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Magnetic ring structures for Lorentz electron microscopy

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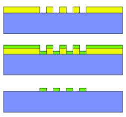
Introduction

Magnetic rings have well-defined, reproducible remanent states and simple switching processes, which is a requirement for industrial applications, e.g. for magnetic sensors and high density data storage. To fully understand the detailed magnetic behaviour of such rings, it is important to carry out direct observations of the magnetic spin structures.

We have employed transmission electron microscopy (TEM), where it is necessary to fabricate the ferromagnetic ring structures on membrane substrates. For the fabrication we employed electron beam lithography with lift-off, avoiding the use of ultrasound which would break the fragile membranes.

Sample Fabrication

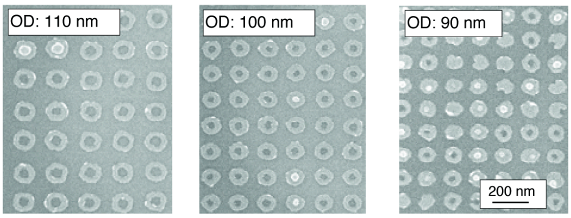
Electron beam lithography with lift-off



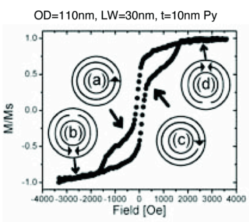
1. **Electron beam writing in polymer resist**
2. **Deposition of magnetic material in MBE chamber**
3. **Removal of resist & unwanted magnetic material in acetone**

Smallest rings achieved on silicon wafer substrates

SEM Images: *PMMA resist:* 25 nm
Ling material: Permalloy 10 nm / Gold 2 nm
Linewidth (LW): 30 nm
Outer diameters (OD): down to 90 nm



MOKE measurement:



In narrow rings there are two stable magnetic states;

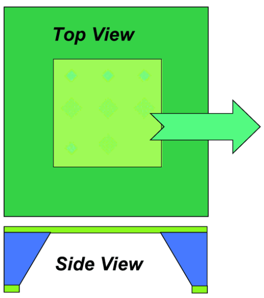
- *the flux-closure vortex state (a & c)*
- *the 'onion' state (b & d), with two opposite head-to-head domain walls*

Thus two transitions occur; at intermediate fields the rings switch from the onion to the vortex state and at high fields they switch from the vortex to the opposite onion state.

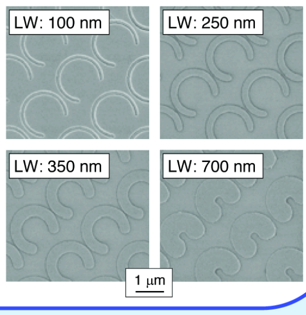
Three-quarter horseshoe ring structures on Si_3N_4 membranes

It was possible to fabricate 'incomplete' rings using a lift-off process without ultrasound. Here the ring centres are removed with the rest of the unwanted material.

Schematic of Si_3N_4 Membrane Substrate:

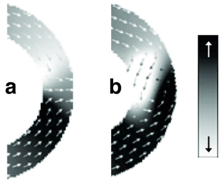


SEM Images ring structures. OD = 1.65 μm. Linewidth (LW) indicated.

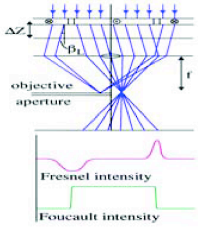


Transmission Electron Microscopy

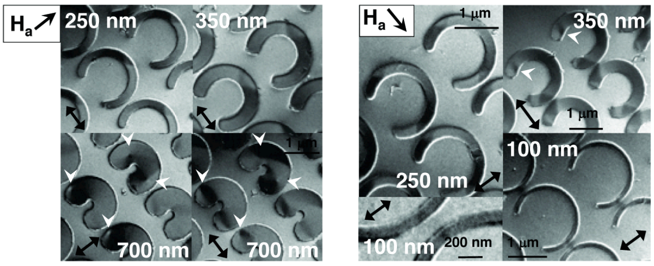
To obtain head-to-head walls, a magnetic field is applied to the sample using the objective lens field, which can be varied by changing the lens current or tilting the sample. These walls can either be transverse (a) or vortex walls (b), depending on the ring geometry.



Foucault Microscopy

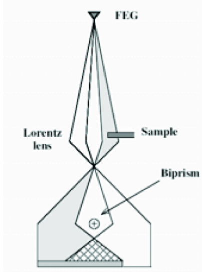


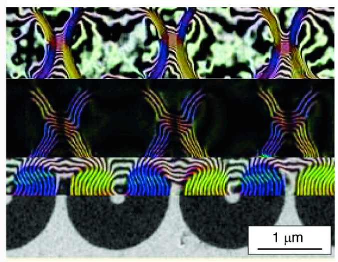
In the TEM, part of the diffraction pattern is blocked with the objective aperture and from the resulting contrast the direction of magnetisation can be qualitatively determined (double headed arrow below indicates "sensitivity direction"). We have observed both tranverse walls and vortices (indicated by white arrowheads below) in ferromagentic ring structures. Applying a magnetic field, H_a, in two orthogonal directions reveals the effect of stray field interactions on the domain wall configurations.



Electron Holography

Off-axis holography involves applying a voltage to an electron biprism resulting in the overlap of part of a coherent electron wave that has passed through a sample with the part that has passed vacuum only. Analysis of the resulting inrerference pattern allows the phase shift of the electron wave to be recovered and a quantitative map of the in-plane induction can be obtained. This provides a high spatial resolution information about the domain walls and interactions via their field.





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