Electron Ptychography and Aberration-Corrected 4D-STEM for Magnetic Imaging

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Meeting-report

Electron Ptychography and Aberration-Corrected 4D-STEM for Magnetic Imaging

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The discovery of non-trivial topological textures, including flux-closure, vortices, skyrmions, merons and hopfion in ferromagnetic systems have required electron microscopy to resolve their internal structures. A major obstacle for microscopy however has been the decoupling of specimen tilt, dynamical diffraction and channeling artifacts from the desired magnetic dipole signal. 4D-STEM and electron ptychography providing a more diverse range of input signals, increasing the options for recognizing and resolving these phenomena. Key to all these measurements is a high-speed, high-dynamic-range pixelated detector. Our latest detector design, the EMPAD-G2, allows us to measure a full diffraction pattern with over 4 nA in the incident beam, resulting in high signal-to-noise diffraction patterns recorded at rate of 10,000 frames/second. This makes it possible to record small maps at live/almost live speeds [1].

Differential phase contrast (DPC) imaging in Lorentz scanning TEM (LSTEM) is a simple and direct method for imaging magnetic domain, and has been used, on and off, since the 1970s. It uses a focused probe and can potentially reach atomic resolution. It measures the beam deflection angle, or equivalently the gradient of the phase shift, from the local magnetic induction field in the sample. This is straightforward for interpretation and quantification. However, the lack of low-noise, high dynamic-range detectors made DPC for magnetic imaging less widely adopted than LTEM. The situation is changing now, with the new generation of fast pixelated detectors. Here, using an EMPAD, we show that ultrahigh angular precision, ~ 0.1 μrad, can be achieved (Figure 1). As a demonstration, we imaged magnetic domain structures in embedded cobalt films where the magnetic layers was only ~4 atoms thick (Figure 1B). The signal sensitivity should be sufficient to image magnetic monolayers.

Separating slowly-varying from rapidly varying spatial signals by proper choice of collection angles on the detector can help to select the slowly-varying ferromagnetic signal from rapidly-varying electrostatic grain boundary contrast – imaging of chiral grains and the associated change of skyrmion handedness across chiral twin boundaries in FeGe is a good example [2].

Lorentz electron ptychography (LEP) enable high-resolution, high-sensitivity magnetic field imaging for widely available electron microscopes with the addition of a direct-electron detector. The resolution of Lorentz electron ptychography is not set by the diffraction limit of the lens optics, but instead is determined by the maximum scattering angle at which a statistically meaningful dose can still be recorded—this can be a two to six-fold improvement depending on the allowable dose. Using FeGe as the model system, we realize a more accurate magnetic field measurement of skyrmions with an improved spatial resolution and sensitivity by also correcting the probe-damping effect from the imaging optics via Lorentz electron ptychography. Figure 2A shows high-precision measurements of the internal structure of an FeGe magnetic skyrmion measured at 100K. LEP allowed us to directly resolve subtle internal structures of magnetic skyrmions near the skyrmion cores, boundaries, and dislocations in an FeGe single crystal [3].

Figure 2B shows a position-averaged CBED pattern from our aberration-corrected, field-free Lorentz STEM mode on our Spectra 300 CFEG. This suggests 3-4Å resolution is possible in DPC mode, and 1 Å should be possible by LEP, with usable phase information in the dark field region (Figure 2C). This instrument is available to external users through the paradigm.org MIP national facility [4].

