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Collective coordinate descriptions of magnetic domain wall motion in perpendicularly magnetized nanostructures under the application of in-plane fields

S. Ali Nasseri[a,b,*], Eduardo Martinez[c], Gianfranco Durin[a,d]

[a] ISI Foundation, Via Chisola 5, 10126 Torino, Italy
[b] Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[c] University of Salamanca, Dpto Fisica Aplicada, Plaza de los Caidos s/n., E37008 Salamanca, Spain
[d] Istituto Nazionale di Ricerca Metrologica (INRiM), Strada delle Cacce 91, 10135 Torino, Italy

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ABSTRACT

Manipulation of magnetic domain walls in nanostructures can be used to improve the capabilities of the next generation of memory and sensing devices. Materials of interest for such devices include heterostructures of ultrathin ferromagnets sandwiched between a heavy metal and an oxide, where spin–orbit coupling and broken inversion symmetry give rise to the Dzyaloshinskii-Moriya interaction (DMI), stabilizing chiral domain walls. The efficiency of the motion of these chiral domain walls may be controlled using in-plane magnetic fields. This property has been used both for measurement of DMI strength, and for improved performance in applications. While micromagnetic simulations are able to accurately predict domain wall motion under in-plane fields in these materials, collective coordinate models such as the $q{-}\phi$ and $q{-}\phi{-}\chi$ models fail to reproduce the micromagnetic results. In this theoretical work, we present a set of extended collective coordinate models including canting in the domains, which better reproduce micromagnetic results, and improve our understanding of the effect of in-plane fields on magnetic domain walls. These models are used in conjunction with micromagnetic simulations to develop simpler descriptions of DW motion under specific conditions. Our new models and results help in the development of future domain wall based devices based on perpendicularly magnetized materials.

1. Introduction

Manipulating magnetic domain walls (DWs) within nanostructures has been linked with the development of spintronic logic [1,2], memory [3–6] and sensing [7] devices. The next generation of magnetic memory and storage devices could rely on DWs moving along magnetic tracks or wires, with different principles for such devices being explored to achieve mass storage without the need for mechanical moving parts [4,5]. Simulation capabilities are key to better understand the underlying processes in these systems, and to assess different design concepts. The main computational framework to analyze these ferromagnetic systems is based on the Landau-Lifshitz-Gilbert (LLG) equation which is applicable to a wide range of problems in magnetism, including DW motion. However, the use of micromagnetic simulations specially for large samples is computationally costly and time consuming, as the numerical solution for the magnetic configuration needs to be determined both spatially and temporally.

Alternatively, simpler models may be extracted from the LLG equation to analyze the motion of specific topological defects of interest, such as vortices and DWs [8–17]. The simplified nature of these collective coordinate models (CCMs) is due to the introduction of an ansatz which characterizes the structure of the spin texture of interest. In 1972, Slonczewski used a Lagrangian approach to propose a CCM for analyzing DW motion in perpendicularly magnetized materials (the $q{-}\phi$ model) [8]. This model relates the DW position (q), and the DW's supposedly uniform magnetization (ϕ) to the different interactions affecting the system. Thiaville and Nakatani later extended the $q{-}\phi$ model to in-plane systems and introduced the DW width parameter (Δ) as an additional time varying coordinate, leading to the $q{-}\phi{-}\Delta$ model [13]. However, their findings showed that the evolution of Δ has minimal effect on the dynamics and could be neglected. Due to interest in current-driven DW motion at the time, the spin-transfer torque (STT) mechanism was also implemented as part of these newer models [11,12].

Recent studies on DW motion have focused on perpendicular magnetic anisotropy (PMA) heterostructures in which ultrathin

* Corresponding author at: ISI Foundation, Via Chisola 5, 10126 Torino, Italy.
E-mail address: ali.nasseri@isi.it (S.A. Nasseri).

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ferromagnets are sandwiched between a heavy metal layer and an oxide ($HM/FM/Ox$). In these structures, spin-orbit coupling (SOC) and broken inversion symmetry (BIC) modify the static structure of the DW and contribute to DW motion [18–22]. Specifically, the Dzyaloshinski-Moriya interaction (DMI) present in these systems stabilizes Néel DW structures of specific chirality. SOC has also been linked to enhanced current induced DW motion, with the spin Hall effect (SHE) suggested as the dominant mechanism for this observation [22]. Moving DWs tend to tilt in the plane of the sample in these systems, with the $q-\phi-\chi$ model (where χ denotes the DW tilting) developed to describe DW motion in these systems [14].

The efficiency of DW motion depends on the internal magnetic structure of the DW. As such, applied fields in-plane of the sample can be used to control DW chirality, enhancing the efficiency of current-driven DW motion [14,17,23–29]. While micromagnetic simulations of this problem are in agreement with experiments, conventional CCMs (such as the $q-\phi$ and $q-\phi-\chi$ models) fail to reproduce the micromagnetic results [17,24].

