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Microarticle

On the temperature dependence of spin pumping in ferromagnet–topological insulator–ferromagnet spin valves

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ABSTRACT

Topological insulators (TIs) have a large potential for spintronic devices owing to their spin-polarized, counter-propagating surface states. Recently, we have investigated spin pumping in a ferromagnet–TI–ferromagnet structure at room temperature. Here, we present the temperature-dependent measurement of spin pumping down to 10 K, which shows no variation with temperature.

Introduction

Topological insulators (TIs) [1,2] are characterized by a bulk bandgap and a topologically protected surface state (TSS) with fully spin-polarized counter-propagating conduction channels. This novel class of materials lends itself to spintronic applications, through the large spin-orbit coupling [3] and interactions with the surface state itself [4,5].

Recently, we investigated the magnetodynamics of the TSS via spin pumping in a ferromagnet(FM)–TI–FM spin-valve structure [6,7]. We studied $Co_{50}Fe_{50}$ (30 nm)/Bi_2Se_3 (x nm)/$Ni_{81}Fe_{19}$ (30 nm) heterostructures with x = 4, 8, 16, 20 nm by using vector network analyzer (VNA) based ferromagnetic resonance (FMR) and element-specific, time-resolved X-ray detected ferromagnetic resonance (XFMR) at room-temperature (materials here referred to as CoFe, BiSe, and NiFe). Studies of the thickness dependence of interactions found that the TI functions as an efficient angular momentum sink, extracting spin pumping damping by comparison with bare ferromagnetic layers [6,7]. We note that measurements of resonance field showed no evidence of a static exchange interaction in these samples. The maximum spin mixing conductance was calculated to be $\tilde{g}_{\uparrow\downarrow} = (2.49 \pm 0.1) \times 10^{15}\ \mathrm{cm}^{-2}$ for the CoFe/TI interface and $(4.2 \pm 0.5) \times 10^{15}\ \mathrm{cm}^{-2}$ for the NiFe/TI interface, comparable with that of a good spin conductor and with those recently reported for NiFe/Bi_2Te_3 interfaces [8]. These differing values indicate a slight asymmetry of the two interfaces, likely arising at the growth stage. XFMR measurements, however, confirmed the presence of a weak interaction between the two FMs, able to persist for at least 8 nm, and possibly mediated by the TSS.

Measurement of the temperature dependence of the Gilbert damping forms an important part of the spin pumping study as it should allow for a clear separation between the contribution of the undesired bulk carriers, which can be frozen out at low temperatures, and the TSS. Despite the name, TIs such as Bi_2Se_3 typically have a room-temperature 2D sheet resistance $R_\square$ on the order of some 100 Ω (for a thickness of ∼25 nm), due to conduction through the bulk of the material. The spin pumping process is dependent on the spin flip and momentum scattering lifetimes [9], so it should be sensitive to bulk transport. On the other hand, spin pumping into the surface state should not be affected by a change in temperature. Recent transport studies using inverse spin-Hall effect techniques have suggested the presence of a pronounced temperature dependence as bulk carriers are removed from the system [10], allowing clearer detection of the TSS. Shifts in the FMR frequency, ascribed to a temperature-dependent effective field, have also been observed [11], along with the development of an out-of-plane spin-orbit torque [12].

Here, we investigate the effects of temperature on the spin-pumping phenomenon of FM–TI heterostructures by VNA-FMR. We find no temperature-dependence of spin pumping, indicating the robust nature of spin phenomena in TIs.

