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Soft X-ray Ptychography for Imaging of Magnetic Domains and Skyrmions in Sub-100 nm Scales.

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The size of magnetic features in modern materials, i.e. magnetic domain walls, vortices or skyrmions, can be at length scales below 100 nm. Imaging them requires methods with advanced resolution capabilities like ptychography, a combination of diffraction imaging and scanning transmission microscopy. Ptychography can achieve potentially wavelength limited resolution [1] over extended sample areas using an iterative reconstruction algorithm which provides phase and amplitude information. Resonant X-ray ptychography for imaging of magnetic domains using hard [2] and soft X-rays [3] has shown significant improvement of resolution in comparison with conventional X-ray imaging techniques. The goal of this work was to understand limitations and advantages of ptychography for imaging of magnetic materials by studying domain labyrinth and skyrmion samples, with special focus on comparing the results of ptychographic imaging with classical STXM.

Ptychography and STXM measurements were performed at MAXYMUS beamline UE46 at BESSY II synchrotron (Berlin, Germany). The samples were illuminated with a zone plate with 100 nm outer zone width, which provided the best results when scanned with the step size of 100 nm. The central X-ray spot provides about 50% of overlap between neighboring exposures with additional contribution from the side lobes of illumination profile but at variable intensity levels. A CCD camera was placed 8 cm downstream of the sample, resulting in around 11 nm output pixel size at Fe L_3 absorption edge (708,4 eV) and 10 nm at Co L_3 edge (781.4 eV). Each scanning point was exposed for 200 ms, stacking about 100 images, to ensure sufficient dynamic range. The reconstructions of phase and amplitude components were done using SHARP ptychography package [4], while for classic STXM images were generated with an FZP with 18 nm outer most zone width for a resolution of about 22 nm.

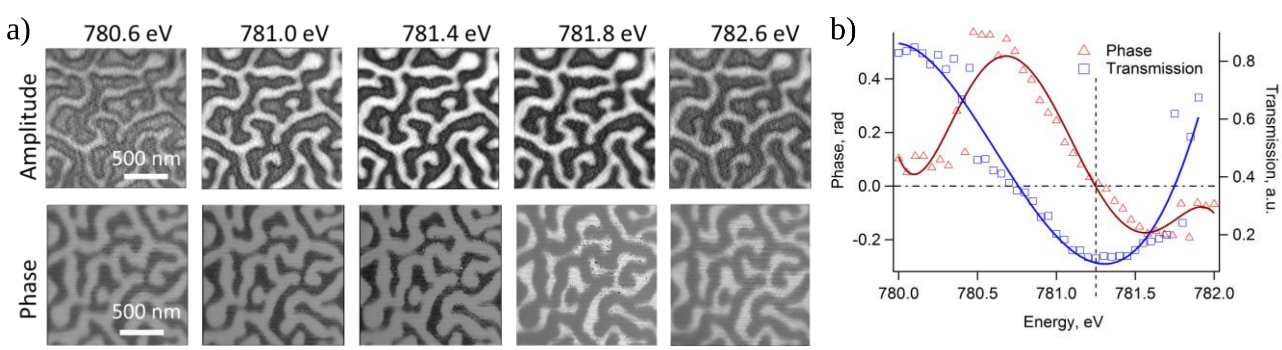

Figure. 1. Phase and amplitude data obtained by ptychography using left circular polarized X-ray light as a function of energy across Co L_3 edge: a) corresponding images; b) phase and amplitude contrast for the same domain area obtained from the presented image set.

To image domain structures a Ta(3nm)/Pd(3nm)/[Co(0.5nm)Pd(0.8nm)]30/Pd(1.2nm) multilayer sample, which features labyrinth domain structures with 100 nm width, was scanned around the Co L_3-edge. Fig. 1 a) shows the results of ptychographic reconstructions depending on X-ray energy. The magnetic contrast of the amplitude images has a maximum directly on the peak of the L_3 edge, while phase contrast images demonstrate contrast reversal right around the absorption peak. The corresponding contrast values are shown in Fig. 1 b), obtained from the same domain. The curves are proportional to the real and imaginary parts f'_m and f''_m of magnetization depended scattering factor and correspond to δ_m and β_m of the optical constants for magnetically saturated Co. Fourier ring correlation (FRC) of ptychographic images showed 17 nm resolution using 1/7 threshold.

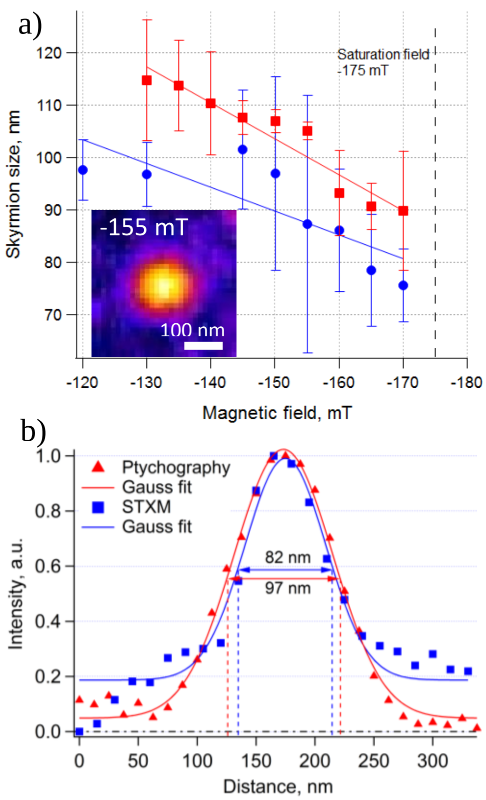

Figure. 2. Skyrmion sizes a) in dependence on applied OOP magnetic field imaged by STXM (blue line ●) and ptychography (red line ■). On the left: skyrmion image obtained by ptychography; b) line profiles of skyrmions at -170 mT field with estimated FWHM.

Skyrmion imaging was performed on Ta(5nm)/[CoFeB(1.2nm)/MgO(2nm)/Ta(3nm)]15 multilayer samples, which show sub-100 nm sized skyrmions at room temperature stabilized by applying an external out-of-plane magnetic field. The sample was saturated at the magnetic field of 175 mT. Reducing the field first creates a stripe domain state, which is biased towards the domains with magnetization aligned with the external field. With sufficient negative bias field, the remnants of the domains in positive directions shrink till they reach skyrmion state. Imaging the domain state with ptychography gave higher resolution than STXM, with about 1.5 lower domain wall width. However ptychographic contrast drops when approaching skyrmion state due to reduced scattering. Fig. 2 a) shows skyrmion size decreasing with increasing of absolute value of applied OOP magnetic field, down to 80-90 nm size (Fig. 2 b) at magnetic fields close to saturation value opposite the original magnetization sate.

The work presents the first use of ptychography for skyrmion imaging, with results in good agreement with direct STXM, showing skyrmion sizes down to around 80 nm. Observation of domain walls resulted in a noticeably higher resolution using ptychography, which considering the early state of the method shows the promise of future breakthroughs in magnetic imaging. Ptychography showed certain advantages as a research instrument due to suitability for extended area imaging, fast scanning and possibility for phase sensitive pre-resonance imaging of optically dense specimens. Additionally obtained phase information allows direct estimation of magnetic scattering factors of studied materials.

References:

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