Quantitative Analysis of Magnetic Spin Textures in Fe3-xCoxGeTe2 Compositions using 4D-STEM

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Magnetic spin textures are becoming increasingly important in the field of spintronics due to their potential uses in devices such as racetrack memory. The discovery of skyrmions in Fe3GeTe2 (FGT), has triggered a great interest in studying spin textures in 2D-van der Waals (2D-vdW) magnets. These textures arise from the interplay between the Dzyaloshinskii-Moriya interaction (DMI), exchange interaction and the zeeman interaction in the presence of an external magnetic field [1]. Controlling these textures can further be achieved through factors such as thickness of the material, the temperature and structural defects [2]. Recently, it has been reported that the level of substitution of the Fe within the material by Co can change the ordering temperature and thus the behaviour of the material Fe3-xCoxGeTe2 or (FCGT) [3]. Understanding how these factors affect the behaviour of the skyrmions including the size, mobility and stability is crucial, as these features will be important when considering the materials used in potential spintronic devices such as racetrack memory or in probabilistic computing applications [4].

Here we use transmission electron microscopy (TEM) as well as four-dimensional scanning transmission electron microscopy (4D-STEM) to quantify the behaviour of FCGT as the composition of the material changes. Additionally, we simulate the textures using micromagnetic simulation software mumax3 [5].

In this work we utilize Fresnel imaging in Lorentz TEM (LTEM), a technique where the objective lens of the microscope is turned off to reduce the magnetic field so that the sample is not uniformly magnetized by the magnetic lenses. The beam is then defocused to the order of 0.1 mm so that Fresnel fringes appear caused by the magnetic potential of the sample revealing the spin textures in the sample as seen in Figure 1(a-b). These images can then be reconstructed using transport-of-intensity (TIE) equations to obtain the magnetic field information of the sample, an example of which is demonstrated in Figure 1(c). Chemical vapour transport and standard focused ion beam lift-out procedure were used to prepare the sample. During TEM imaging, the samples were cooled to liquid nitrogen temperatures and then heated to the appropriate temperature desired. The residual magnetic field within the TEM was calibrated using a custom-built in-situ Hall probe holder. The composition mapping was studied using energy dispersive x-ray (EDX) methods. Additional investigations into the material's bulk magnetic properties were carried out using magnetic force microscopy (MFM).

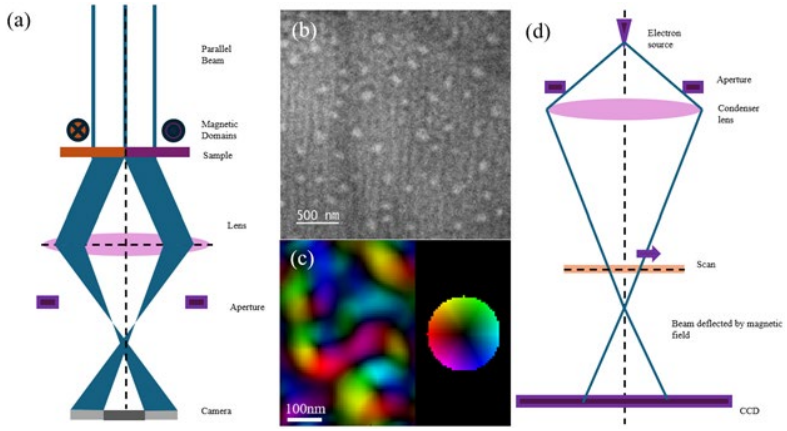
Using the methods described we have studied a range of stoichiometries of FCGT by varying out-ofplane (OOP) magnetic fields and temperatures and have demonstrated how the domain structure and temperatures at which these domains occur vary depending on the composition of the material. We have also confirmed the level of cobalt doping in FGT using EDX methods to quantify how this doping affects the behaviour of the materials, as well as investigated whether the elements are uniformly distributed throughout the material and how this affects the spintronic behaviour. Using the techniques described and through controlling the temperature and OOP magnetic field we have investigated the spin texture the material occupies at any given phase. Micromagnetic simulations were done to estimate the behaviour of the materials at different thicknesses to verify results as well as to improve

the speed of workflow when working on time intensive processes such as MFM and LTEM where the sample has to be cooled before imaging.

We have observed magnetic spin textures in a range of compositions of FCGT, showing that the behaviour of the materials depends directly on the levels of iron and tellurium as well as on any cobalt doping. Work has begun to further quantify the behaviour of these systems more accurately using 4DSTEM methods such as centre of mass measurements (COM) and ptychography, the methodology of which is shown in Figure 1(d).

Figure 1: Experimental setup of Fresnel TEM and 4D-STEM data acquisition. (a) Schematic of Fresnel TEM set up in overfocused condition. (b) Fresel TEM image of FGT showing skyrmions. (c) Reconstruction magnetic data. Here showing TIE reconstruction but other methods such as COM or ptychography would obtain a similar result. (d) Schematic of 4D-STEM experimental configuration.

Graphic:



Keywords:

Skyrmion, Ptychography, 4D-STEM, Fe3GeTe2, LTEM

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