N-7-02
Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp617-618

Vanishing skyrmion Hall effect at the angular momentum compensation temperature of a ferrimagnet

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Abstract

The skyrmion Hall effect[1] has been theoretically predicted to vanish for antiferromagnetic skyrmions because the fictitious magnetic field, proportional to net spin density, is zero[2].We experimentally confirmed this prediction by observing current-driven transverse elongation of pinned ferrimagnetic bubbles in ferrimagnetic GdFeCo film[3].

1. Introduction

In magnetic skyrmion, an effective magnus force for position R, is given as

$$\boldsymbol{F_g} = \boldsymbol{Q}\dot{\boldsymbol{R}} \times \boldsymbol{B} \tag{1}$$

This effective magnus force is defined by the topological charge

$$\boldsymbol{Q} \equiv \int dxdy\boldsymbol{n} \cdot \left(\partial_x \boldsymbol{n} \times \partial_y \boldsymbol{n}\right)/4\pi \tag{2}$$

and the fictitious magnetic field

$$\boldsymbol{B} = -4\pi s_{net}\hat{\boldsymbol{z}} \tag{3}$$

where $\boldsymbol{n}$ is the spin order parameter, s_{net} is the net spin density and $\hat{\boldsymbol{z}}$ is the normal vector to the film plane. For ferromagnetic skyrmions, both topological charge and spin density are finite so that the skyrmion Hall effect emerges. Even for antiferromagnetic skyrmions, the topological charge remains finite because $\boldsymbol{n}$ is defined by the Néel vector (not by alternating atomic spin), which is continuous in space. Thus, the theoretically predicted vanishing skyrmion Hall effect for antiferromagnetic skyrmions is entirely associated with zero s_{net} or, equivalently, zero fictitious magnetic field. This theoretical prediction has not yet been experimentally verified.

2. Results and Discussions

In this work, we experimentally demonstrate the vanishing skyrmion Hall effect by using a rare earth (Gd) and transition metal (FeCo) ferrimagnetic compound where the rare earth and transition metal moments are antiferromagnetically coupled. Rare earth and transition metal elements have different intra-atomic exchanges and thus exhibit different temperature-dependent spin density changes. As a result, the s_{net} of GdFeCo ferrimagnets varies gradually with temperature and vanishes at a specific temperature below the Curie temperature. The nature of magnetic dynamics, which is governed by the angular momentum and their commutation relations, becomes antiferromagnetic at this temperature, called the angular momentum compensation temperature (T_A)[4]. This feature of GdFeCo ferrimagnets allows us to experimentally test the relation of the fictitious magnetic field to the spin density and, in particular, the vanishing skyrmion Hall effect at T_A.

We measured current-driven transverse elongation of pinned ferrimagnetic bubbles in perpendicularly magnetized ferrimagnetic GdFeCo/Pt film by using MOKE(Fig. 1(a)). And we confirmed that the angle between the current and

bubble elongation directions, vanishes at the angular momentum compensation temperature T_A (=287±5 K) where the net spin density vanishes(Fig. 1(b)).

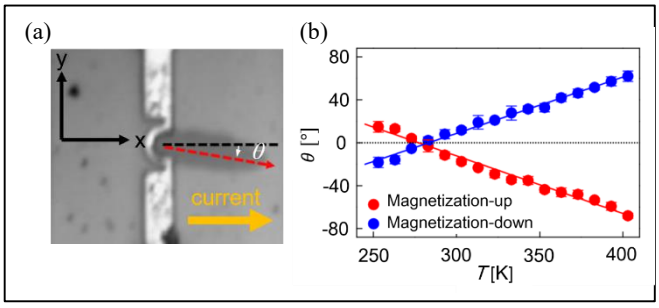

Fig. 1 (a) MOKE image of the current driven elongation of the bubble domain. (b) Elongation angle as a function of temperature (T) for each magnetization state[3].