Despite this shortcoming, equations derived from the $q-\phi-\chi$ model are used in two of the most prominent methods of assessing the strength of the DMI, both of which rely on the manipulation of DW dynamics under in-plane magnetic fields. In the first and most common method, magnetic bubbles are expanded in the thin film of interest under the application of in-plane and out-of-plane fields in the creep regime [30,31]. This method assumes that the points with significant Néel character are located on the axis of the applied in-plane field, and the DMI field is assumed to be equal to the in-plane field which reverses the chirality of the DW. A second method of assessing DMI strength uses a critical longitudinal field which can be identified in current-driven DW motion in nanowires with DMI; at the critical point the DW is locked in place irrespective of applied current, and the value of the longitudinal field at that point is related to the DMI strength [17]. While most experimentalists rely on the $q-\phi-\chi$ model in DMI strength measurements using the methods above, as mentioned previously, these models seem to not be accurate as they cannot reproduce the micromagnetic results. This calls for improvements in collective coordinate modeling of DW motion, both to reproduce micromagnetic results and to help in the assessment of DMI strength in material stacks.

In our previous work [17], we developed an extended collective coordinate model which better reproduced micromagnetic results in the case of current-driven DW motion in PMA systems with strong DMI under the application of in-plane fields. This model was developed based on the Bloch profile and had four collective coordinates (q, ϕ, χ, Δ). The increased accuracy of the model was attributed to the inclusion of an approximation of canting in the domains as an additional parameter in the CCM. Canting in the domains arises from the application of in-plane fields to the system, and was included in the limits of integration when deriving the CCM.

In this paper, we present a new extended set of CCMs based on an inherently canted ansatz to describe DW motion in PMA systems with DMI. We compare this model in mathematical form to past models present in the literature [8,13,14,17]. The models presented in this work are used to study two material stacks, which differ in the strength of DMI and uniaxial anisotropy. Specifically, we find that while our past studies showed that only a four coordinate model can correctly predict the characteristic shape of the DW velocity curve [17], our new canted models maintains higher accuracy when only two coordinates, namely the DW position (q) and magnetization angle (ϕ) are used. This highlights the rigidity of the DW during motion, and the fact that canting in the domains plays an important role in magnetic DW motion under in-plane fields. We also found that the anisotropy of the system plays an important role in the applicability of the models, with minimal difference observed between the different models in systems with high anisotropy (which corresponds to low canting and narrower DWs).

We also showcase in detail the impact of in-plane fields on field- and current-driven DW motion, identifying critical in-plane fields which lead to effects such as no tilting, no movement or a Bloch DW structure in DW dynamics. Analytical solutions are proposed based on the CCMs for these critical points that shed some light on the physics involved, and show how these points could help in measuring the strength of various interactions in experiments.

Table 1
Material parameters of the two systems studied in this work. The DMI strength of the $Pt/CoFe/MgO$ sample is twice that of the $Pt/Co/Ni/Co/MgO/Pt$ sample, while its PMA constant is 1/3 that of the later sample. This difference in material properties helps better understand their effects on DW dynamics.

	$Pt/CoFe/MgO$ [27]	$Pt/Co/Ni/Co/MgO/Pt$ [32]
Saturation magnetization M_s (kA/m)	700	837
Exchange constant A (pJ/m)	10	10
Uniaxial perpendicular anisotropy constant K_u (MJ/m^3)	**0.48**	**1.310**
DW width parameter (nm) $\Delta \sim \sqrt{\frac{A}{K_u - \mu_0 M_S^2/2}}$	7.2	3.39
Gilbert damping α	0.3	0.15
SHE angle θ_{SH}	0.07	0.07 (assumed)
DMI strength D (mJ/m^2)	**−1.2**	**0.6**

2. Methods

2.1. Systems under study

In this work, we study two 2.8 μm long, 160 m wide nanowires with the magnetic properties listed in Table 1 and a 0.6 nm thickness for the ferromagnetic layer. These samples were selected as they both have DMI and PMA; however, the DMI strength of the $Pt/CoFe/MgO$ sample is twice that of the $Pt/Co/Ni/Co/MgO/Pt$ sample, while its PMA constant is 1/3 that of the later sample. This helps us better understand the impact of these two parameters on the structure and dynamics of DWs.

2.2. Micromagnetic simulations

To understand the magnetization dynamics in these samples, we conducted micromagnetic simulations using Mumax^3 [33] which numerically solves the Landau-Lifshitz-Gilbert (LLG) equation. A micromagnetic cell size of 1 nm × 1 nm × 0.6 nm was used for all micromagnetic simulations.

As we are interested in magnetic DW dynamics under applied fields and currents in a perpendicularly magnetized heterostructure, the DMI [34–36], spin-orbit torques (SOTs) [37–39], and the spin transfer torque (STT) mechanism [12,40] were included in addition to the traditional interactions included in the effective field (exchange, anisotropy, magnetostatics, and the Zeeman energy). With these terms, the LLG will take the following form:

$$\frac{d\vec{m}}{dt} = -\gamma\,\vec{m}\times\vec{H}_{eff} + \overbrace{\alpha\,\vec{m}\times\frac{d\vec{m}}{dt}}^{Damping\ term} \overbrace{-(\vec{u}\cdot\nabla)\vec{m}}^{adiabatic\ STT} + \overbrace{\beta\,\vec{m}\times((\vec{u}\cdot\nabla)\vec{m})}^{non-adiabatic\ STT} + \overbrace{\gamma H_{FL}(\vec{m}\times\hat{u}_{SOT})}^{field-like\ SOT} \overbrace{-\gamma H_{SL}\vec{m}\times(\vec{m}\times\hat{u}_{SOT})}^{Slonczewski-like\ SOT} \quad (1)$$

with H_{FL} denoting the field-like components of the spin-orbit torques, H_{SL} denoting the Slonczewski-like component of the spin-orbit torques,