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MAGNETIC CONFIGURATIONS AND MAGNETIC REVERSAL PROCESS IN ARTIFICIAL SPIN ICE STUDIED BY ELECTRON HOLOGRAPHY

Period	6 months beginning not later than March 2021
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This research master's degree research project could be followed by a PhD ☐ **NO**	

Abstract/work package/short bibliography/illustration

Lithographically patterned arrays of magnetic nanostructures, also called artificial spin ices (ASI), have been subject of numerous studies since their inception about 15 years ago as they provide a test bed to understand more complex frustrated physics and demonstrate properties idyllic for modern technologies.. These nano-objects have thus potential applications in magnetic memory, reconfigurable magnonics, and logic devices.

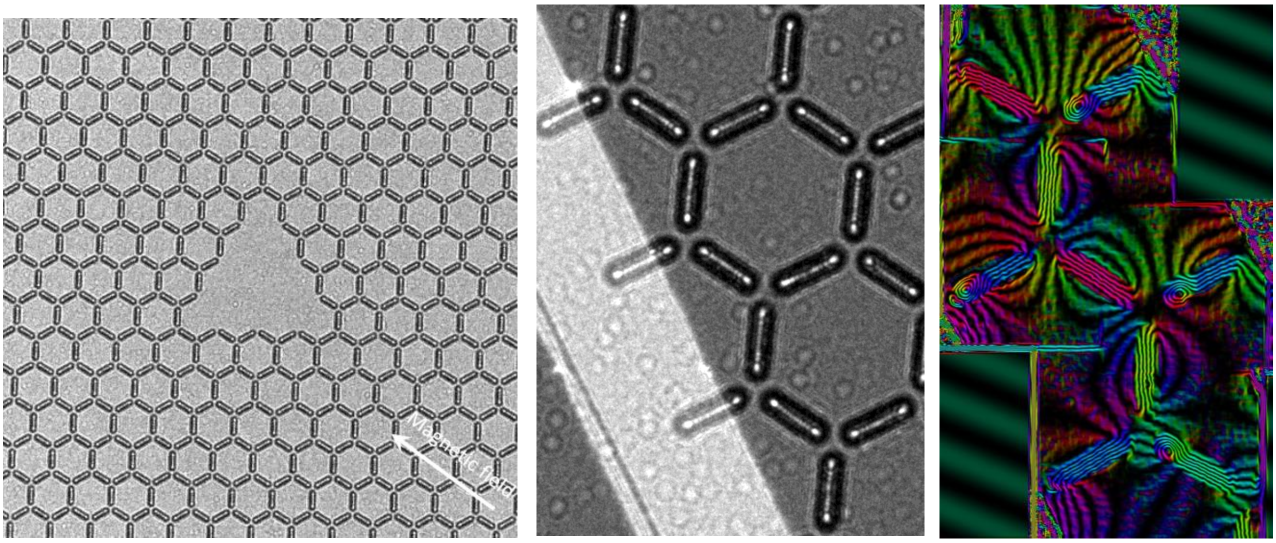
The amazing magnetic properties of the ASIs are related to the individual magnetic behaviour of each NI, this latter interacting with its closest neighbours. It is therefore essential to have a direct access to the local magnetic configuration. The internship aims thus to perform magnetic imaging on ASI using TEM related method for studying their local magnetic properties when an external magnetic field is applied.

ASI of interest for this internship are lithographically patterned arrays of disconnected Py nano-islands (NIs) of about 250 nm long displaying an in-plane magnetisation. Two patterns of hexagonal symmetry and pentagonal structure (Penrose structure) have been fabricated (see fig). Both are magnetically frustrated due to the pattern's intrinsic geometric ordering. From the designed shape anisotropy, the ferromagnetic NIs pattern are predicted to behave as all classical ASI, *i.e.* single domain aligning along the long axis of the structure and the frustration from the other NIs are intended to flip the magnetization in binary fashion such that the intrinsic energy of the array is at a local minimum. Electron Holography (EH) and Lorentz Electron Microscopy (LTEM) are two TEM-based techniques that allow for study of ferromagnetic nanostructures with a nanometre resolution at the remanence and during the *in-situ* magnetic reversal under applied magnetic field.

First EH and LTEM experiments have been performed on the hexagonal pattern and reveal interesting reversal processes depending on the applied field direction due to the frustration state and of defects intentionally grown on the patterns. These experiments have to be repeated on the same pattern and for various applied field directions and the whole set of recorded images has to be analysed to analyse in detail the reversal process to deduce the configuration of minima energy for each direction, determine the spatial magnetic distribution between the nano-islands in the pattern and identify the different interactions occurring at the frustrated vertices. Similar experiments and analyses will be carried out on the Penrose pattern on which even more complex magnetic configuration is expected.

Short bibliography

- Wang, R., Nisoli, C., Freitas, R. *et al.* Artificial 'spin ice' in a geometrically frustrated lattice of nanoscale ferromagnetic islands. *Nature* **439,** 303–306 (2006). https://doi.org/10.1038/nature04447
- de Paiva, T.S., Rodrigues, J.H., Mól, L.A.S. *et al.* Effects of magnetic monopoles charge on the cracking reversal processes in artificial square ices. *Sci Rep* **10,** 9959 (2020). https://doi.org/10.1038/s41598-020-66794-0
- S Lendinez and M B Jungfleisch 2019 *J. Phys.: Condens. Matter* **32** 013001, https://doi.org/10.1088/1361-648X/ab3e78



From left to right: TEM image showing the hexagonal ASI based on ferromagnetic Py disconnected nano-islands; LTEM image indicating the direction of the magnetization within few nano-islands; Phase image obtained by EH evidencing two frustration point.

Keywords, areas of expertise	Artificial spin ice, Electron holography, micromagnetic modelling
Required skills for the internship	Materials science, magnetism, physics