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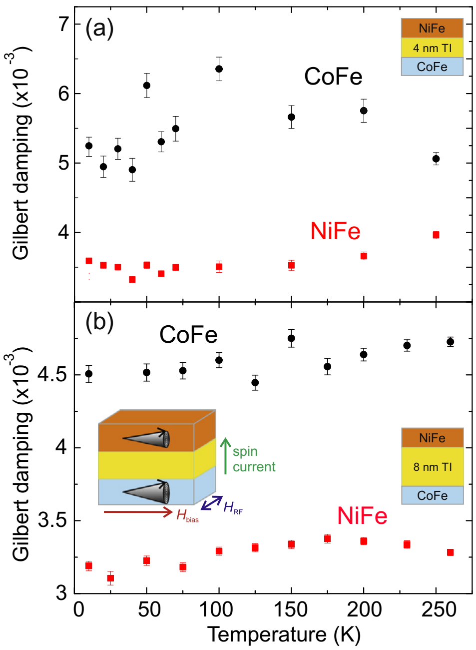

Fig. 1. Temperature dependence of the Gilbert damping for each of the FM layers for samples with (a) $t_{TI} = 4$ nm and (b) $t_{TI} = 8$ nm. Data obtained for measurements along the easy axis of magnetization. In both cases there is little evidence of systematic variation in temperature. Error bars arise from uncertainty on fits to frequency dependent linewidth, which are in the case of the NiFe layer comparable to the point size. The larger change in CoFe damping between the two samples is likely due to differing interface quality and thus spin mixing conductance.

Experimental details and results

Low-temperature VNA-FMR measurements were performed in a vector electromagnet part of a UHV chamber. Samples were mounted using the flip-chip geometry on a coplanar waveguide (CPW) of characteristic impedance 50Ω. The CPW, together with the associated radio frequency (RF) cabling, was mounted on a variable temperature Janis cryo-insert cooled by liquid helium, with a base temperature of ~7 K.

VNA-FMR measurements were performed on two samples ($t_{TI} = 4$ and 8 nm). Field vs frequency transmission maps were recorded with the bias field aligned along the easy axis of magnetization. The dimensionless (intrinsic) Gilbert damping parameter α was determined from the frequency dependence of resonant linewidth, $\Delta H = \alpha 4\pi f/\gamma + \Delta H_0$ [13], where γ is the gyromagnetic ratio and ΔH_0 is the extrinsic broadening, determined as a constant. Results for α for both samples are shown in Fig. 1.

While there are weak indications of a variation of Gilbert damping with temperature, no pattern of increasing or decreasing damping emerges. The NiFe layers of both samples show slight decreases in damping with decreasing temperature, but in both cases the variation is extremely small. The data for the CoFe layers has larger measurement uncertainty, with weak hints of a reduced damping at low temperatures. Neither layer exhibits a clear transition, indicative of a significant change in spin transfer properties as bulk carriers are frozen out and the TSS becomes more pronounced below ~10 K [14]. We note also that we observed no shift in resonance frequency as a function of temperature, in contrast to Ref. [11].

Discussion and conclusions

The presented data demonstrate that there is no systematic variation of Gilbert damping with temperature. Previous work demonstrated significant spin pumping damping in these samples [6,7], and the stability of the total damping indicates that the spin pumping component does not vary either. This suggests that the suppression of bulk conduction channels does not have a significant impact on the efficiency of the transmission of a pure spin current. In contrast, recent studies of temperature-dependent spin pumping [11] and spin transfer torque [12] on FM/TI heterostructures have demonstrated the enhancement of the TSS effects at low temperatures.

While these results might initially seem counter-intuitive, it is important to note that the symmetry-protected TSSs have been observed at room temperature [15]. In fact, spin pumping for bulk-insulating millimeter-thick TIs with NiFe films has been also observed at room temperature and claimed to be due to the TSS on the TI surface [10]. Therefore, any transmission of spin angular momentum through the surface state should persist across temperatures. Similarly, the absorption of a pure spin current within the bulk of the TI seems to occur across the full temperature range, suggesting that spin flip scattering, which appears to be the dominant scattering mechanism, does not have a strong temperature dependence.

These results demonstrate the great potential of TIs for device applications, as spin pumping manifests itself at room temperature and low magnetic fields, as well as being a fertile ground for investigation of fundamental physical phenomena.

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