Measurement of the magnetic induction: off-axis electron holography compared to 4D-STEM COM technique

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Recent developments in Transmission Electron Microscopy (TEM) allow for the quantitative imaging of magnetic induction with nanometer spatial resolution and very high sensitivity. In this work, state-of-the-art developments for off-axis electron holography and 4D-STEM are used to measure the magnetic induction of a ferromagnetic Fe80Ni20 nanowire of 60 nm diameter. Both methods will be described, then a comparison of the quantitative measurements will be discussed.

Phase images measured by off-axis electron holography contain two main contributions, φ^E sensitive to the electrostatic potential and φ^M sensitive to the magnetic vector potential projected on the electron propagation direction. Thus the imaging of the in-plane components of electrostatic or magnetic fields are obtained by a simple derivative of the phase images. Recently, the development of Scanning Transmission Electron Microscopy (STEM) imaging using a pixelated detector allows to record the diffraction pattern from each point of the scan, to obtain a 4D-STEM dataset. As the electron beam is deflected by electric or magnetic fields perpendicular to the electron propagation direction, one can quantify these fields for each point of the STEM map by analyzing the center-of-mass (COM) displacement of the transmitted beam of each diffraction pattern [1]. This technique can be viewed as an evolution of the standard Differential Phase Contract (DPC) imaging, performed with a pixelated detector for more accuracy.

The imaging of magnetic samples generally requires a field-free environment of the sample. Thus, experiments were performed in an imaging-corrected Lorentz configuration of the TEM for holography, and in a particular probe-corrected low-mag STEM configuration with the objective lens switched off [2] for 4D-STEM, with a probe size of 210 rad. Experiments were performed on FEI Titan microscopes, at 200 kV acceleration voltage. For electron holography, the separation of both electrostatic and magnetic contributions of the sample is usually performed by acquiring two datasets, before and after inverting the sample in the sample-holder of the microscope [3] (see Figure 1). We show that this method can be extended to the 4D-STEM COM technique, in order to image both magnetic and electrostatic fields independently.

The holography measurement uses a summation technique [4] to improve drastically the phase sensitivity. We show a phase sensitivity of 2π/1250 rad for the magnetic fringing field of the nanowire, with a 3.5 nm spatial resolution. The magnetic field is thus obtained with a sensitivity of 0.4 T.nm in Figure 2, and an induction of 0.9 T is measured in the wire. The 4D-STEM dataset needs a calibration of diffraction images and of the relative rotation between the STEM scan and the diffraction pattern. Then we show a COM reconstruction with a deflection sensitivity of 12 nrad, with 15 nm spatial resolution. It corresponds to a magnetic field sensitivity of 0.02 T.nm in Figure 2.

Acknowledgements:

This work was supported by the ERC Starting Grant ID 306535 Holoview.

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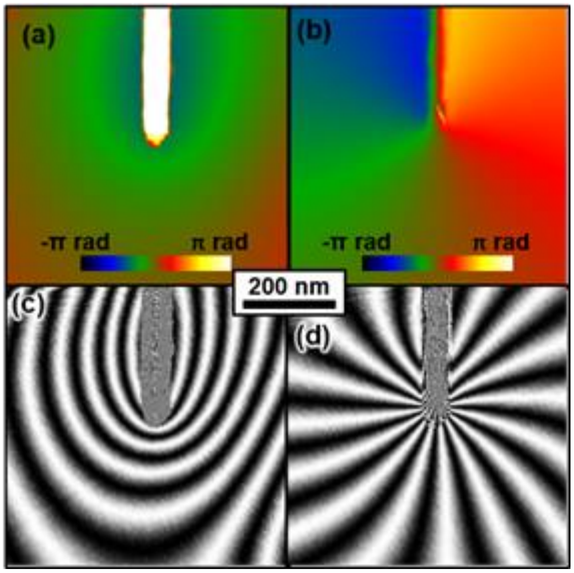

Figure 1: (a) Electrostatic phase and (b) magnetic phase images of a FeNi nanowire measured by off-axis electron holography. (c) depicts the electrostatic field and (d) the magnetic field lines, by taking the cosine of the phase images amplified by a factor 30.

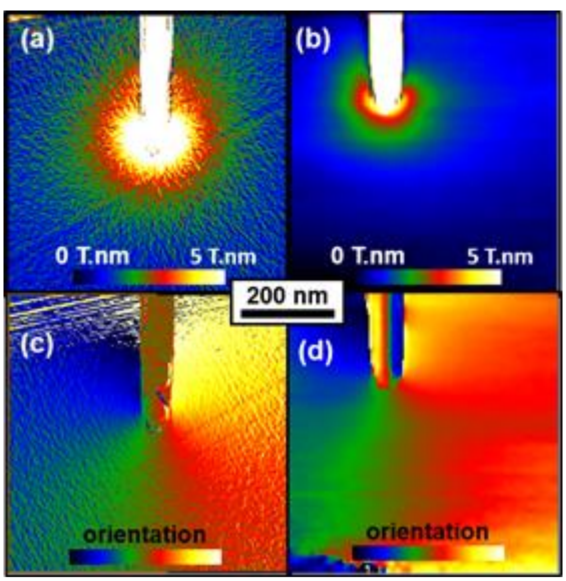

Figure 2: (a) and (b) show the magnitude of the in-plane magnetic induction over the electron path measured respectively by electron holography and 4D-STEM COM techniques. (c) and (d) are the orientation maps of the magnetic induction measured respectively by electron holography and 4D-STEM COM techniques.