Magnetic imaging of spin structures in FeGe

°A. Kovács[1], K. Shibata[2], J. Caron[1], Z.-A. Li[1], Y. Tokura[2], R. E. Dunin-Borkowski[1] (1. Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons, Forschungszentrum Jülich, Germany, 2. Department of Applied Physics and Quantum-Phase Electronics Center, University of Tokyo, Japan)

E-mail: a.kovacs@fz-juelich.de

Topological vortex-like spin textures, which are referred to as skyrmions, have interesting solid state properties and are promising as information carriers in future spintronic devices that can be controlled using low spin-polarized currents [1]. Experimental observations of skyrmion structures using small angle neutron scattering in bulk crystals [2] and Lorentz transmission electron microscopy (LTEM) [3] have recently been reported. LTEM provides real-space images of skyrmions in thin electron-transparent samples as a result of the deflection of electrons due to the directional variation of magnetic fields in the sample. However, quantitative analysis of the magnetic flux with this technique is difficult, both because the large defocus used to record the LTEM images limits the resolution and because of contributions to contrast from non-magnetic features in the specimen. Off-axis electron holography (EH) is a powerful technique that allows the phase shift of the electron wave that has passed through an electron-transparent specimen in the TEM to be recorded directly and interpreted in terms of the magnetic flux with high-spatial resolution. Here we use both EH and LTEM to study magnetic spin structures in the helimagnet FeGe, which has a with non-centrosymmetric B20 structure, exhibits helical transition at 280 K and has a flexible helical axis [4].

TEM specimens were prepared from bulk FeGe crystals using a dual beam FEI Helios scanning electron microscope and focused ion beam system and studied at liquid nitrogen temperature using a variable temperature Gatan double-tilt cooling holder in an aberration-corrected FEI Titan microscope operated at 300 kV. Magnetic induction maps were recorded using off-axis electron holography and compared with the magnetic phase diagram of FeGe, which shows three distinct magnetic phases: a helical phase, a skyrmion lattice phase and a field-saturated phase. Transitions between the magnetic phases could be studied by saturating the samples magnetically using the magnetic field of the TEM objective lens and recording the transformations using LTEM with a high-speed camera. Maps of projected magnetisation could al so be calculated from magnetic phase images by using an iterative reconstruction algorithm based on a forward model and a priori information introduced in the form of regularization parameters.

[1] A. Fert, V. Cros, J. Sampaio. Skyrmions on the track. Nature Nanotechnology 8, 152 (2013).

[2] S. Mühlbauer, B. Binz, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, P. Böni. Skyrmion lattice in a chiral magnet. Science 323, 915 (2009)

[3] X. Z. Yu, Y. Onose, N. Kanazawa, J.H. Park, J.H. Han, Y. Matsui, N. Nagaosa and Y. Tokura. Real-space observation of a two-dimensional skyrmion crystal. Nature 465, 901 (2010).

[4] X. Z. Yu, N. Kanazawa, Y. Onose, K. Kimoto, W.Z. Zhang, S. Ishiwata, Y. Matsui, Y. Tokura. Near room-temperature formation of a skyrmion crystal in thin films of the helimagnet FeGe. Nature Materials 10, 106 (2011).