Lorentz TEM investigation of the switching behavior in artificial spin ice building blocks

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Frustration – the inability to simultaneously satisfy all interactions – occurs in a wide range of systems including neural networks, water ice and magnetic systems. An example of the latter is the so called spin-ice in pyrochlore materials [1] which have attracted a lot of interest not least due to the emergence of magnetic monopole defects when the 'ice rules' governing the local ordering breaks down [2]. However it is not possible to directly measure the frustrated property – the direction of the magnetic moments – in such spin ice systems with current experimental techniques. This problem can be solved by instead studying artificial spin-ice systems where the molecular magnetic moments are replaced by nanoscale ferromagnetic islands [3-8]. Two different arrangements of the ferromagnetic islands have been shown to exhibit spin ice behaviour: a square lattice maintaining four moments at each vertex [3,8] and the Kagome lattice which has only three moments per vertex but equivalent interactions between them [4-7]. Magnetic monopole defects have been observed in both types of lattices [7-8]. One of the challenges when studying these artificial spin-ice systems is that it is difficult to arrive at the fully demagnetised ground-state [6-8].

Here we present a study of the switching behaviour of building blocks of the Kagome lattice influenced by the termination of the lattice. Ferromagnetic islands of nominal size 1000 nm by 100 nm were fabricated in five island blocks using electron-beam lithography and lift-off techniques of evaporated 18 nm Permalloy ($Ni_{80}Fe_{20}$) films. Each block consists of a central island with four arms terminated by a different number and placement of 'injection pads', see Figure 1. The islands are single domain and magnetised along their long axis. The structures were grown on a 50 nm thick electron transparent silicon nitride membrane to allow TEM observation, which was back-coated with a 5 nm film of Au to prevent charge build-up during the TEM experiments.

To study the switching behaviour the sample was subjected to a magnetic field strong enough to magnetise all the blocks in one direction, see Figure 1. Each block obeys the Kagome lattice 'ice-rules' of "2-in, 1-out" or "1-in, 2-out" in this fully magnetised state. Fresnel mode Lorentz TEM images of the sample were then recorded as a magnetic field of increasing magnitude was applied in the opposite direction. While the Fresnel mode is normally used to image magnetic domain structures [9] for these types of samples it is possible to deduce the direction of the magnetisation from the Lorentz contrast [5]. All images were recorded at the same over-focus judged to give good Lorentz contrast.

The magnetisation was found to switch at different magnitudes of the applied field for nominally identical blocks. However, trends could still be identified: all the blocks with any injection pads, regardless of placement and number, switched the direction of the magnetisation of their central island at significantly smaller magnitudes of the applied magnetic field than the blocks without injection pads. It can therefore be concluded that the addition of an injection pad lowers the energy barrier to switching the connected island, acting as a nucleation site for monopole defects. In these five island blocks the defects immediately propagate through to the other side, but in a larger lattice the monopoles could potentially become trapped at a vertex and observed [10].

References

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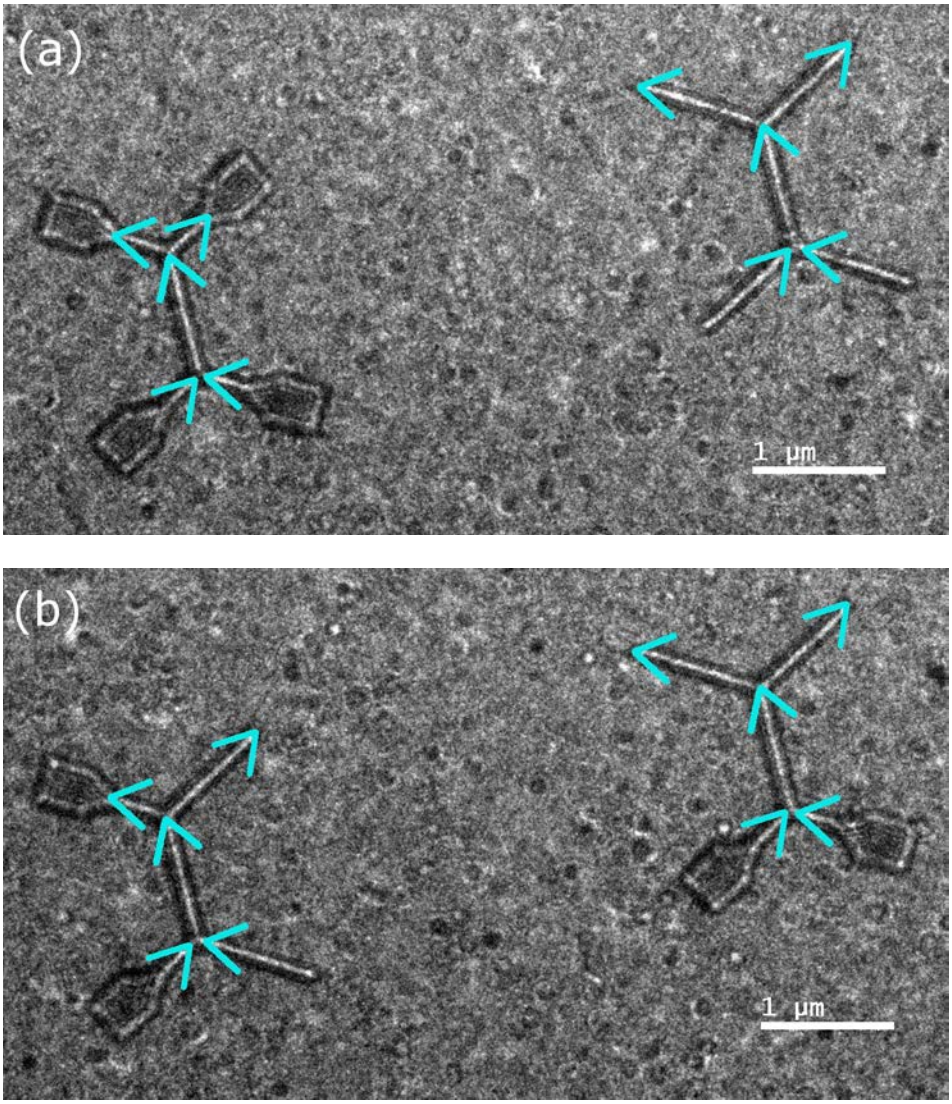

Figure 1. *Lorentz TEM image of a) the two extreme examples of different five-island artificial spin-ice building-blocks with injection pads on every branch (right) and with no injection pads (left) and b) the two examples of different five-island artificial spin-ice building-blocks with two injection pads all in the 'up' magnetized state. The arrows indicate the direction of the magnetization of each bar as determined from the Lorentz contrast. The scale bar is 1* μ*m long.*