Characterizing Dzyaloshinskii Domain Walls in Asymmetric [Pt/Co/Ni/Ir]$_N$ Multi-Layers using Lorentz TEM

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Chiral magnetic structures, such as Skyrmions, have attracted a great deal of attention in recent years due to the efficiency with which they can be manipulated by electric current. These features are stabilized by the Dzyaloshinskii-Moriya interaction (DMI) which favors a deterministic winding of neighboring spins. DMI has been observed in bulk magnetic materials such as FeGe [1] and MnSi [2], but more recently has been engineered in magnetic multi-layers with perpendicular magnetic anisotropy and asymmetric stacking sequences [3]. It is well-established that the interfacial DMI favors Néel walls with preferred chirality, called Dzyaloshinskii domain walls (DWs), over the magnetostatically favored Bloch walls, which we explore further in this paper using multi-layer thin films.

We contrast multi-layers based on symmetric Ta(3)/Pt(3)/[Co(0.2)/Ni(0.6)]$_{10}$/Pt(3)/Ta(3) and asymmetric Ta(3)/Pt(3)/[Pt(0.5)/Co(0.2)/Ni(0.6)/Ir(0.5)]$_{10}$/Pt(3)/Ta(3) stacking sequences prepared by magnetron sputtering on SiN membranes (thicknesses are in nm). The asymmetric repeat unit leverages the known difference in sign of DMI for Pt/Co and Ir/Ni interfaces, which gives rise to an additive effect. The preserved inversion symmetry of the symmetric film stack is expected to give zero interfacial DMI. Consequently, we expect the films to display Bloch walls and Néel walls in the symmetric and asymmetric designs, respectively. Standard $\theta/2\theta$ x-ray diffractometry confirms the FCC(111) texture necessary to sustain perpendicular anisotropy in both cases, which is also evidenced by the alternating gradient field magnetometry measurements in Fig. 1. The slant of the perpendicular hysteresis loops is characteristic of magnetic bubble materials that spontaneously demagnetize into a labyrinth domain pattern.

To interpret Lorentz TEM images, we have performed Micromagnetic energy minimization using MuMax^3 [4] with magnetic properties fixed at A = 1x10^{-11} J/m, M_s = 600 kA/m, and K$_{eff}$ = 2.5x10^5 J/m^3 with D$_{int}$ = 2.0 mJ/m^2 added for the asymmetric case (Figure 2a-b). As shown in Figures 2b and e, for untilted specimen in Fresnel-mode Lorentz TEM, Bloch walls have a characteristic DW contrast while Néel walls show none. When a tilt is applied to these calculations, DW contrast becomes apparent in the minimizations with DMI while little change is observed in those without DMI. Therefore, any contrast seen in the untilted image results from the Bloch-component of the domain wall. If contrast is observed only in the tilted image, it can be concluded that Néel walls are present.

Experimental Lorentz TEM images of Co/Ni and Pt/Co/Ni/Ir multi-layers are shown in Figure 3. DW contrast is readily observed in symmetric Co/Ni in the untilted state indicating the presence of primarily Bloch walls (Figure 3a). This is to be expected as no interfacial DMI should be present in this multi-layer to promote Néel walls. On the other hand, no discernable magnetic contrast is observed in asymmetric Pt/Co/Ni/Ir in the untilted state (Figure 3c). However, upon tilting the sample magnetic contrast becomes apparent and a labyrinth domain pattern is revealed as seen in Figure 3d. This reveals that the DMI induced by the asymmetric stacking sequence stabilizes the formation of Néel walls over Bloch walls. Future work will further characterize chiral spin textures stabilized by DMI as well as tailoring its magnitude through the number of repeat units in these asymmetric Pt/Co/Ni/Ir multi-layers.

References:

[1] X. Z. Yu et al., Nature Materials **10**, (2011) p. 106.

[2] S. Muhlbauer et al., Science **323**, (2009) p. 915.

[3] A. Thiaville et al., EPL (Europhysics Letters) **100**, (2012) p. 57002.

[4] A. Vansteenkiste et al., AIP Advances **4**, (2014) p. 107133.

