Analytical Modeling of Domain Wall Motion in PMA Materials under Spin Hall Effect and in-Plane Fields

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***Abstract* —Recent studies on heterostructures of ultrathin ferromagnets sandwiched between a heavy metal layer and an oxide have highlighted the importance of spin-orbit coupling (SOC) and broken inversion symmetry in domain wall (DW) motion. Specifically, chiral DWs are stabilized in these systems due to the Dzyaloshinskii-Moriya interaction (DMI). SOC can also lead to enhanced current induced DW motion, with the spin Hall effect (SHE) suggested as the dominant mechanism for this observation. The efficiency of SHE driven DW motion depends on the internal magnetic structure of the DW, which could be controlled using externally applied longitudinal in-plane fields. In this work, micromagnetic simulations and analytical models are used to study current-driven DW motion under high in-plane fields in perpendicularly magnetized samples with strong DMI. An extended analytical model is developed to describe the micromagnetic results. While this extended model shows improvements over previous analytical models in describing the dynamics, there are still discrepancies between the model and micromagnetic simulations. Addition of a prefactor to the ansatz or the DW width parameter used to develop the analytical model could be key to increasing the accuracy of this model.**

Index Magnetic DW Motion – PMA Material – Spin Hall Effect

I. Introduction

Manipulating magnetic domain walls (DWs) within nanostructures has been linked with applications in the development of spintronic logic, storage and sensing devices [1]. Such applications have led to increased interest within the scientific community in developing models which can qualitatively or quantitatively describe DW motion under applied fields and currents.

In perpendicularly magnetized heterostructures with high Dzyaloshinskii-Moriya interaction (DMI), applied fields in-plane of the sample could be used to control DW chirality, enhancing the efficiency of current-driven DW motion. Micromagnetic (μM) simulations of this problem are in agreement with experiments, showing an increase in DW velocity with fields parallel to the internal magnetization of the DW. However, the conventional analytical models (q-Φ and q-Φ-χ) fail to reproduce these results. This calls for improvements in analytical modeling of DW motion in such systems.

In this paper, DW motion driven by the spin Hall effect (SHE) under high in-plane fields is studied in perpendicular magnetocrystalline anisotropy (PMA) materials. In order to improve the agreement of analytical models with μM simulations, the conventional analytical model is extended by including the DW width and canting of the magnetization in the domains.

II. Problem Description

In this work, current-driven DW motion along a Pt/CoFe/MgO nanowire is evaluated. The dimensions of the CoFe strip are 2.8 µm x 160 nm x 0.6 nm. Typical parameters are adopted: saturation magnetization M_s =700 kA/m, exchange constant A = 0.1 pJ/m, uniaxial perpendicular anisotropy constant K_u = 480 kJ/m^3, and Gilbert damping α = 0.3. The magnitude of the DMI and the SHE angle are D = -1.2 mJ/m^2 and θ_{SH}=0.07, respectively.

The Landau-Lifshitz-Gilbert equation in such a system reads:

$$\frac{d\vec{m}}{dt} = -\gamma_0\vec{m}\times\vec{H}_{eff} + \alpha\vec{m}\times\frac{d\vec{m}}{dt} - \gamma_0 H_{SL}\vec{m}\times\left(\vec{m}\times\hat{u}_y\right) \quad (1)$$

where the effective field H_{eff} includes the effects of exchange, magnetostatics, PMA, DMI and the applied in-plane fields (B_x). The last term in (1) is the Slonczewski-like torque due to the SHE, which is characterized by $H_{SL} = \frac{\hbar\theta_{SHE}J}{2\ e\ M_s t_f}$, where J is the current, θ_{SHE} is the SHE angle and t_f denotes the thickness of the ferromagnetic layer.

III. Static Structure of DWs under in-plane fields

To understand the effect of in-plane fields on the DW structure, μM simulations were conducted in mumax^3 [2]. Fig. 1 shows the results for two values of in-plane fields under static conditions.

The application of B_x tilts the magnetization in the domains into the plane, reducing the m_z component (or $\theta = \text{acos}(m_z)$). When the DMI and B_x are supporting each other within the DW (B_x >0 in Fig. 1b), the DW width increases and the DW is further stabilized. In cases where the DMI and B_x are competing (B_x <0 in Fig. 1c), a sufficiently large in-plane field can change the chirality and tilt the DW plane.

Fig. 1a shows that in the absence of in-plane fields, the Bloch profile describes the change in θ acceptably, while the DW profile slightly deviates from the Bloch profile under longitudinal fields. It can be shown that the Bloch profile can fit the transition from one domain to the next under in-plane fields, if the value of the DW width is adjusted or a prefactor is added to the ansatz.

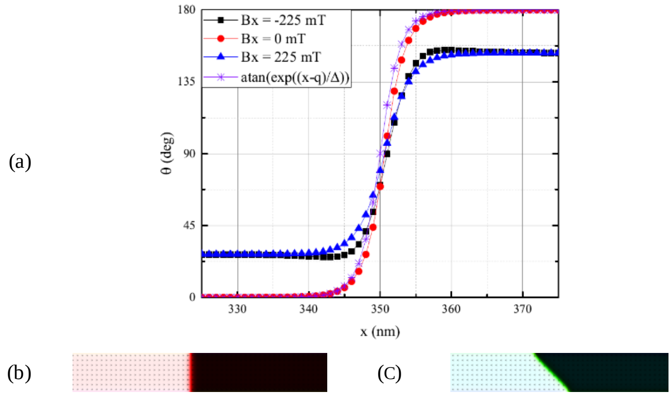

Fig. 1. Characterization of the static DW structure under the application of in-plane fields along the length of the wire. (a) Change in the spherical coordinate θ at the center of the wire under different longitudinal fields compared to the conventional Bloch DW profile [3,4], (b) DW structure under B_x = 225 mT, (c) DW structure under B_x = -225 mT.

