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論 文 要 旨

THESIS SUMMARY

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要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

Topological insulators (TIs) are quantum materials with bulk insulating or semiconducting states but Dirac-like 1D edge or 2D surface states. This class of material exhibits a strong spin Hall effect due to the band inversion induced by strong spin-orbit coupling and possesses time-reversal-symmetry topological surface states. With such attractive features, TIs have become candidates for many magnetic storage devices such as spin-orbit torque (SOT) magnetoresistive random access memories (MRAM), racetrack memories, spin Hall oscillators, and hard disk drive (HDD) readers. Among TIs, BiSb has stood out as a conductive TI with a colossal spin Hall effect. In this dissertation, we focus on integrating BiSb with ferromagnetic multilayers for magnetic storage devices. This work is structured as follows.

In Chapter 1, we quickly review the history of computer and memory development. We show how computing demand has sharpened the memory industry throughout history. This chapter ends by introducing the rising demand for ultralow power consumption, high speed of operation, and ultrahigh bit-density memory devices for the futuristic artificial intelligent computing.

In Chapter 2 we present the fundamental physics of spin-related phenomena in spin Hall materials. Here we focus on the charge-to-spin conversion via the spin Hall effect and spin-to-charge conversion via the inverse spin Hall effect. Later, we introduce TIs and their unique properties including band inversion and topological surface states. Finally, this chapter delves into the properties and spin Hall effect of BiSb TI, which distinguishes them from other TIs and conventional heavy metals.

In Chapter 3, we introduce the fabrication tools and the characterization techniques used in this dissertation. For material growth, we employ industrial-friendly deposition technique, i.e., magnetron sputtering with the goal to achieve the manufacturability of BiSb. Regaring the sample evaluation, the X-ray diffraction is employed to determine the crystallinity of BiSb while the second harmonic Hall measurement is used to establish the spin Hall angle of the stacks.

In Chapter 4 we demonstrate a proof-of-concept SOT reader using the large inverse spin Hall effect of BiSb. Starting with a noise analysis of the reader, we identify that BiSb must have a spin Hall angle of larger than 2 to achieve a sufficient signal-to-noise ratio of 28 dB using a bias current of 400 μA. Afterwards, we perform the spin Hall angle optimization by integrating BiSb together with typical ferromagnetic materials such as Co, CoFeB, NiFe, and CoFe. A large spin Hall angle of 5.1 was observed in the stack of BiSb/MgO/CoFe/Buffer on Si/SiO_x substrate. Finally, we adopted and modified this stack to fabricate the SOT reader. Our SOT reader shows a giant inverse spin Hall angle of 61 that is capable of generating a large output voltage of 15 mV with 9.4 kA/cm^2. This performance is approximately two million times stronger than that of the Pt-based SOT reader, which indicates the potential of BiSb for use in the SOT reader for beyond 4 Tb/in^2 HDD technology.

In Chapter 5, we develop a perpendicular magnetized anisotropy (PMA) CoFeB/MgO and bottom BiSb stacks using an oxide interfacial layer for ultralow power SOT-MRAM cache memory. By integrating CrO_x (chromium oxide) as the interface between BiSb and CoFeB/MgO, we can realize the PMA and obtain a relatively large spin Hall angle of 2.8. The dependence of the spin Hall angle on the CrO_x thickness can be explained by the extrinsic factor, i.e., spin transparency of CrO_x, and the intrinsic factor, i.e., the suppression of Sb migration by the CrO_x barrier. Eventually, we achieve the SOT magnetization switching by a small current density of 3.1 MA/cm^2 with a pulse width of 50 μs, which is an order of magnitude smaller than that in heavy metals. Via the thermal activation model, we

estimate a bit retention of more than 500 seconds, which could be sufficient for last-level SOT-MRAM cache memory applications.

In Chapter 6, we address concern about the manufacturability of BiSb. Although BiSb has displayed an appealing performance, the low melting point of approximately 280℃ quickly drives the interests away due to the incompatibility with the back-end-of-line manufacturing process. To overcome this obstacle, we introduce a melting and recrystallization process of BiSb at 400℃ that not only satisfies the thermal budget requirement but also preserves the PMA and the large spin Hall angle as well as induces single-phase BiSb. It is worth noticing that the single-phase BiSb, so far, has been realized only on the crystallized substrates such as GaAs, c-plane sapphire, and BaF_2. Such a process is facilitated by sandwiching BiSb between oxide buffer/seed layers and a protection layer. We obaserved a large spin Hall angle and demonstrated a small threshold switching current density in the melted and recrystallized samples. This result indicates the potential of integrating BiSb with CMOS electronics for the mass production of BiSb-based SOT-MRAM and other magnetic memory applications.

Finally, Chapter 7 concludes the dissertation.