Magnetic Skyrmions in an FeGe Nanostripe Revealed by in situ Electron Holography

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Intense research interest in magnetic skyrmions is presently driving the development of new fundamental concepts and applications[1]. Magnetic skyrmions are particle-like, topologically protected swirling spin textures, in which the peripheral spins are oriented vertically, the central spins are oriented in the opposite direction and the intermediate spins rotate smoothly between these two opposite orientations, as shown in the inset to Fig. 1(a). In a range of applied magnetic fields, skyrmion lattices form in certain chiral magnets, such as B20-type magnets, in which a lack of inversion symmetry and spin-orbit coupling gives rise to the Dzyaloshinskii-Moriya interaction. The typical sizes of skyrmions are between 3 and 100 nm. For technically relevant applications, a full understanding of skyrmion formation, stability, manipulation and annihilation is required. Recent experiments have demonstrated the formation of magnetic skyrmion chains in geometrically confined nanostructures[2], as shown schematically in Fig. 1(b). A critical step towards real-world device applications involves the development of an approach that can be used to controllably create, manipulate and annihilate skyrmions in magnetic nanostructures, including wire-like geometries.

Real-space imaging of complex skyrmion spin configurations using Lorentz microscopy (LM) in the transmission electron microscope (TEM) has enabled the direct observation of skyrmion lattice formation and transformations between different magnetic states with nanometre spatial resolution[3]. However, the finite size and the inherently weak magnetization of such magnetic nanostructures imposes great experimental challenges for LM. In particular, Fresnel fringe contrast at the specimen edge makes extremely difficult to use LM to obtain magnetic signals in samples that have lateral dimensions of below 10 nm. In contrast, off-axis electron holography (EH) in the TEM, which allows electron-optical phase images to be recorded directly with nanometre spatial resolution and high phase sensitivity, provides easier access to magnetic states in nanostructures. Digital acquisition and analysis of electron holograms and sophisticated image analysis software are then essential in studies of weak and slowly varying phase objects such as magnetic skyrmions[4].

Here, we use both LM and EH to study magnetic skyrmions in a B20-type FeGe nanostripe. The use of liquid nitrogen specimen holder (Gatan model 636) allows the specimen temperature to be varied between 95 and 370 K, and the objective lens of the microscope (FEI Titan 60-300) can be used to apply magnetic fields to the specimen of 0 to 1.5 T. The aim of our study is to resolve the fine magnetic structures of geometrically confined skyrmions and to understand their formation process. Figures 2(a-b) show Lorentz images of a typical FeGe nanostripe, in which a helix to skyrmion transition occurs in response to an applied magnetic field. Figure 2(c) shows a colour-contour composite map derived from a phase image recorded using EH. The slight asymmetry of the contours results from the wedge-shaped specimen thickness profile. Artefacts associated with local changes in specimen thickness in such images can be removed from such images by separating the mean inner potential contribution from the magnetic contribution to the phase, for examples by evaluating the difference between phase images recorded at two different specimen temperatures.

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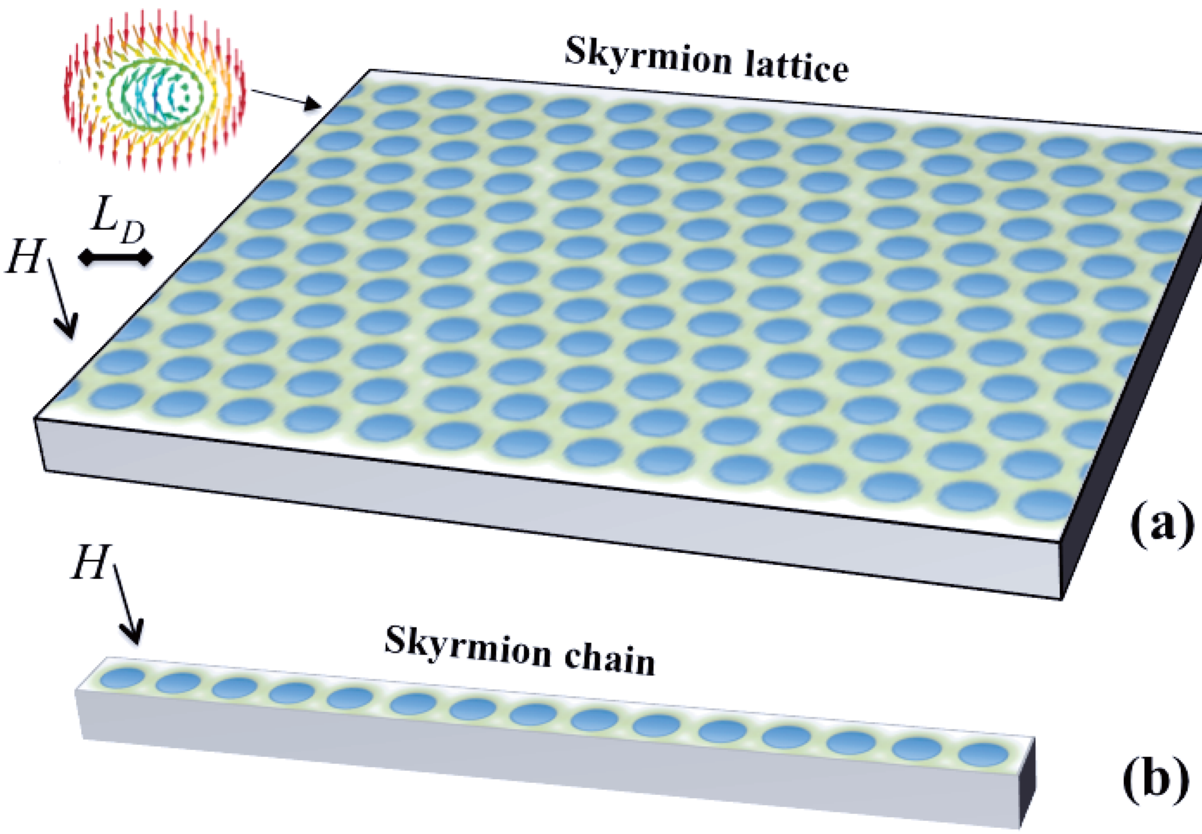

