Magnetic imaging of various topological spin textures and their dynamics by using Lorentz TEM and DPC-STEM

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The nanometer-scale vortex-like topological spin textures, such as magnetic skyrmion and antiskyrmion, have recently attracted enormous attention due to their topological properties [1-2]. To confirm such minute twisted spin textures and their dynamics with external stimuli, the real space imaging technique with high spatial resolution and high-speed recording system are required.

To realize magnetic skyrmion, typical topological spin textures carrying a topological number $N_S = -1$, we have developed a proper technique not only to create skyrmions by precise control of the magnetic field in a standard transmission electron microscope (TEM) but also to directly observe skyrmions and their dynamics at a Lorentz TEM mode [3]. In addition, a phase imaging technique, called differential phase contrast (DPC) at the scanning TEM (STEM) mode is also optimized to characterize antiskyrmions with $N_{antiS} = +1$[4]. The in-situ Lorentz TEM observations demonstrated the controlled transformation between antiskyrmion and skyrmion by tunning in-plane field, temperature, and sample geometry (sample thickness)[5-6]. To manipulate and track individual skyrmions and their lattice structure using a relatively low electric current, we designed a microdevice composed of a thin helimagnet of FeGe with a notch hole, which allowed the local spin current in a specific area near the corner of the notch[7]. Generation, annihilation, Hall motion, and torque motion of single 80-nm skyrmions and their bunches and lattice are tracked by directional currents at low current density, three orders smaller than for moving magnetic domain walls. To tune the magnetic twists from Bloch-type bubbles to Néel-type skyrmionic bubbles by engineering capping layers and hence interfacial spin-orbital interaction (DMI) in vdW-magnet Fe_3GeTe_2 (FGT), the heterostructure FGT (Pt/oxidized-FGT/FGT/oxidized-FGT) has been prepared[8]. Using Lorentz TEM jointly with sample tilt, we observe that the Néel-type skyrmionic bubbles show no contrast at zero tilt and contrast that reverses intensity at opposite tilt angles in a heterostructure FGT with Pt-capping layer. In contrast, the Bloch-type bubbles that appear in the thin plate FGT thinned from a bulky FGT show clear contrast at zero tilt angle and hold random helicities. To identify Néel-type skyrmionic bubbles in the heterostructure FGT, we use an in-plane magnetic field to align the magnetic twists in the two thin samples with almost the same thickness ~ 60 nm, and compare the field-induced ***q***-vector reorientation with micromagnetic simulations. We measure that a weak in-plane magnetic field aligns the ***q***-vector of Néel-type twists perpendicular to the field direction in the heterostructure FGT, while the aligned Bloch-type twists in the thin plate FGT show a rotated ***q***-vector to the in-plane field[9].

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