

Advanced Scanning Transmission Electron Microscopy as a Tool for Direct Real-Space Visualization and Artificial Control of Quantum Spin Textures

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Magnetic skyrmion - a topologically protected unique quantum spin texture with nanometer length scale - is attracting much attention as the promising candidate utilized in future memory devices featuring ultralow energy consumption. For such practical applications, however, interaction of skyrmion with various kinds of structural defects is critically important. Real-space visualization techniques of skyrmion and structural defects with high spatial resolution are essential to elucidate such interactions.

We developed aberration-corrected differential phase contrast scanning transmission electron microscopy (DPC STEM) [1] to realize simultaneous imaging of magnetic skyrmions and structural defects in real-space at a live speed (Figure 1). Equipment of an independent annular dark field (ADF) detector combined with highly sensitive multiple segmented annular all-field (SAAF) detector has enabled such simultaneous visualization of individual magnetic skyrmion and structural defects. Using the DPC STEM system, we found a unique core structure of a skyrmion $\Sigma 7$ domain boundary induced by an edge of a single crystal grain of $\text{FeGe}_{1-x}\text{Si}_x$ [2]. We also found that a unique joint of skyrmion lattices is created along a small-angle grain boundary in a thin plate of $\text{FeGe}_{1-x}\text{Si}_x$ [3]. These findings were only possible by the direct real-space imaging technique with high spatial resolution.

A focused electron beam in a STEM is useful not only for imaging but also for fabricating artificial structural defects with nanometer length scale. We fabricated a sequence of tiny surface pits in a thin plate of $\text{Co}_8\text{Zn}_8\text{Mn}_4$ by using a focused electron beam in a STEM to investigate the interaction of skyrmion with the surface defects (Figure 2) [4]. We found a stable single skyrmion state located at the center of an 800 nm equilateral triangular corral at a room temperature (295 K) under the perpendicular magnetic field of 60 mT. Under the residual field of the objective lens (~ 20 mT), the single-skyrmion state turned into a triple-skyrmion state. The transition from the single-skyrmion state to the triple-skyrmion state occurred in a very narrow range of perpendicular magnetic field (40.0 ± 1.0 mT). Intriguingly, no two-skyrmion state was evident during the transition. Furthermore, we confirmed that only the single-skyrmion state is stable in a triangular corral with a reduced size (440 nm). Since it is well known that magnetic spin textures in general are strongly influenced by various kinds of structural defects, we expect our technique should be useful to control other magnetic spin textures as well.

Recently, with the development of a new magnetic objective lens system combined with a state-of-the-art aberration corrector [5], direct atom-resolved imaging of magnetic materials in a magnetic field free environment has been achieved [6]. We will present some applications of the new advanced transmission electron microscope [7].

References:

- [1] N Shibata et al., Nat. Phys. **8** (2012), p. 611.
 [2] T Matsumoto et al., Sci. Adv. **2** (2016), p. 1501280.
 [3] T Matsumoto et al., Sci. Rep. **6** (2016), p. 35880.
 [4] T Matsumoto et al., Nano Lett. **18** (2018), p. 754.
 [5] Y Kohno, S Morishita and N Shibata, Microscopy and Microanalysis **23 (S1)** (2017), p. 456.
 [6] N Shibata et al., submitted.
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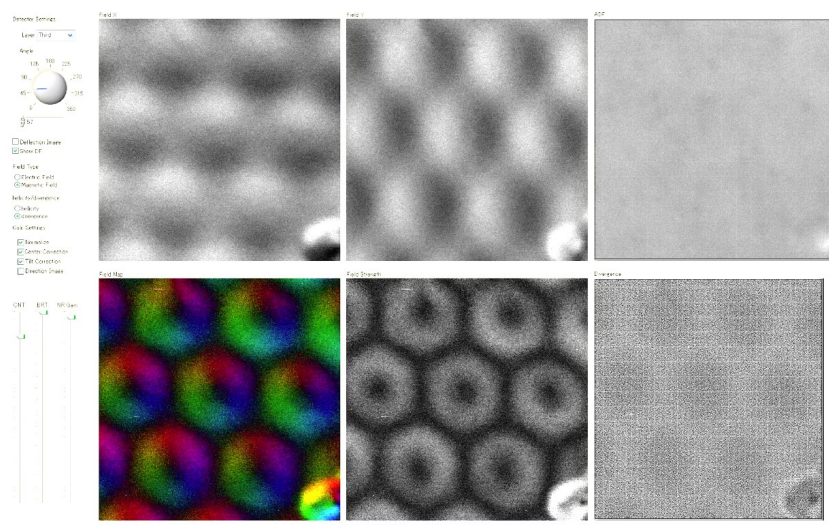


Figure 1. Live observation of magnetic skyrmion lattice in a thin plate of $\text{FeGe}_{1-x}\text{Si}_x$ by DPC STEM. The three panels in the upper row show the horizontal (left) and vertical (center) component of in-plane magnetization, and ADF image (right). The three panels in the lower row show the vector color map (left) and intensity (center) of in-plane magnetization, and the helicity image (right). The dwell time is 20 $\mu\text{sec./pixel}$.

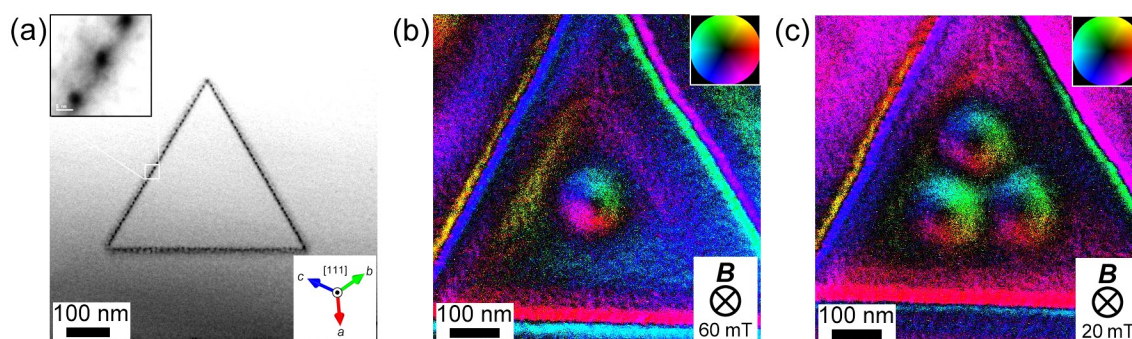


Figure 2. (a) A plan-view ADF STEM image of a 440 nm equilateral triangular corral of linear surface defects (enlarged in the inset) fabricated by scanning a focused electron beam. Stable skyrmion states confined to an 800 nm equilateral triangular corral in a thin plate of $\text{Co}_8\text{Zn}_8\text{Mn}_4$ at a room temperature (295 K) are demonstrated in two in-plane magnetization vector maps under perpendicular magnetic field of 60 mT (b) and 20 mT (c).