Use of Aharonov-Bohm effect and chirality control in magnetic phase plates for transmission microscopy

C J Edgcombe\textsuperscript{1} and J C Loudon\textsuperscript{2}

\textsuperscript{1}TFM Group, Department of Physics, University of Cambridge, JJ Thomson Avenue, Cambridge CB3 0HE, UK

\textsuperscript{2}Department of Materials, University of Cambridge, Pembroke Street, Cambridge, CB2 3QZ, UK

E-mail: cje1@cam.ac.uk

Abstract. Initial holographic tests on thin rings of cobalt have demonstrated both onion (O) and vortex (V) states of magnetization, and show that the vortex state provides a uniform phase difference between inside and outside the ring as expected from the Aharonov-Bohm effect. Simple circular rings show a relatively small difference between the in-plane switching fields $O \rightarrow V$ and $V \rightarrow O$ and have unpredictable chirality (sense of flux rotation in the vortex mode). Simulations suggest that D-shaped rings provide both predictable chirality and a wider range between switching fields.

1. Introduction
In cryo- and other transmission electron microscopy of biological specimens, there is a need to minimise the electron dose by increasing the image contrast for given beam current. This can be achieved by use of a phase plate, designed to change by about 90 degrees the phase difference between scattered and direct electron waves. We propose to achieve the required phase change by use of the Aharonov-Bohm effect produced by a ring of magnetic flux set up in a thin magnetic ring inserted in the plane of the objective aperture. The ring dimensions are chosen so that scattered electrons pass outside the ring while direct electrons pass through it. For use in a microscope column, such rings would ideally be fabricated on a refractory support, but such fabrication is not discussed here.

2. Vortex and onion flux patterns observed in rings
Trial rings have been fabricated and tested by holography. Circular rings with ranges of diameters and widths were written by e-beam lithography on a silicon nitride membrane of thickness 50 nanometres, supported on a silicon frame [2]. The frame was approximately 2.9mm square so as to be suitable for insertion in an objective aperture holder. The rings were made by MBE deposition of 20 nanometres of cobalt on an adhesion layer of 10 nm of copper, followed by an anti-oxidation layer of 3 nanometres of gold, followed by lift-off. The sets of rings were magnetized by applying a field of $-400$ mT followed by one of $+124$ mT, both in-plane, and were then tested in a CM300 TEM equipped for holography. The first results shown here were obtained with no coating to minimize charging, and with no excitation of the objective lens. In further tests an anti-charging coating has been added.
Figure 1. (a)-(d) Ring of outer diameter 2 micrometres, width 200nm; (e)-(h) Ring of outer diameter 3 micrometres, width 100nm. (a),(e) hologram; (b),(f) cos(2*phase); (c),(g) unwrapped phase; (d),(h) phase profile over path in (c) or (g).

Figure 1(a)-(d) shows results from a ring of diameter 2 micrometers and width 200nm, located at the specimen position. There is a nearly uniform phase gradient across the interior of the ring in the direction sampled, together with divergence of flux from two points on the circumference of the ring. This is the behaviour expected from a ring magnetized in the ‘onion’ mode. In contrast, figure 1(e)-(h) shows results obtained from a ring of diameter 3 micrometres and width 100nm. It is clear that the phase inside the second ring is approximately uniform and that there is a difference of phase between inside and outside the ring of about 3.7 radians. The uniformity of phase within the ring shows that it was magnetized in the vortex mode and that relative to a direct beam passing through the ring, scattered waves will be changed in phase uniformly at all azimuthal angles around the beam.

Figure 2. Switching fields as functions of ring width for circular cobalt ring of outer diameter 1 micrometre and thickness 20nm.
Simulations of the magnetic behavior using the OOMMF package [3] show why a single magnetizing field produced different magnetic states in the two rings. Figure 2 shows values for the switching fields, onion to vortex (O→V) and vortex to onion (V→O), found by simulation of circular cobalt rings. The field of 124mT used to magnetize the rings in Figure 1 was chosen to switch a ring of width 100 nm into the vortex state, while the same field applied to the ring of width 200 nm appears to have switched it through the vortex and into the onion state. The variation of the switching fields with ring diameter is small.

