TEM study of controlled localisation of skyrmion nucleation by focused ion beam irradiation

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A magnetic skyrmion is a topologically stabilised, particle-like swirl of magnetisation. They appear in systems with a Dzyaloshinskii-Moriya interaction (DMI) - this occurs when there is both a lack of inversion symmetry and strong spin-orbit coupling. Skyrmions have great potential for low energy spintronic devices owing to their small size, stability and high mobility under spin-polarised currents [1,2]. Recent research efforts have centred on finding a material system capable of nucleating individual skyrmions at room temperature and low magnetic fields with the aim of realising a skyrmion-based spintronic device.

One crucial step, necessary for realising such a device, lies in finding a reliable and controllable method of nucleating skyrmions. Several nucleation methods have been explored, namely current injection, field induced by SPM tip and laser induction. We report on a novel, controllable skyrmion nucleation method, utilising a Ga^+ focused ion beam (FIB) microscope to create nanoscale nucleation sites in 10×[Pt(1nm)|Co(0.6nm)|Ir(1nm)] multilayer stacks deposited on an amorphous carbon film. This material has strong perpendicular magnetic anisotropy. We have created point defects by using the ion beam to locally disrupt the physical structure of the layers and hence alter the magnetic properties (with similar methodology to [3] and [4], the latter explores extended FIB defects that nucleate Bloch skyrmions and anti-skyrmions in contrast to this work where point defects nucleate Néel skyrmions).

Figure 1 shows transmission electron microscope (TEM) Fresnel images taken at room temperature of the sample before and after FIB irradiation. The sample was tilted to 20° to generate contrast from the domain walls [5]. Image (a) shows the film, before FIB exposure, in a magnetic field of 350Oe corresponding to an almost demagnetized state. Image (b) shows the film after point defects were created with Ga^+ FIB (doses between 2×10^{16} and 2×10^{17} ions/cm^2) in the remnant field of the microscope (100Oe). The magnetic contrast visible in the film with defects is markedly different to that in (a), with single Néel skyrmion formation at most defect sites compared to random maze-like Néel wall formation in the unirradiated film. Defect sites with and without a skyrmion from image (b) are shown enlarged in images (c) and (d) respectively. Line traces from each are shown in (e) and reveal the skyrmion to be ~300nm in diameter and the defect, when uniformly magnetized, to be closer to 250nm in diameter. We will report on the skyrmion formation with ion dose and spatial extent of the defect. In addition to *in situ* field and temperature Fresnel TEM studies, we will provide quantitative induction maps acquired via STEM pixelated differential phase contrast (DPC) of the skyrmions with a resolution of 1nm [6]. Our experiments already show clear evidence of FIB induced property changes, however we also plan to further explore this from chemical and structural perspectives using STEM. Data acquired from the techniques of dual-range electron energy loss spectroscopy (DualEELS) and high angle annular dark field (HAADF) imaging will be used to analyse structural and compositional changes in a cross-section of the irradiated multilayer.

EU grant MAGicSky No. FET-Open-665095, ANR grant TOPSky and EPSRC grant EP/M024423/1 are acknowledged.

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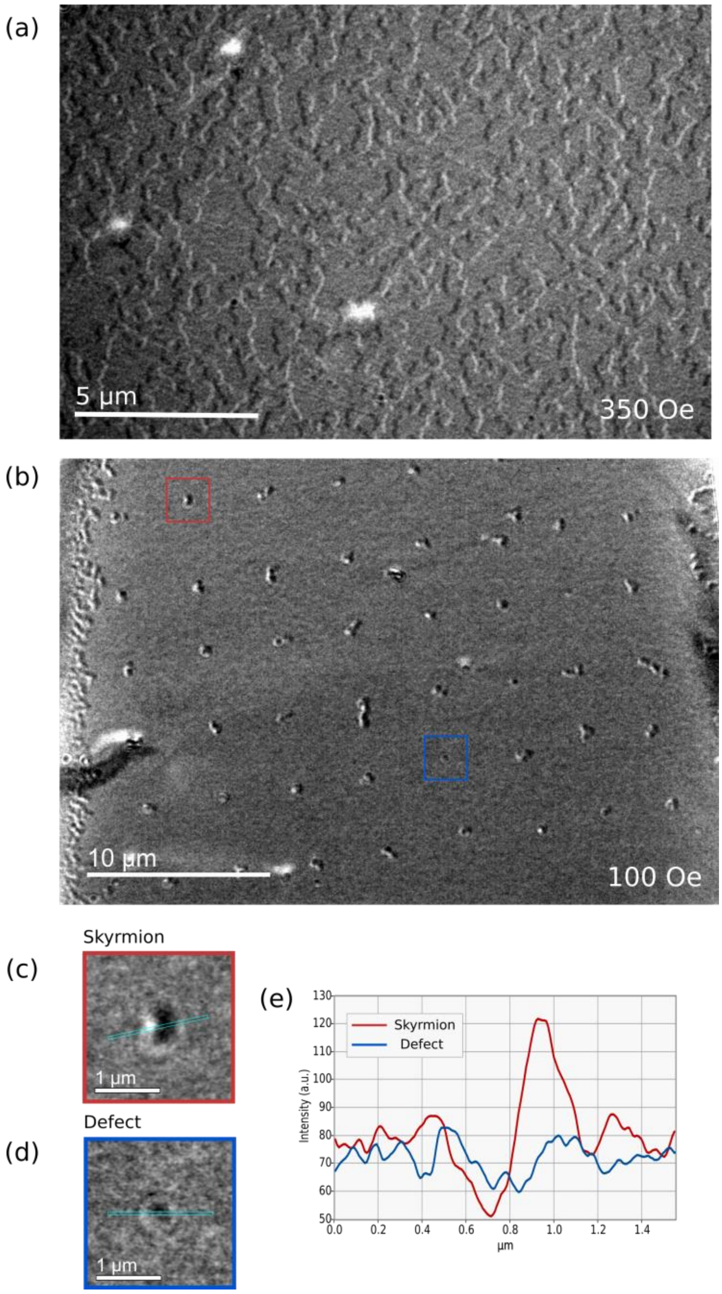

Figure 1: Images (a) and (b) are Fresnel (domain wall) images taken at room temperature on a JEOL 200F cold FEG microscope with a sample tilt of 20°. (a) shows the continuous film in an external field of 350Oe - notice the dense maze-like domain structure. (b) shows the film in the remnant field of the microscope (100Oe) after point defects were created with Ga+ ions using a FEI NOVA FIB-SEM system. At the defect sites there is favoured skyrmion formation at a much lower field than the complex domain wall structure generated in an unirradiated film seen in (a). (c) and (d) respectively show the Fresnel contrast from a defect site with and without a skyrmion. Line traces taken across these structures are shown in (e) to show the clear skyrmion contrast in relation to the non-magnetic phase contrast at the defect.