Figure 1 Schematic representations of (a) a magnetic skyrmion lattice in an extended thin film and (b) a skyrmion chain in a confined nanostripe-like geometry. LD indicates the characteristic length of a magnetic system with a Dzyaloshinskii-Moriya interaction. The applied magnetic field H is normal to the specimen plane.

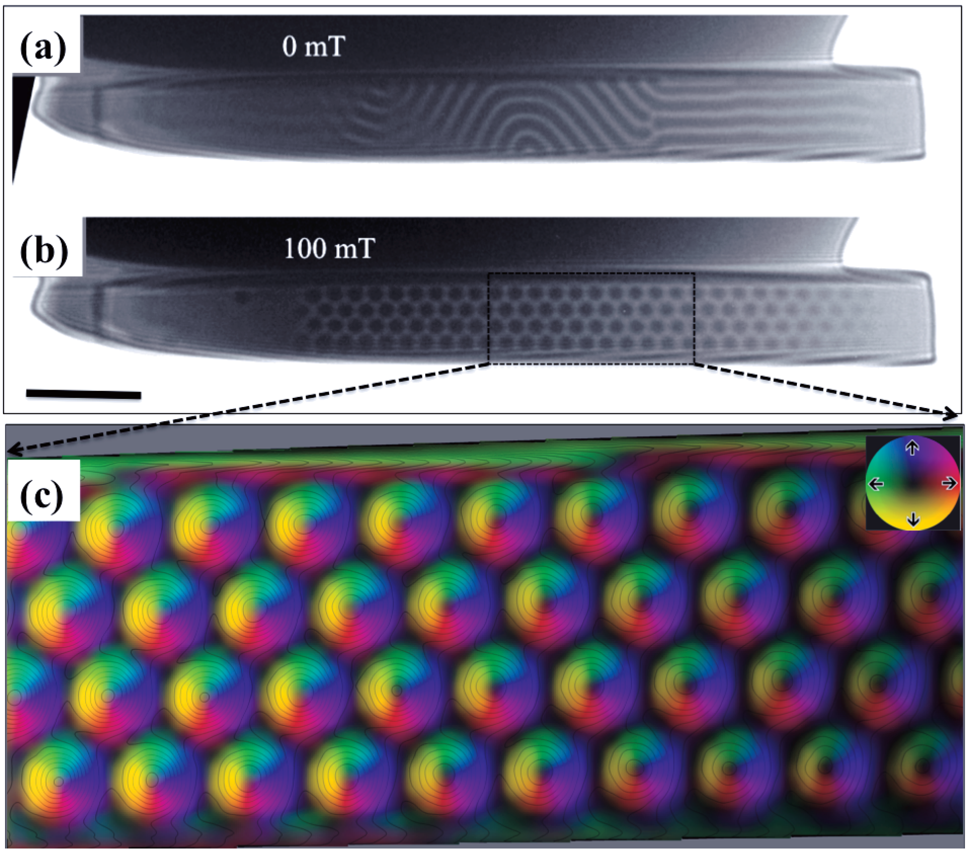

Figure 2 Lorentz micrographs showing the evolution of the magnetic structure in an FeGe nanostripe at 240 K from (a) a helical state to (b) skyrmion chains in the presence of different magnetic fields (indicated) applied normal to the specimen plane. The scale bar in (b) is 500 nm. (c) Color-contour composited image determined from the total phase recorded using off-axis electron holography. The colour wheel (inset) shows the direction of the phase gradient. The contour spacing is 2π/20 radians.