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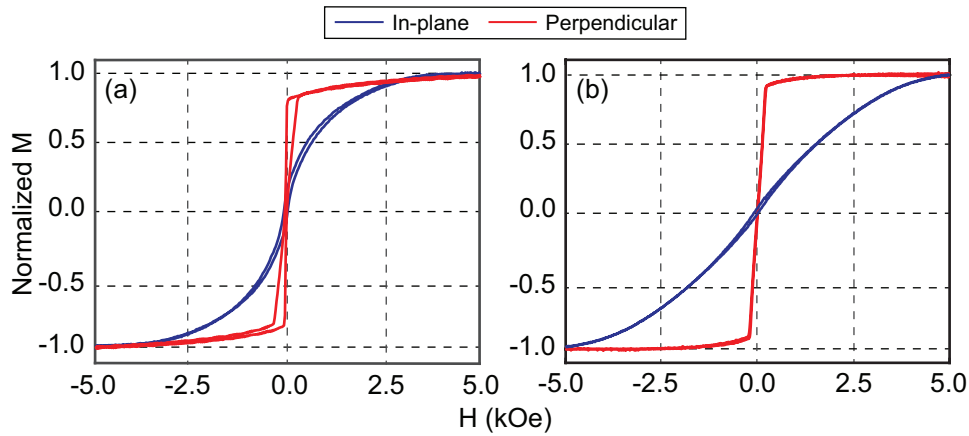

Figure 1: M-H loops of (a) symmetric Co/Ni and (b) asymmetric Pt/Co/Ni/Ir multi-layers measured by alternating gradient field magnetometry for perpendicular and in-plane orientations.
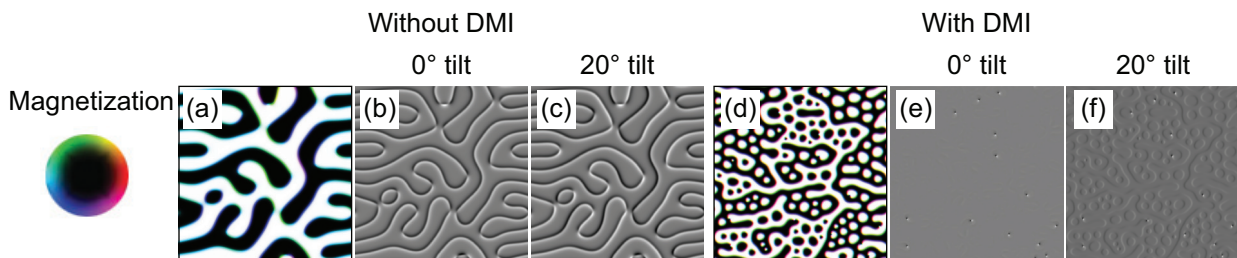

Figure 2: Micromagnetic energy minimizations of labyrinth domains and respective Fresnel-mode Lorentz calculations (a-c) in the absence and (d-f) with the presence of DMI.
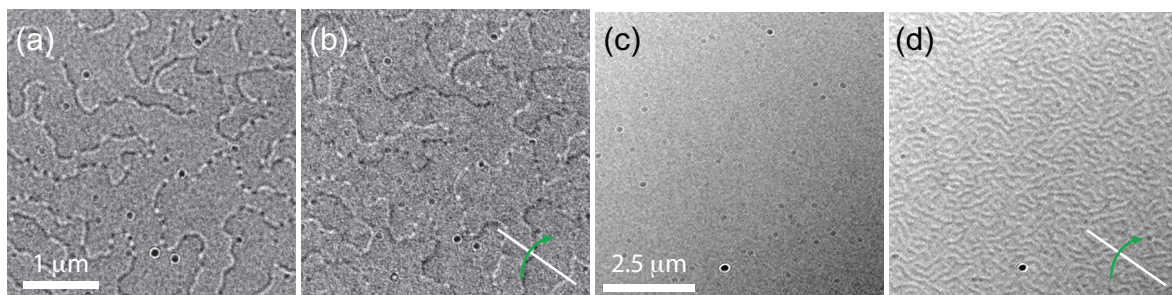

Figure 3: Lorentz TEM micrographs of as-prepared Co/Ni and Pt/Co/Ni/Ir multi-layers (a,c) in the absence of and (b,d) with 20° tilt, respectively.