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Quantitative Measurement of Topological Spin Textures via Differential Phase Contrast

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Since the discovery of topological spin textures called magnetic skyrmions, much interest has been focused towards these vortex-like textures [1,2] for use as storage bits for future computing applications [3]. There are two magnetic systems of particular interest due to their appealing physical properties. One is the multi-layered system, generally consisting of multiple stacks of heavy metal/magnet sandwiches, each layer a few nanometers thick, and the number of stacks theoretically determining the type of magnetic structures that emerge. The interplay between the dipole interaction through the thickness and the Dzyaloshinskii-Moriya interaction (DMI) at the multiple interfaces allows for the emergence of magnetic skyrmions with an appropriate external energy input in the form of either an applied current of magnetic field. The other is two-dimensional (2D) van der Waals magnets, desirable for their physical properties as well as integration with other 2D structures to form distinctive heterostructures [4].

Here we report the emergence of skyrmion spin textures within both systems using Differential Phase Contrast (DPC) Microscopy. DPC is a technique that enables direct measurement of the full magnetic field (both magnetization and stray field) in focus and at no tilt. Figure 1 (a-d) shows a biskyrmion like spin texture within repeating stacks of PtCoTa at room temperature. The initial magnetic state consists of several magnetic domains separated by Bloch-type domain walls. When we apply an external oblique magnetic field equivalent to an $B_{||,ext}$=12 mT in-plane and $B_{z,ext}$=32 mT, isolated spin textures emerge as shown in-focus and at 0^o tilt in Figure 1(a). DPC reveals these spin textures to have a biskyrmion-like in-plane magnetization (Figure 1 (a-b)). The cross-sectional profiles of a selected spin texture are shown in Figure 1 (c-d). The in-plane magnetization of a 2D magnet made from Pt/Fe_3GeTe_2/O- Fe_3GeTe_2/Au is shown in Figure 1 (e-h), where an oblique field of $B_{||,ext}$=14 mT in-plane and $B_{z,ext}$=38 mT out-of-plane applied while cooling the magnet to 135 K leads to the emergence of a skyrmion lattice. The DPC signal taken at no tilt suggests that the skyrmions are Bloch-type, as shown in the in-plane magnetization of a selected skyrmion in Figure 1 (f) along with the cross-sectional profiles in Figure 1 (g-h). For comparison, we simulated both Bloch-type skyrmions and biskyrmions and plot the in-plane magnetizations and cross-sectional profiles in Figure 2, which matches qualitatively well with the profiles in Figure 1.

As both of these systems theoretically favour DMI, Neél-type domain walls are expected to emerge. The appearance of biskyrmion and Bloch-type skyrmion lattice within such systems suggests that a more complex energy landscape may exist, with Bloch-type domain-favouring dipole interactions playing a more dominant role than previously thought. DPC enables us to measure these in-plane magnetizations quantitatively, which in turn allows us to more easily identify unknown spin textures.

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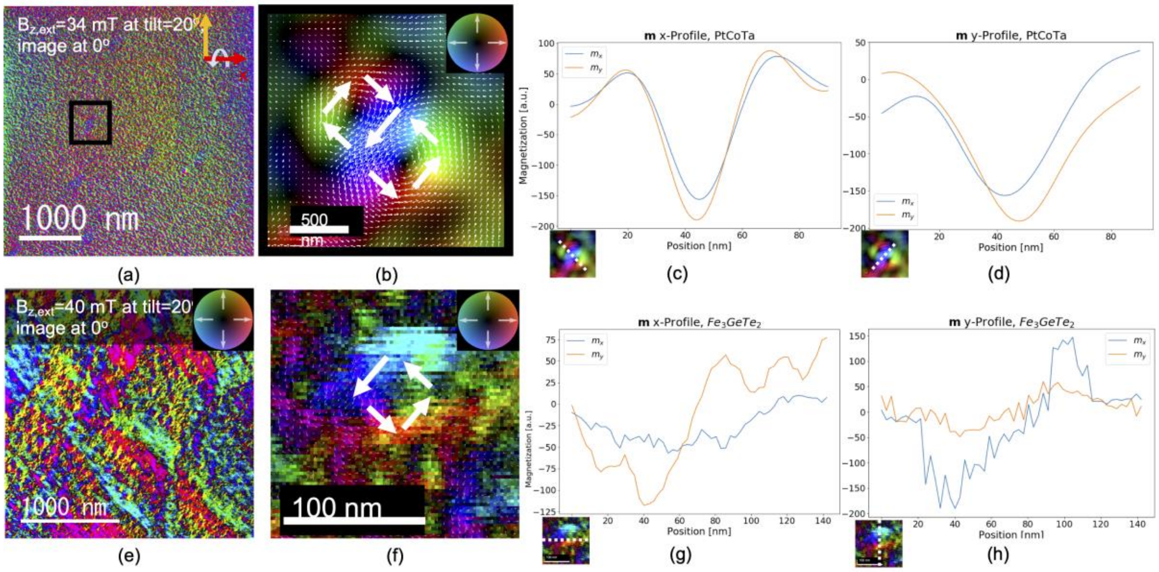

