Magnetic imaging of skyrmions in FeGe using off-axis electron holography

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Magnetic skyrmions are topologically protected spin structures that have recently attracted considerable interest as a result of their physical properties and potential applications in energy-efficient spintronic devices for information technology [1]. Magnetic skyrmions were first observed in B20 compounds, whose non-centrosymmetric crystal structure gives rise to strong spin-orbit coupling. In these materials, the Dzaloshinskii-Moriya interaction results in the formation of a particle-like chiral spin structure in a regular hexagonal lattice. Transmission electron microscopy (TEM) offers a variety of methods for imaging the magnetic structure of skyrmions, including the Fresnel mode of Lorentz TEM combined with phase retrieval based on the transport of intensity equation, scanning TEM combined with differential phase contrast imaging and off-axis electron holography (EH). Here, we discuss recent advances in EH-based methods and related techniques for imaging skyrmion and helical spin structures in B20 FeGe single crystals as a function of temperature and applied magnetic field.

Focused ion beam (FIB) milling was used to prepare TEM specimens of FeGe with a homogenous thickness of ~100 nm and a large surface area of ~50 μm^2. FIB-induced damage was reduced by using low energy (<1 kV) ion milling. In order to form helical and skyrmion spin structures [2], the FeGe specimens were cooled below 280 K using a Gatan 636 liquid nitrogen cooling holder. Fresnel images and off-axis electron holograms were recorded using an FEI Titan 60-300 TEM operated at 300 kV in magnetic field free conditions (<0.5 mT) in aberration-corrected mode. The microscope was equipped with a conventional Gatan Ultrascan 2k x 2k charge-coupled device (CCD) camera and two biprisms, which were located in the first and second selected area aperture planes.

Figure 1 shows experimental magnetic phase images and corresponding magnetic induction maps of skyrmion and helical spin structures in FeGe recorded using EH. The mean inner potential and magnetic contributions to the total phase shift were separated by taking differences between measurements recorded at low temperature and at room temperature (when the FeGe is non-magnetic). The phase resolution of the EH experiments was optimised by acquiring multiple series of electron holograms and combining them after cross-correlation, as well as by recording electron holograms with a direct electron detection (Gatan K2-IS) camera, which offers an improved detective quantum efficiency and modulation transfer function when compared with standard CCD cameras [3]. Skyrmions were studied as a function of both temperature and magnetic field, which was applied parallel to the electron beam direction using the objective lens of the microscope (in free lens control mode). The twin construction of the objective lens used allowed the strength and polarity of the magnetic field to be changed continuously, in order to study the magnetization reversal dynamics of the skyrmions *in situ* in the TEM. The recorded magnetic phase images were also used to calculate the projected in-plane magnetization distribution in the sample using a model-based iterative reconstruction technique. As the inverse problem of reconstructing the magnetization distribution is ill-posed, regularisation parameters were used to constrain the solution. Examples of the resulting magnetisation maps are shown in Fig. 2 for the helical and skyrmion structures.