IV. Four Coordinate 1-D Model for DW Motion

Based on the LLG equation and using a Lagrangian description [3-6], a collective coordinates model (CCM) was developed taking into account the canting of the domains and four collective coordinates, namely the DW position (q), the DW magnetization angle (Φ), the DW width (Δ), and the tilting angle of the DW plane (χ). For the system being studied, this model has the form:

$$\dot{\phi} + \alpha\cos\theta_c \frac{\dot{q}}{\Delta}\cos\chi = \frac{\pi - 2\theta_c}{2}\mu_0\gamma H_{SL}\cos\phi \tag{2}$$

$$\frac{\dot{q}}{\Delta}\cos\chi - \alpha\cos\theta_c\dot{\phi} = \frac{1}{2}\mu_0\gamma\cos\theta_c M_s\left(N_y - N_x\right)\sin 2(\phi-\chi) + \frac{\pi - 2\theta_c}{2}\mu_0\gamma\left[H_x\sin\phi - \frac{D}{\mu_0 M_s \Delta}\sin(\phi-\chi)\right] \tag{3}$$

$$\frac{\alpha b}{2}\left(\frac{\dot{\Delta}}{\Delta} + \frac{\dot{\chi}}{\cos\chi}\sin\chi\right) = \frac{\gamma}{M_s}\cos\theta_c\left[\frac{A}{\Delta^2} - K\right] + \frac{\pi - 2\theta_c}{2}\mu_0\gamma H_x\cos\phi \tag{4}$$

$$-\frac{\alpha b}{2}\left(\frac{\dot{\Delta}}{\Delta}\sin\chi + \frac{\dot{\chi}}{\cos\chi}\left[\frac{1}{6b}\left(\frac{w}{\Delta}\right)^2 + \sin^2\chi\right]\right) = \frac{\pi - 2\theta_c}{2}\mu_0\gamma\left[\frac{D}{\mu_0 M_s \Delta}\sin\phi - H_x\cos\phi\right] + \frac{\gamma}{M_s}\cos\theta_c\sin\chi\left[\frac{A}{\Delta^2} + K - \frac{1}{2}\mu_0 M_s^2(N_y - N_x)\tan\chi\sin 2(\phi-\chi)\right] \tag{5}$$

where $K = K_u + \frac{1}{2}\mu_0 M_s^2\left(N_x\cos^2(\phi-\chi) + N_y\sin^2(\phi-\chi) - N_z\right)$ is the effective anisotropy and $\theta_c = \operatorname{asin}\left(\frac{M_s|B_x|}{2K_u}\right)$ is the canting angle of the domains which is included in the integration limits when developing the CCM. $b \leq \frac{\pi^2}{6}$ is a parameter dependent on the applied in-plane field.

Fig. 2 illustrates the steady state velocity predictions from μM simulations and different forms of the canted CCMs. Including canting in the derivation of the collective coordinate models improves the accuracy of predictions compared to the original models proposed in [3-6] (the results from models without canting are not shown in Fig. 2). For the cases with negative in-plane fields (which gives rise to the tilting of the DW under static conditions), the CCM based on q, Φ and χ was able to predict the right trend in DW velocity up to B_x = -125 mT, while models including all four coordinates consistently predicted the trend correctly, but could not be integrated for fields B_x < -150 mT.

For positive in-plane fields, micromagnetic simulations suggest that the DW width should be the determining factor; however, models taking into account the DW width were not able to reproduce the results from micromagnetic simulations. The q-Φ and q-Φ-χ models reproduced the results up to Bx = 50 mT and fail for higher fields.

The low accuracy of the CCMs in the case of high positive longitudinal fields could be attributed to two factors. Firstly, it was observed that the CCMs with DW width as a coordinate miscalculate the DW width for the case of positive longitudinal fields, which would in turn affect DW velocity predictions. This had already been described in previous work [6]. Second, the magnetization angle at the center of the wall is rather fixed when high positive longitudinal fields are applied. This could explain the inaccuracy of analytical models, as such models only rely on the perturbation of this angle as the major coordinate driving magnetization dynamics.

Addition of a prefactor to the ansatz or redefinition of the DW width in the profile used to develop the CCM is currently being investigated as a means to improve the accuracy of the CCM.

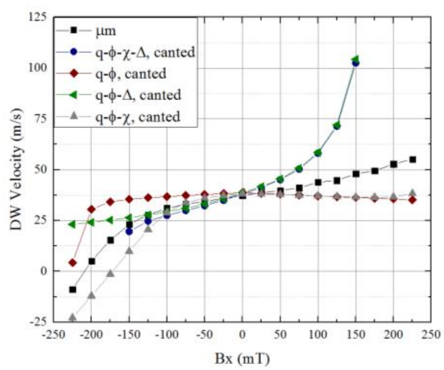

Fig. 2. Variation of DW velocity with in-plane field. Simulations were performed for a current density of J = 0.1 TA/m[2].

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