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Deformation mapping in Lorentz transmission electron microscopy images of magnetic skyrmion lattices

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Background

Magnetic skyrmions are quasi-particles with a swirling spin texture. In chiral magnets, skyrmions are stabilized by the balance between the exchange interaction and the Dzaloshinskii-Moriya interaction. They have raised interest because of their potential applications in the field of spintronics, for instance in racetrack memories where they are treated as information carriers [1]. Axially symmetric chiral skyrmions usually form 2D hexagonal close-packed lattices [2]. Similarly to atomic lattices, skyrmion lattices can exhibit local deformations and crystalline defects such as dislocations and grain boundaries depending on the geometric constraints and the external magnetic fields [3]. Measuring deformations in skyrmion lattices is important to understand the interplay between the lattice structure and external influences.

In previous studies, skyrmion lattice deformations were investigated using real-space methods applied to Lorentz transmission electron microscopy (LTEM) images, which involves detecting intensity maxima or minima, finding nearest neighbors and calculating inter-skyrmion distances [3,4]. Here, we investigate the applicability of geometric phase analysis (GPA) [5]. GPA is a lattice deformation analysis technique based on Fourier transforms primarily used in high resolution TEM images. Compared to real-space methods, GPA is straightforward computationally because there is no need to detect individual maxima and perform any pixel-to-pixel operation. A Fourier transform of the image is first calculated and numerical apertures are applied to a pair of Bragg spots with non-colinear reciprocal lattice g-vectors. After inverse Fourier transform, the geometric phase term $\phi(r)=-2\pi g.u(r)$ associated to each g-vector is retrieved, where u is the displacement vector. The deformation fields are then obtained using differentiation of the displacement fields.

Methods

Experiments were carried out using a TFS Titan TEM equipped with a Schottky field emission gun operated at 300 kV, a CEOS image aberration corrector and a 4k*4k Gatan K2-IS direct electron detector. The microscope was operated in Lorentz mode by using the first transfer lens of the aberration corrector as the main imaging lens. The objective lens was used to apply magnetic fields perpendicular to the sample which were precalibrated using a Hall probe. A liquid-nitrogen-cooled specimen holder (Gatan model 636) was used to vary the sample temperature. The Digital Micrograph software and a GPA plugin were used to calculate deformation maps. A TEM lamella of FeGe was prepared from a bulk crystal using focused Ga+ ion beam sputtering in a scanning electron microscope (FIB-SEM) FEI Helios dual-beam platform.

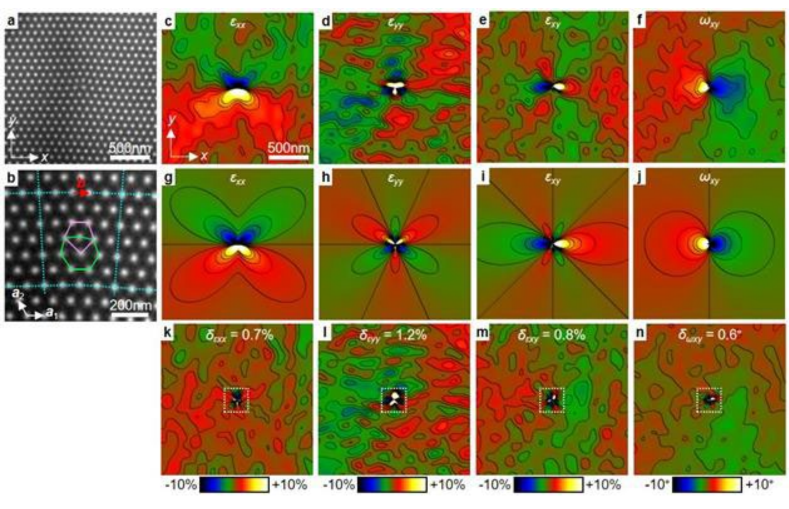
Results

Figure (a) shows an example of Lorentz TEM image of a skyrmion lattice in a 150 nm thick FeGe lamella recorded at 230 K with a defocus of 800 µm and in the presence of an external magnetic field of 145 mT. Normally, each skyrmion has 6 neighbors in a hexagonal lattice. However, it is common to observe dislocations formed by pairs of 5 and 7-coordinated skyrmions. Such a dislocation is present in the middle of the image and it is magnified in Fig. (b) where the heptagon and the pentagon have been drawn. A Burgers circuit has also been traced to show the Burgers vector b. Figure (c-f) shows the experimental deformation fields calculated using GPA and Fig. (g-j) shows the corresponding theoretical deformation fields calculated from linear elastic theory. The horizontal deformation εxx, along the direction parallel to the Burgers vector, shows a butterfly shape with negative (compressive) deformation in the top part of the image and positive (tensile) deformation in the bottom part. The vertical deformation εyy shows a three-fold symmetry with alternating negative and positive deformations around the dislocation core. The shear deformation εxy and the rigid-body rotation ωxy show primarily loops oriented along the horizontal direction, parallel to the Burgers vector. Visually, the shape of the experimental and theoretical deformation fields is in good agreement even though the experimental images show some random fluctuations. To provide a quantitative comparison, Fig. (k-n) shows the difference between the experimental and theoretical deformation fields. The standard deviation δ was calculated and is indicated on each image. The region in the vicinity of the core (approximately 150 nm around the core, as indicated by the dotted square) was excluded from the measurement. The small values of δ ≈ 1% or 1° indicate a good quantitative agreement.

Conclusions

We have studied deformations in skyrmion lattices in a sample of FeGe by applying GPA to Lorentz TEM images. Deformation fields measured around a single dislocation were found to be in good agreement with deformation fields calculated from linear elastic theory. In the conference presentation, we will also show rotation fields measured at the boundaries between crystal grains and compare them with angles calculated from the density of dislocations. We will also discuss the evolution of deformation fields in applied magnetic fields series of LTEM images and explain how to calculate an orientational order parameter to study the evolution of the disorder. The influence of potential artifacts such as geometric distortions and large defoci will also be discussed.

Graphic:



Keywords:

skyrmions, Fresnel, deformations, lattice, GPA

Reference:

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