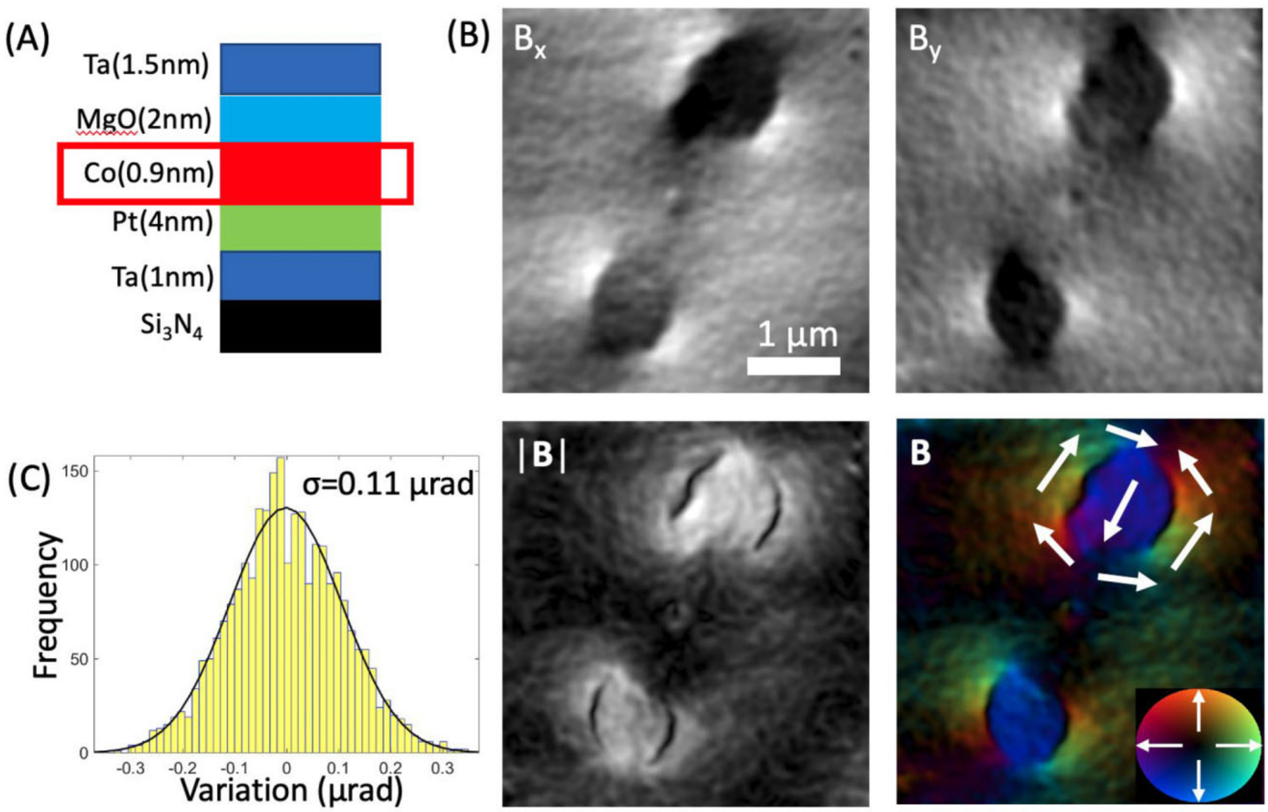

Fig. 1. Prospects for imaging single-atomic layer magnets: Lorentz-STEM imaging of (A) a 4-atom-thick Co layer embedded in a strongly-scattering, heavy-metal stack on a silicon nitride support. (B) CoM imaging of the magnetic induction field in the sample after tilting to 20° to detect the Néel-type Magnetic bubbles. (C) scatter in the magnetic signal from a uniform part of the sample showing a standard deviation of 0.11 μrad on the deflection signal, more than sufficient for detecting single-layer magnetism.

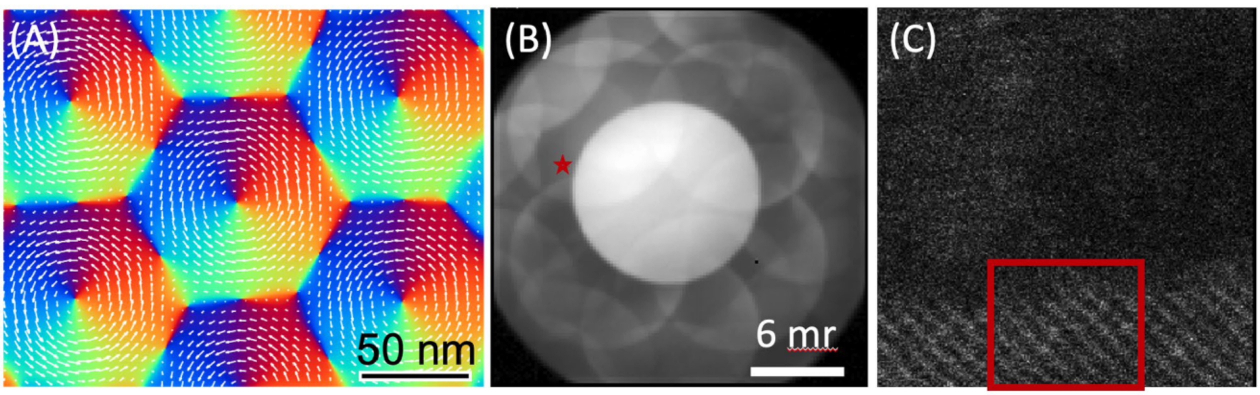

Fig. 2. (A) Electron ptychography of Bloch Skyrmions in FeGe, imaged at 100 K in uncorrected Lorentz STEM mode. (B) PACBED pattern of $SrTiO_3$ from 4D-STEM in corrected Lorentz mode with a 6 mrad aperture, showing rich overlap contrast out to 10 mrad, suggesting ptychographic reconstructions to 1 Å resolution should be possible in this field-free mode. (C) Dark-field contrast from the red starred pixel in (B) showing overlap contrast needed for reconstruction. The red box shows PACBED location.

References

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