doi:10.1017/S1431927619000850
Microsc. Microanal. 25 (Suppl 2), 2019

Lorentz TEM Imaging of Topological Magnetic Features in Asymmetric $[Pt/(Co/Ni)_M/Ir]_N$ based Multi-Layers

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Chiral spin textures, such as Skyrmions and chiral domain walls, have garnered a great deal of attention for use in future spintronic devices. These textures are stabilized by the Dzyaloshinskii-Moriya interaction (DMI) which is found in systems lacking crystallographic inversion symmetry [1,2]. The discovery of DMI at the interface between a ferromagnet and a heavy metal, which is known to stabilize Néel type domain walls, has sparked new avenues in materials selection and multi-layer design to support such chiral spin textures [3]. To understand the effects that DMI can have on the stability of Skyrmions and other topological defects contained within chiral magnetic domain walls (e.g. vertical Bloch lines or domain wall Skyrmions), a material system that allows for the tuning of DMI without compromising favorable magnetic parameters is desirable. Here we examine asymmetric $[Pt/(Co/Ni)_M/Ir]_N$-based multi-layers as a highly tunable platform for investigating chiral spin textures. The ferromagnetic layer thickness, determined by M, can be used to vary DMI and M_S while the total number of repeats, N, is used stabilize different remnant domain structures without loss of perpendicular magnetic anisotropy. The existence of Skyrmions and internal domain wall defects are studied by Fresnel mode Lorentz TEM for a series of different asymmetric film stacks.

$[Pt(0.5)/(Co(0.2)/Ni(0.8))_M/Ir(0.5)]_N$ multi-layers were prepared via magnetron sputtering on amorphous Si_3N_4 membranes (thicknesses in nm). All films were deposited onto Ta(3)/Pt(3) seed layers and capped with Pt(3)/Ta(3). Perpendicular anisotropy of the samples was confirmed using vibrating sample magnetometry (VSM) measurements. DMI was determined for a sample with M=2, N=1 to be -0.39 mJ/m^2 using the asymmetric bubble expansion method on a magneto-optic Kerr effect microscope, which has been confirmed by Brillouin light scattering.[4] Fresnel-mode Lorentz TEM images were acquired using an aberration-corrected FEI Titan G2 80-300 operated in Lorentz mode.

In the absence of sample tilt, no discernible magnetic contrast is observed in the out-of-focus images for all samples with M ≤ 5. Only when the sample is tilted off the electron beam axis is magnetic contrast observed, which is the signature for Néel walls. The appearance of magnetic contrast upon tilting is due to a component of the domain's induction lying perpendicular to the electron beam, which is confirmed with reconstructed in-plane induction maps. As M is further increased, exhibit a clear magnetic contrast in the absence of sample tilt due to a Bloch component of the domain wall consistent with a reduction in DMI. With increased N, there is a transition from a larger, stochastic domain configuration to a periodic labyrinth pattern, which occurs when the domains are stabilized by dipolar interactions. A perpendicular magnetic field was applied in-situ on an $M = 2$, $N = 20$ sample by exciting the objective lens of the TEM. It is observed that alternating domains form long worm-like structures before forming individual Néel Skyrmions of $\sim$80 nm in diameter. The magnetic origin of the observed magnetic contrast is confirmed with through-focus images as well as their disappearance with a greater field applied. We also note a marked change in the appearance of defects within the domain walls as a function of N. With decreasing N, internal domain wall defects are seen in greater densities and found to form stable pile-ups along the domain wall.

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[5] Authors acknowledge support by the DARPA program on Topological Excitations in Electronics (TEE) under grant number D18AP00011, the Neil and Jo Bushnell Fellowship at Carnegie Mellon University, and use of the Materials Characterization Facility at Carnegie Mellon University under grant MCF-677785.

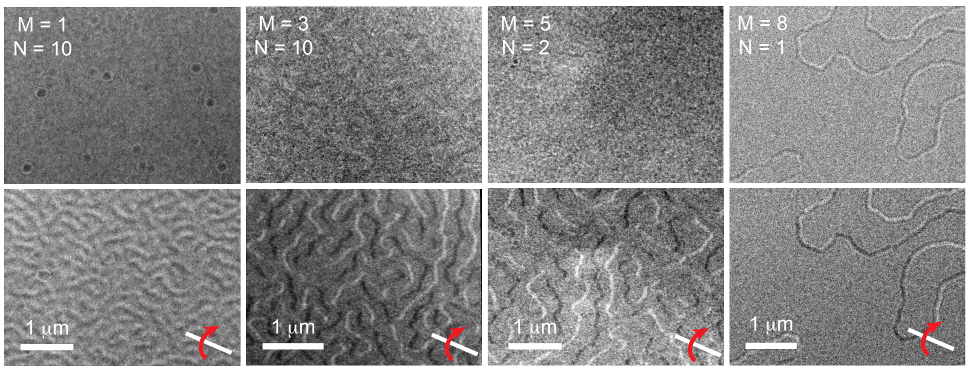

Figure 1: Lorentz TEM micrographs of asymmetric [Pt/(Co/Ni)$_M$/Ir]$_N$ in the non-tilted and tilted states with varied M. It is apparent that magnetic contrast is not observed in the absence of sample tilt but is in the tilted state confirming the presence of Néel domain walls and thus interfacial DMI. Domain walls become more Bloch-like as M is increased further while topological defects are observed clearly when N = 1.

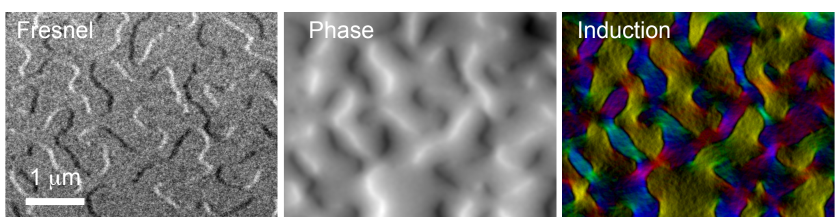

Figure 2: Lorentz TEM micrograph, reconstructed phase map, and in-plane induction map of [Pt/(Co/Ni)$_5$/Ir]$_2$. Note the signal in induction map originates from effective in-plane induction from tilted perpendicular domains.

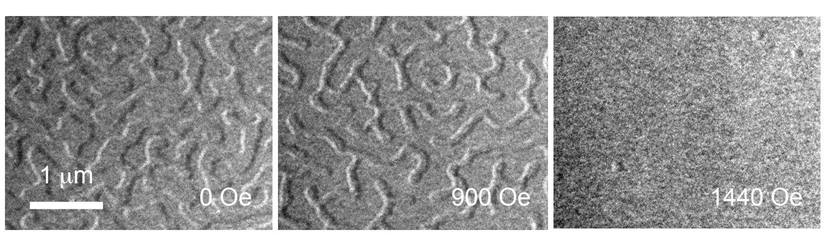

Figure 3: Lorentz TEM micrographs of [Pt/(Co/Ni)$_2$/Ir]$_{20}$ with a perpendicular field applied in-situ. Sub-100 nm Néel Skyrmions can be observed at fields close to saturation.

https://doi.org/10.1017/S1431927619000850 Published online by Cambridge University Press