Figure 1. (a) The magnetic state in PtCoTa multilayer thin film at room temperature resulting from applying an oblique field of 34 mT, and then a pure out-of-plane field while imaging. (b) An individual biskyrmion-like spin texture magnified from (a) and its (c-d) cross-sectional magnetization profiles. (e) Skyrmion lattice state imaged within an Pt/Fe3GeTe2/O-Fe3GeTe2/Au 2D van der Waal's heterostructure. (f) shows an individual skyrmion and its (g-h) cross-sectional magnetization profiles.

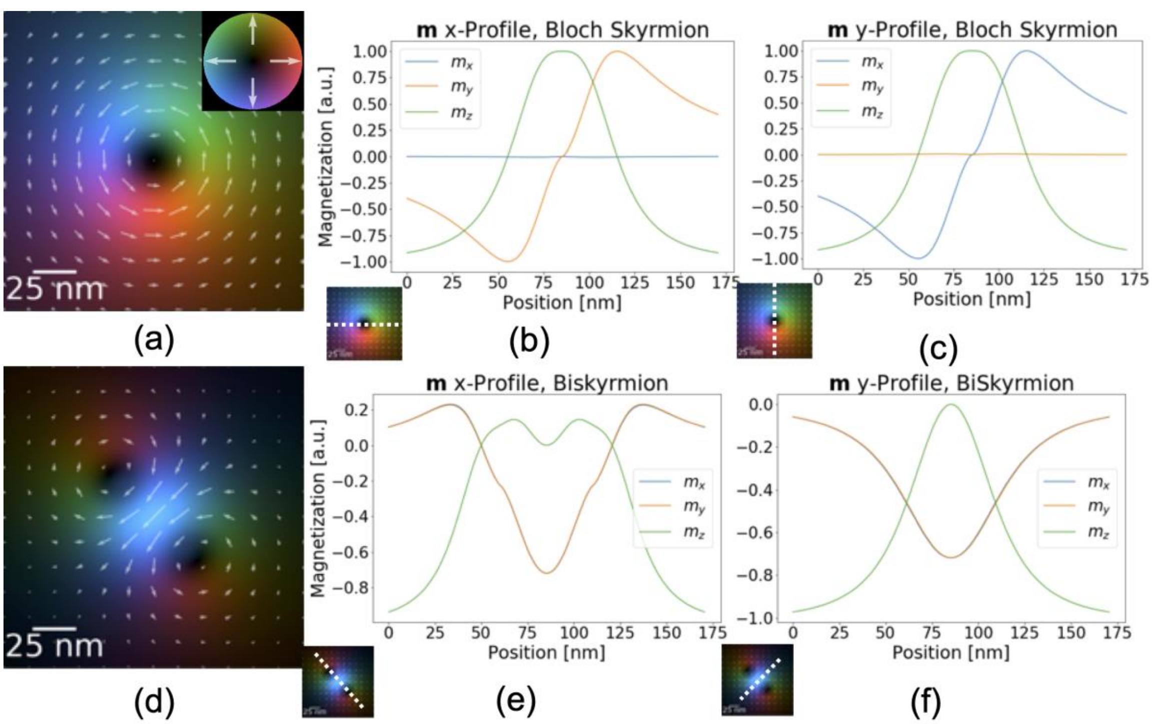

Figure 2. In-plane magnetization of a simulated (a) Bloch skyrmion and (d) biskyrmion. (b-c, e-f) shows their cross-sectional profiles, which aids in the identification of such spin textures in experiment.

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