Progress in probing magnetic information at the atomic scale using dynamic electron vortices in a TEM

A. Béché*, R. Van Boxem, L. Clark, G. Guzzinati, R. Juchtmans, G. Van Tendeloo and J. Verbeeck

EMAT, University of Antwerp, Groenenborgerlaan 171, 2020 Antwerp, Belgium

*armand.beche@uantwerp.be; Phone : +32 32 65 34 72

1. INTRODUCTION

In a transmission electron microscope (TEM), materials are probed by electron plane waves, but alternative beams are possible and especially cylindrical harmonics are an interesting option. Here, the plane waves are replaced by waves with an azimuthal phase factor $\exp(im\varphi)$, φ being the angle in the plane perpendicular to the optical axis and m the so-called topological charge. Such waves also referred to as vortex waves, carry an orbital angular momentum (OAM) $m\hbar$ as well as a quantized magnetic moment $m\mu_B$ due to the electron charge [1]. Electron vortex beams have been successfully applied to rotate nanoparticles [2] and characterize chiral crystals [3].

2. RESULTS

2.1 Creating efficient vortex beams

The magnetic field generated at the tip of a long ferromagnetic rod resembles the one of a perfect magnetic monopole and can be used to create efficient electron vortex beams [4]. Such a rod was realized in a Focused Ion Beam (FIB) microscope which offers the sufficient spatial precision and resolution to accurately shape the magnetic material to the required dimensions. Indeed, obtaining electron vortex beams with very high OAM purity requires a parallel sided rod of a few tens of microns long and only a few hundred nanometers wide, as displayed in Figure 1.

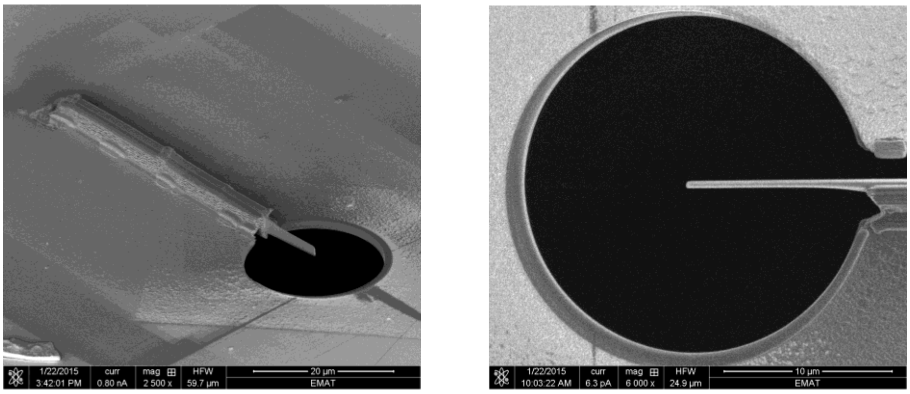

Figure 1. SEM pictures of the magnetic rod with one end suspended over a round 20 μm aperture.

2.2 Exhaustive vortex characterization

In order to reach the desired OAM value, the phase of the electron wave generated at the tip of the magnetic rod was investigated using electron holography. Utilising a step by step approach where the rod width was sequentially reduced in the FIB and the phase at its tip checked by holography, it was possible to create an aperture with a total OAM m=1, as displayed in Figure 2a.

The efficiency of the magnetic rod as vortex generator depends on the existence of a single magnetic domain over its full length, most likely to exist due to the high aspect ratio of the rod. Holograms were acquired along the visible part of the rod to check for the absence of return flux. The far field image of the vortex aperture was then recorded in a through focus series. As expected for a vortex, a typical doughnut-like beam shape is recorded (Figure 2b). Upon focusing, the central dark part of the beam, issued from the destructive interference of all the phases, never disappears. As an extra proof of the presence of the phase vortex, the centre of a defocused probe was cut with the sharp edge of a selected area aperture. The π phase expected for a vortex of OAM=1 cut in two results in an extra Fresnel fringe forking from the core of the vortex beam, as displayed in Figure 2c.

