties of BiSb films.

B. Spin Hall Efficiency

We performed ST-FMR measurements to examine the spin Hall efficiency in the BiSb/IL/FM heterostructures, as shown in Figure 1. Applying an RF charge current in the BiSb layer generates an oscillating transverse spin current. This spin current transfers spin angular momentum to the FM layer through the IL, exciting FMR. The resulting FMR signal contains an anti-symmetric Lorentzian line shape (V_A) and a symmetric Lorentzian line shape (V_S). The V_A results from the Oersted field and the field-like torque, while the V_S is related to the damping-like torque from the spin current. All the samples show clear ST-FMR spectra.

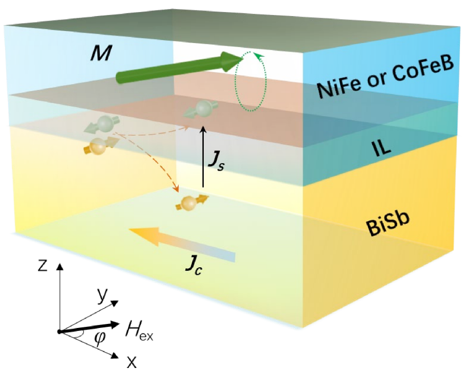

Fig. 1. Illustration of BiSb-based heterostructure and ST-FMR measurement.

Figure 2 shows representative ST-FMR spectra measured in the as-deposited samples of BiSb (10 nm)/NiFe (15 nm) and BiSb (10 nm)/Ti (2 nm)/NiFe (15 nm). A significantly large value of V_S/V_A was observed in the sample with Ti interlayer, indicating an enhancement of the spin Hall efficiency. After annealing at 400 K, the BiSb/NiFe sample without IL exhibited a spin Hall efficiency of ~0.3. The insertion of a Ti IL increased the spin Hall efficiency to ~1.2, indicating more than a fourfold improvement. This enhancement also persisted after 45-day ambient aging, demonstrating the thermal and temporal robustness of the Ti-inserted heterostructures. In the BiSb/IL/CoFeB systems, ST-FMR measurements showed that TiN_x as the IL yielded a relatively high spin Hall efficiency, while Ti and TiO_x showed moderate values. These differences suggest that a suitable IL can preserve the topological surface states of BiSb and suppress elemental interdiffusion, maintaining an effective large spin current across the interface.

IV. Conclusion

The engineering of topological heterostructures through the strategic use of interlayers demonstrates a significant enhancement in spin Hall efficiency for BiSb-based systems. The observed improvements, particularly with Ti and TiN_x interlayers, by protecting topological surface states and mitigating interdiffusion, are crucial for topological heterostructures. These findings highlight the potential of utilizing such interface-engineered TI/FM systems for developing advanced spintronic components, contributing towards next-generation read head technologies for HDDs where efficient spin-charge interconversion and robust material interfaces are imperative.

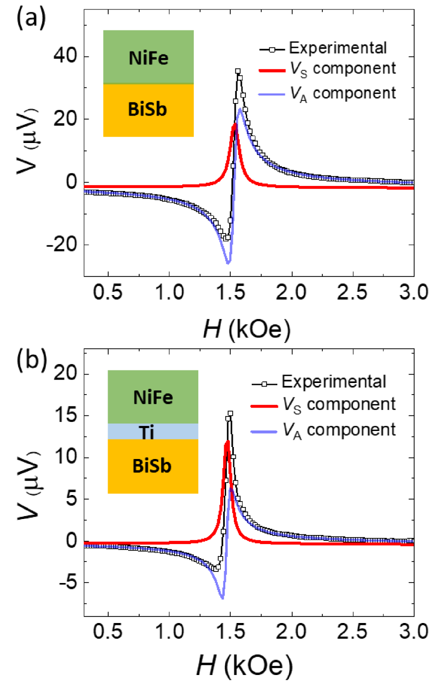

Fig. 2. Representative ST-FMR spectrum (f = 2 GHz, P = 15 dBm, and φ = 45°) in the samples of (a) BiSb (10 nm)/NiFe (15 nm) and (b) BiSb (10 nm)/Ti (2 nm)/NiFe (15 nm).

References

[1] N. H. D. Khang, Y. Ueda, and P. N. Hai, "A conductive topological insulator with large spin Hall effect for ultralow power spin–orbit torque switching," *Nat. Mater.*, vol. 17, pp. 808–813, Jul. 2018, doi: 10.1038/s41563-018-0137-y.

[2] T. Manoj *et al.*, "Spin–Orbit Torque Modulated by Interface Chemistry in Topological BiSb/NiFe Bilayers with Titanium Insertion," *ACS Appl. Electron. Mater.*, vol. 6, no. 6, pp. 4269–4276, Jun. 2024, doi: 10.1021/acsaelm.4c00357.

[3] X.-G. Zhu *et al.*, "Three Dirac points on the (110) surface of the topological insulator Bi1−xSbx," *New J. Phys.*, vol. 15, no. 10, p. 103011, Oct. 2013, doi: 10.1088/1367-2630/15/10/103011.

[4] V. T. Pham *et al.*, "Spin–orbit magnetic state readout in scaled ferromagnetic/heavy metal nanostructures," *Nat. Electron.*, vol. 3, no. 6, pp. 309–315, Jun. 2020, doi: 10.1038/s41928-020-0395-y.

[5] H. H. Huy *et al.*, "Large inverse spin Hall effect in BiSb topological insulator for 4 Tb/in2 magnetic recording technology," *Appl. Phys. Lett.*, vol. 122, no. 5, p. 052401, Jan. 2023, doi: 10.1063/5.0135831.

[6] M. Liu *et al.*, "Spin Hall magnetic field sensing device using topological insulator," *Appl. Phys. Lett.*, vol. 125, no. 24, p. 242401, Dec. 2024, doi: 10.1063/5.0233246.