According to simulation, the vortex state in rings with width greater than their thickness should tolerate an out-of-plane field of 1T or more from the objective lens. Work is in progress to determine the experimental relation between ring dimensions, magnetization, $M_s$, resulting phase shift, and the out-of-plane field (from the objective lens) that these rings can tolerate.

3. Disadvantages of circular rings

Figure 2 shows that for a given width of ring, the switching fields differ by about 40 mT over the range of width simulated. In the simulations, a fixed anisotropy file was used with cells set to random directions. Crystalline anisotropy then had little effect in the simulations, but the polycrystalline deposition used in practice may produce larger grains and so may cause some variability of switching fields. Thus it is desirable to extend the range between switching fields if possible. Also, when circular rings are magnetized in vortex mode, the chirality, or sense of flux circulation, is liable to be set at random by thermal effects [4]. This happens because switching from onion to vortex state proceeds by movement of one domain wall around half the ring. Motion in either direction is possible, and in each instance behaviour depends on any slight asymmetry of crystal anisotropy or the initial location of the domain wall in the ring, relative to the applied field. Thus when circular rings are magnetized, the resulting chirality is unpredictable.

4. Behaviour of modified rings

The behaviour of circular rings suggested that if their shapes were modified so that the two possible paths for a domain wall differed geometrically, this might help to ensure that the wall followed one particular path on switching from onion to vortex. Simulations were therefore carried out on rings with the general form of a semicircle joined to its diameter, as shown in figure 3. The tests showed that a variation in width at these junctions could cause the domain walls to be pinned there more precisely than in purely circular rings, and that the difference in paths ensures that the domain wall always moves along the same path. Then, with a switching field of given sense, the vortex mode in a particular ring is always created with the same chirality. In addition, the size of the O→V switching field is strongly influenced by the detailed shape of the junctions. Unexpectedly, a restriction in width
there can cause the domain wall to start moving at a lower field than for a uniform width of wall. The upper switching field (V→O) varies much less with the shape of the ring.

The switching fields found for the shape with a 45 degree chamfer in figure 3 are shown in figure 4. It can be seen that the range between the two switching fields is very much greater than that found for circular rings in figure 2, thereby giving more tolerance of effects of crystal anisotropy and of possible variations in fabrication.

![Figure 4. Switching fields as functions of ring width for chamfered semi-circular Co ring of outside radius 0.5 micrometre and thickness 20nm.](image)

5. Summary
Initial holographic tests on thin rings of cobalt have demonstrated both onion and vortex states of magnetization, and show that the vortex state provides a uniform phase difference between inside and outside the ring as expected from the Aharonov-Bohm effect. Simple circular rings show a limited range between the in-plane switching fields O→V and V→O and are unpredictable as to chirality. Simulation suggests that D-shaped rings can provide both control of chirality and a wider range between switching fields.

Acknowledgments
The authors thank Arthur Blackburn (Hitachi Lab, Cambridge), Adrian Ionescu and Theo Trypiniotis for e-beam lithography, MBE deposition and magnetization.

References
[1] Edgcombe C J 2009 Electron Microscopy and Analysis Group Conf. (Sheffield) Journal of Physics: Conf. Series 241 ed R T Baker (Bristol: IoP Publishing) p 012005
[2] Silson Ltd, [http://www.silson.com](http://www.silson.com)
[3] Donahue M J and Porter D G 1999 OOMMF User's Guide, Version 1.0 National Institute of Standards and Technology Interagency Report NISTIR 6376 (Gaithersburg, MD: NIST); [http://math.nist.gov/oommf](http://math.nist.gov/oommf)
[4] Hayward T J, Moore T A, Tse D H Y, Bland J A C, Castano F J and Ross C A 2005 Phys. Rev. B 72, 184430.