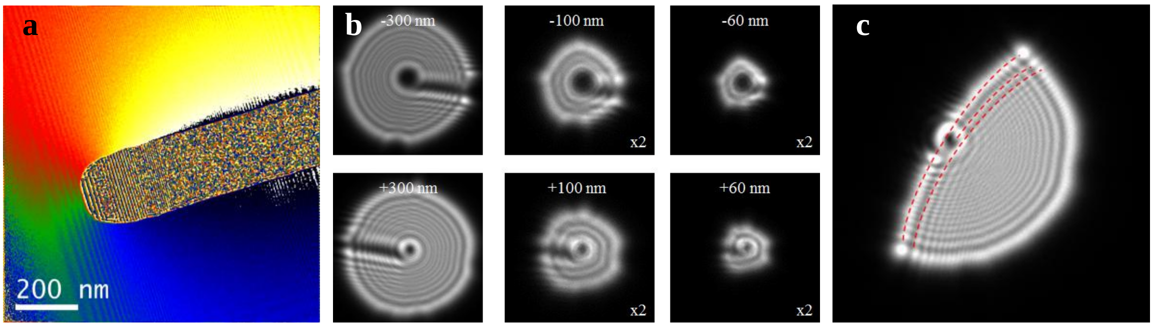

Figure 2. (a) Reconstructed phase map around the tip of the magnetic rod. (b) Through focus series of the vortex aperture's far field image. (c) Defocused vortex probe cut with the sharp edge of a selected area aperture.

2.3 Crossing the dynamic boundary

Different strategies have been applied to create a vortex beam whose OAM can be modified in-situ. The most reliable one consists of surrounding a vortex aperture based on a magnetic rod with a solenoid. When a sufficient current is applied on the solenoid, the magnetic domain of the magnetic rod switches sense, generating a vortex of opposite handedness (Figure 3a and 3b). Atomically resolved STEM images can then be acquired with such vortex probes, presenting only a small shift upon OAM flipping.

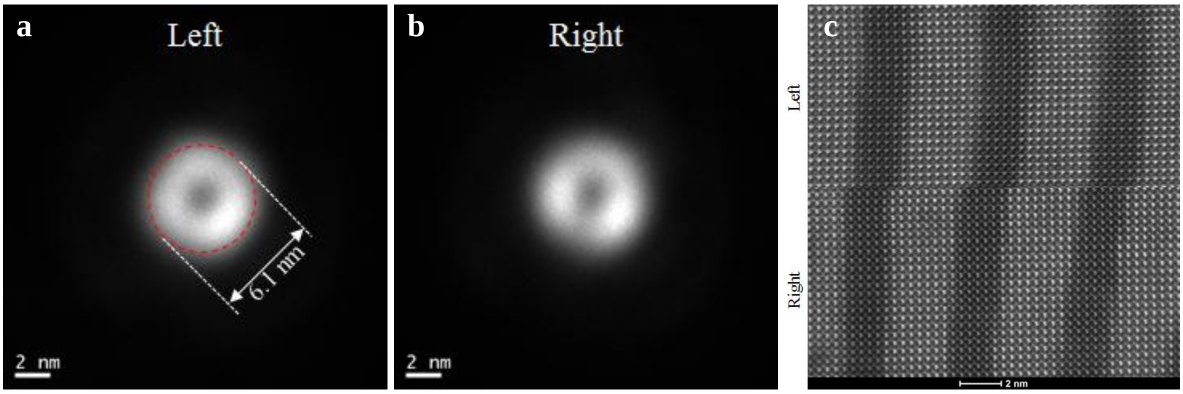

Figure 3. (a) Left vortex probe in TEM mode and (b) corresponding right probe. (c) Single High Resolution STEM image acquired with a left (top) and right (bottom) vortex probe.

3. CONCLUSION

Reaching atomic resolution with dynamic electron vortex probes is now possible thanks to magnetic rod based apertures surrounded by a small solenoid. The interaction of such an electron beam with magnetic samples will be discussed. Special attention is paid to the atomic resolution magnetic dependence of the EELS, linked to electron magnetic chiral dichroism (EMCD).

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