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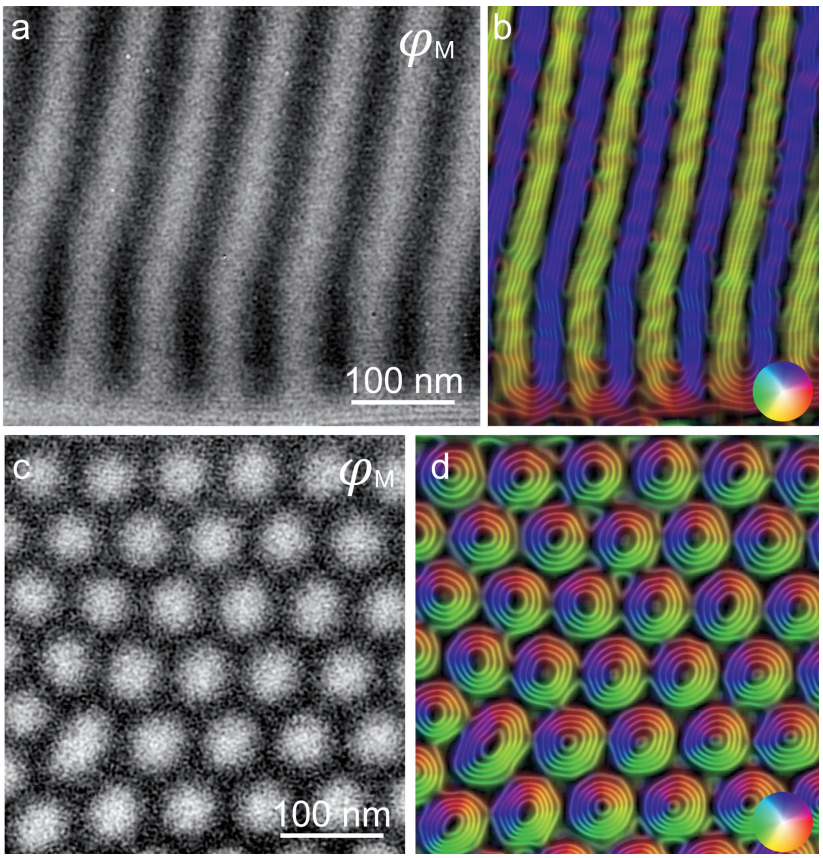

Figure 1. (a, c) Magnetic phase images and (b, d) corresponding magnetic induction maps of helical and skyrmion structures in FeGe recorded at 95 K using off-axis electron holography. The contour spacing in (b) and (d) is 0.1 radians.

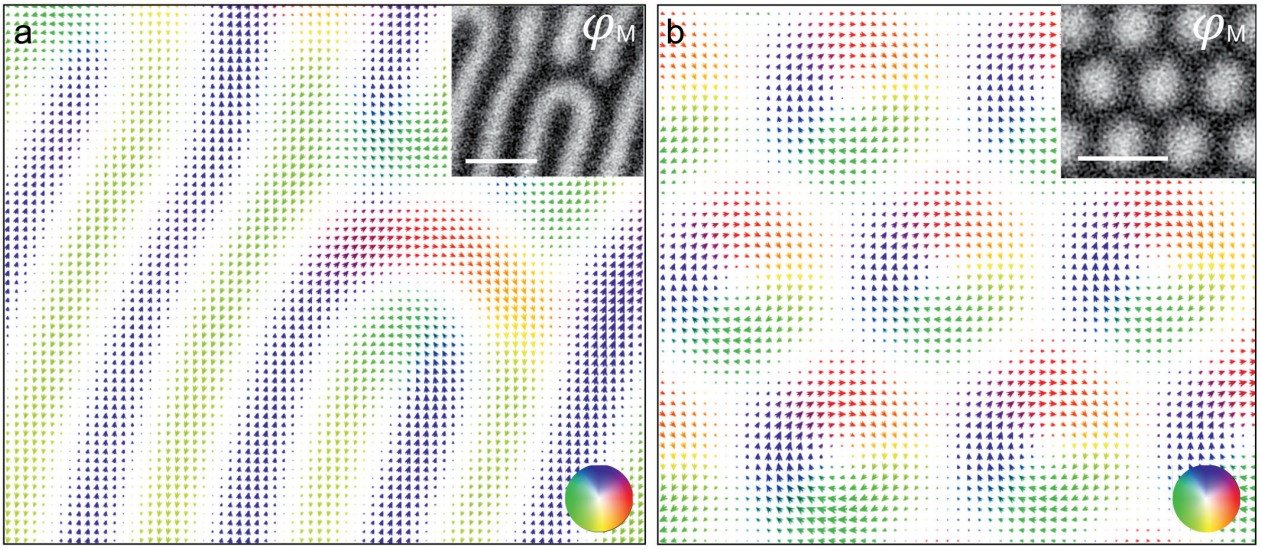

Figure 2. Projected in-plane magnetisation of (a) helical and (b) skyrmion structures in FeGe extracted from experimental magnetic phase shift images (shown as insets) using an iterative model-based algorithm.