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In-situ Study of Skyrmions at High Resolution using Differential Phase Contrast Microscopy

Hui Ru Tan[1,2], * I.M. Andersen[2], Ming Lin[1], Xiaoye Chen[1], Hang Khume Tan[1], Anjan Soumyanarayanan[1,3] and Chris Boothroyd[4]

[1.] Institute of Materials Research and Engineering, Agency for Science, Technology & Research (A*STAR), Singapore, Singapore
[2.] School of Material Science and Engineering, Nanyang Technological University (NTU), Singapore, Singapore
[3.] Physics Department, National University of Singapore (NUS), Singapore, Singapore
[4.] Facility for Analysis, Characterisation, Testing and Simulation (FACTS), Nanyang Technological University, Singapore, Singapore
* Corresponding author: tanhr@imre.a-star.edu.sg

Magnetic skyrmions are nanoscale topological spin structures that show great potential in future spintronic technology. In particular, skyrmions in multilayer systems open up the avenue to controlling and varying skyrmion properties for functional devices. Co/Pt-based multilayer systems have been shown to host magnetic skyrmions at room temperature, while incorporation of Ir and Fe further offers a materials platform with tunable magnetic properties [1]. In our previous studies on Ir/Fe/Co/Pt multilayers, we used Lorentz transmission electron microscopy (TEM) to characterize the chirality, formation mechanism, and evolution of room-temperature skyrmions [2]. This is the most direct imaging method for in-situ TEM studies of magnetic processes. However, as we work with multilayer films approaching the ultrathin (1 nm) limit, highly defocused Lorentz TEM images (Figure 1) prove limiting in both spatial resolution and magnetic sensitivity.

Differential phase contrast microscopy in scanning TEM (DPC-STEM) is an alternative magnetic imaging technique of higher sensitivity and spatial resolution [3, 4]. It relies on the Lorentz deflection of the incident electron probe when passing through the specimen. This deflection can be determined from the recorded central diffraction disks at each pixel position, and a spatial map that is proportional to the magnetic induction integrated along the electron path can be generated.

In this work, we present a DPC-STEM imaging study on the formation and evolution of chiral spin textures with varying sizes, densities, and structures in few-repeat Ir/Fe/Co/Pt, by applying external magnetic fields in-situ in the transmission electron microscope. With an aberration-corrected STEM, the high spatial resolution makes it possible to conduct quantitative analysis on the spin structure and size of skyrmions hosted in these challenging materials systems. An example of stripe domains imaged at high resolution using DPC is shown in Figure 2. Some traces of the grain structure (visible in the annular dark-field images, Figures 2a and e) are still present and contributing noise to the DPC images (Figures 2b-d, f-h) so a background subtraction method is being implemented to remove this non-magnetic contribution. This will in turn enhance the signal due to the magnetic deflection [5].