To interpret these results, we developed a simple theory for the elongation of a pinned magnetic bubble driven by SOT. Specifically, we modelled an elongated bubble with one pinned end at the origin as a composite object that consisted of a half skyrmion($Q = \pm 1/2$) at the free end and a straight rod that connected the two ends,

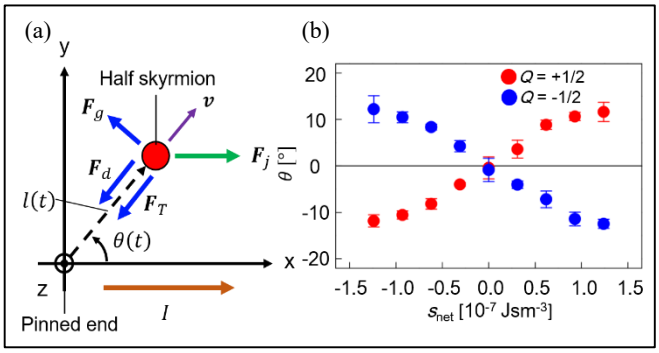

Fig. 2 (a) Forces acting on a half skyrmion, for current-driven elongation of a pinned ferrimagnet bubble. represented by the red solid circle. (b) Numerically obtained angle θ as a function of s_{net} for the topological charges $Q = \pm 1/2$[3].

The state of the bubble can be described by two variables, the rod length $l(t)$ and the elongation angle $\theta(t)$ from the direction of the current density $\boldsymbol{j}$. Their equations of motion can be obtained using the collective coordinate approach. Several forces act on the half skyrmion the SOT-induced force, $\boldsymbol{F}_j$, the Magnus force, $\boldsymbol{F}_g$, is proportional to both the spin density and the topological charge $Q = \pm 1/2$, the viscous force, $\boldsymbol{F}_d$, is rooted in the Gilbert damping, and the tension, $\boldsymbol{F}_T$, is associated with the stretching of the rod. By balancing these forces and the associated torques on the bubble, we obtained the steady-state solution with uniform growth and a constant angle for sufficiently large currents, $\dot{l}(t) = v$ and $\theta(t) = \theta_{SkH}$ with

$$\theta_{SkH} \approx \tan^{-1}\left(\frac{2s_{net}Q\lambda}{\alpha s_{total} r}\right) \tag{4}$$

where s_{total} is the sum of the sublattice spin density magnitudes, α is the Gilbert damping constant, λ is the domain wall width that forms the bubble boundary and r is the radius of the half skyrmion. The elongation angle obtained for the bubble is identical to the expression for the skyrmion Hall angle for an isolated skyrmion[2]. As the temperature approaches T_A, s_{net} goes to zero and, consequently, the elongation angle θ_{SkH} goes to zero. This implies the skyrmion Hall effect vanishes at T_A, as was experimentally observed. We also performed numerical simulations based on the atomistic Landau–Lifshitz–Gilbert equation. Fig. 2(b) summarizes the numerically obtained elongation angles as a function of s_{net}. At $s_{net} = 0$, the elongation angle is nearly zero, consistent with both experiment and theory.

3. Conclusions

We experimentally observed that the skyrmion Hall effect in an antiferromagnetically coupled ferrimagnet varies with temperature and vanishes at T_A. Combined with theoretical and numerical support, this observation demonstrates that the fictitious magnetic field for magnetic skyrmions is proportional to s_{net}. This demonstration of a vanishing skyrmion Hall effect is of importance for realizing an efficient skyrmion racetrack memory without information loss.

Acknowledgements

This work was supported by the JSPS KAKENHI (Grant Numbers 15H05702, 26103002, and 26103004), Collaborative Research Program of the Institute for Chemical Research, Kyoto University, and R & D project for ICT Key Technology of MEXT from the Japan Society for the Promotion of Science (JSPS). This work was partly supported by The Cooperative Research Project Program of the Research Institute of Electrical Communication, Tohoku University. D.H.K. was supported as an Overseas Researcher under the Postdoctoral Fellowship of JSPS (Grant Number P16314). D.K.L., S.H.O., and K.J.L. were supported by the National Research Foundation of Korea (NRF-2015M3D1A1070465, 2017R1A2B2006119) and the KIST Institutional Program (Project No. 2V05750). S.K.K. and Y.T. were supported by the Army Research Office under Contract No. W911NF-14-1-0016.

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