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Determination of Dzyaloshinskii-Moriya Interaction Energy by Extended Droplet Model

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Abstract

It has been known that lack of structural inversion symmetry with strong spin-orbit coupling at an interface of a ferromagnet (FM)/non-magnet (NM) bilayer generates the Dzyaloshinskii–Moriya interaction (DMI) which results in chirality in spin textures. Since chiral spin textures such as a skyrmion are an essential object for the next generation spintronics devises, it is important to determine DMI energy density (*D*). In this study, we provide a simple method to estimate the *D* value using a conventional anomalous Hall effect (AHE) measurement.

1. Introduction

DMI between two atomic spins with an adjacent nonmagnetic atom having a strong spin-orbit coupling, is an essential mechanism in the FM/NM bi- (or multi-) layer system for developing state-of-the art spin-orbitronic devices [1-3]. Recently, sub 100-nm-sized skyrmion-like bubble has been found to be a stable magnetic object with a sizable *D* [4-5]. Also, few hundreds m/s velocity of a Neel type domain wall (DW) arising from DMI is achievable [6]. Furthermore, DMI influences the current-driven switching and diode effect of the magnetic tunnel junction [7,8]. Therefore, it is important to determine the *D* value in FM/NM systems for realization of the next generation spintronic devices. In this presentation, we demonstrate how the DMI affects the magnetic domain nucleation under in-plane magnetic field (H_x), which provides a simple way of estimating *D*.

2. Results and Discussions

For a magnetic droplet in a perpendicularly magnetized medium, a nucleation field (H_n) is determined by the Zeeman energy and total DW energy (σ_{DW}) of the magnetic droplet, thereby H_n=$\sigma_{DW}{}^2$. Here, we extend this droplet model as follows. The σ_{DW} with a single magnetization direction is given by [9];

$$\sigma_{DW}(H_x) = \begin{cases} \sigma_0 - \dfrac{\pi^2 \Delta M_S{}^2 \mu_0{}^2}{8K_D}(H_x + H_{DMI})^2, & \text{for } \mu_0|H_x + H_{DMI}| \cdot \\ \sigma_0 + 2K_D\Delta - \pi\Delta M_S\mu_0|H_x + H_{DMI}| & \text{otherwise,} \end{cases} \quad (1)$$

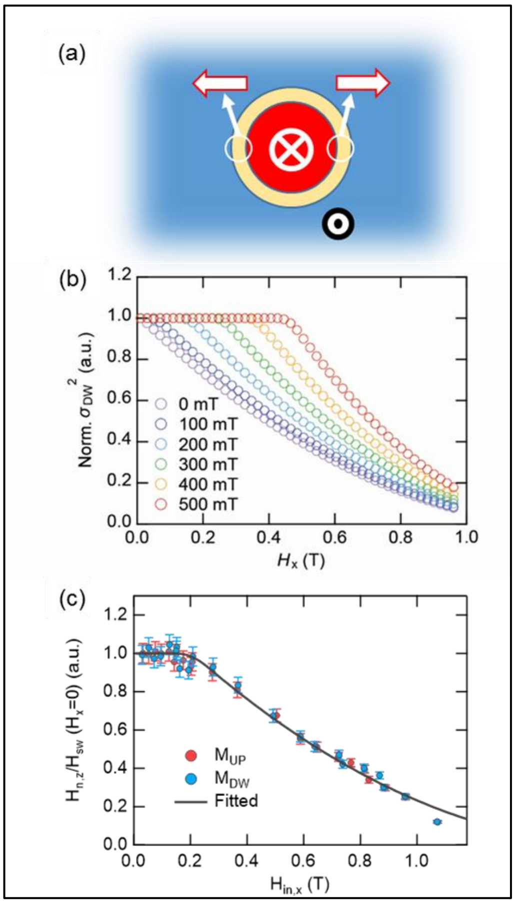

Figure 1. (a) A magnetic droplet with Néel DWs in a perpendicularly magnetized matter. (b) The normalized $\sigma_{DW,total}{}^2$ as a function of H_x. (c) The normalized H_n vs. H_{in} curve of the Co/Ni multilayer on Pt.

where σ_0 ($=4\sqrt{AK_{eff}}$) is the energy of a Bloch-type DW, *A* is the exchange stiffness constant, K_{eff} is the effective perpendicular anisotropy energy, and Δ ($=\sqrt{A/K_{eff}}$) is the DW width. When the DMI is stronger than DW anisotropy energy (K_D), homochiral Nèel type DWs are formed. Here, we assume that two DW magnetizations, parallel and antiparallel to H_{in}, dominate the σ_{DW} of the droplet [see red arrows in Fig. 1(a)]. As a result, the total σ_{DW} is given by

$\sigma_{\mathrm{DW,total}}(|H_x|) = \sigma_{\mathrm{DW1}}(+H_x) + \sigma_{\mathrm{DW2}}(-H_x)$ because the left DW (DW1) and the right DW (DW2) are parallel and antiparallel to the direction of H_x, respectively. Figure 1 (b) is the normalized ${\sigma_{\mathrm{DW,total}}}^2$ vs. H_x curves in terms of H_{DMI}. Note that there is a critical field point. When the H_x is smaller than the critical field point, H_n does not depend on H_x. It is also clearly seen that the critical field is proportional to magnitude of H_{DMI}.

To prove the extended droplet model, we experimentally examined the H_n of the Co/Ni multilayer in terms of H_x. The Hn was estimated from the AHE signal. As predicted by the extended droplet model, the plot of H_n vs. H_x exhibits the critical point. H_{DMI} and D are confirmed to be 228±60 mT and 0.45±0.15 mJ/m^2, respectively, from the best fitting.

Our model and simulation results are reproduced by the simulation. We calculate an energy barrier as a function of H_x and an out-of-plane field, based on the string method [10]. We find that the energy barrier varies significantly around a certain magnitude of H_x. This indicates that H_{DMI} is completely compensated in the x direction at the critical field strength. Therefore, H_{DMI} can be also calculated from the simulation. Finally, we estimate a DMI value of $D \cong 0.45$ mJ/m^2 from the simulation result, which demonstrates the extended droplet model.

3. Conclusions

This study provide a simple model to describe the DMI effect on the nucleation of a perpendicularly magnetized droplet and a simple electrical measurement method to quantitatively determine the D, which is a key factor for next generation spin-orbitronic devices.

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