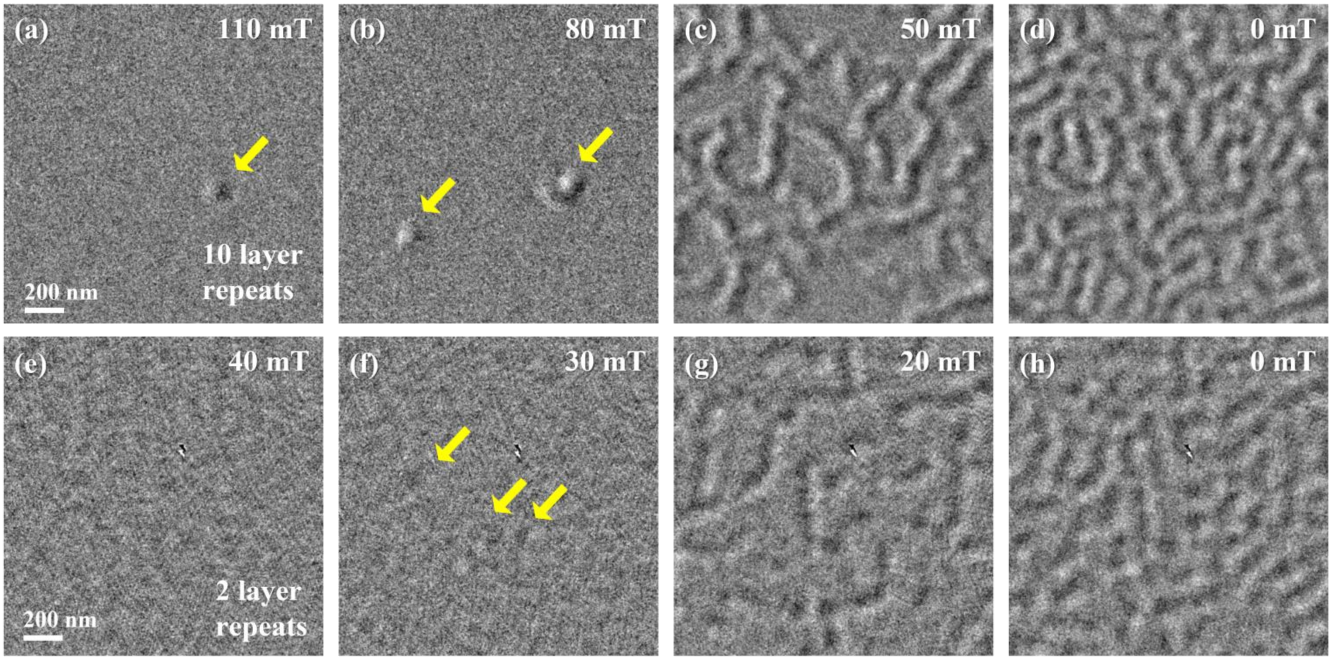

Figure 1. Background-subtracted Lorentz TEM images of Ir/Fe/Co/Pt multilayer films with 10 layer repeats (a-d) and 2 layer repeats (e-h), under different magnetic fields. In the film with 2 layer repeats, the magnetic stripes (g-h) are not clear even after background subtraction; the magnetic skyrmions, as indicated by yellow arrow in (f), are also barely visible.

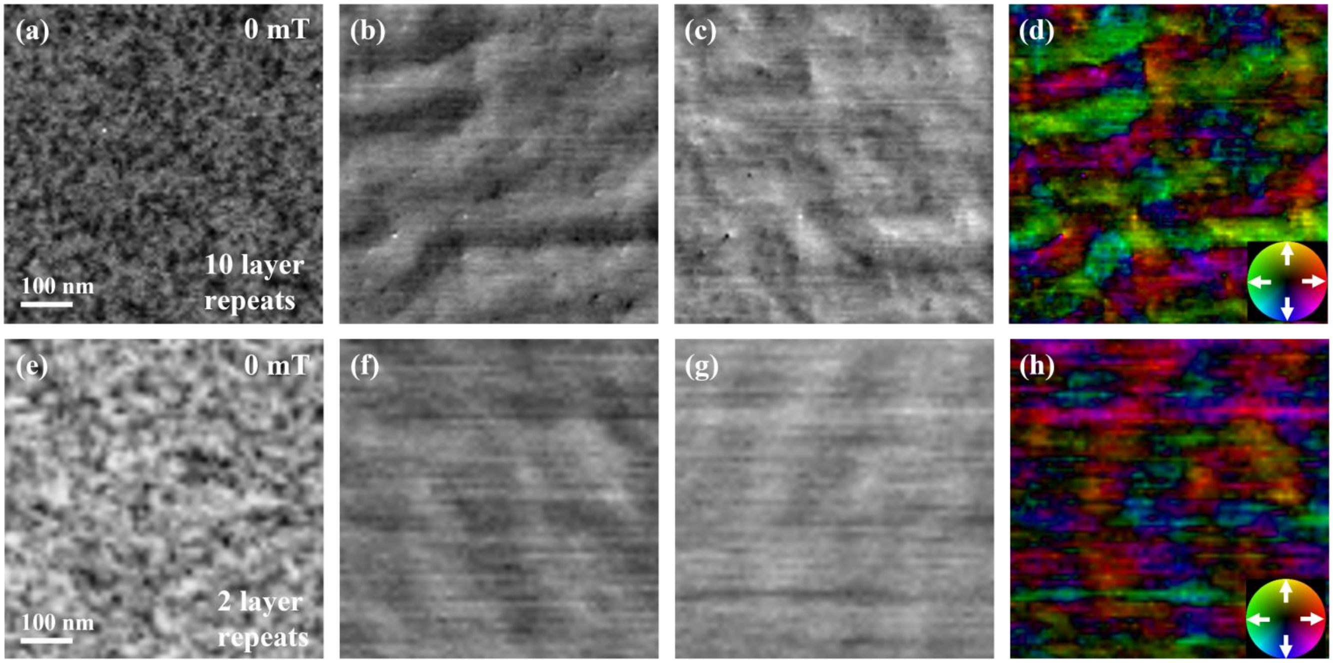

Figure 2. (a,e) Annular dark-field images of Ir/Fe/Co/Pt multilayer films with 10 layer repeats and 2 layer repeats, and their corresponding (b,f) DPC x-shift images, (c,g) DPC y-shift images, and (d,h) DPC colour maps, showing magnetic induction directions of the magnetic stripes at 0 mT. The shifts measured for the film with 2 layer repeats (f,g) are significantly lower than those from 10 layer repeats (b,c), but a suitable background subtraction method will help to improve the signal-to-noise ratio.

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