Imaging Nanomagnetism with Interference and Spins of Electrons

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Meeting-report

Imaging Nanomagnetism with Interference and Spins of Electrons

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Magnetism and spintronics play increasingly significant roles in modern technologies such as data storage and logic devices, sensors, quantum computing, and transportation and electricity generation. The nanoscale spin texture within magnetic materials plays a large role in the behavior of these technologies, and also provides a rich area of fundamental study. Much of this development has been enabled by electron, x-ray, and scanning probe microscopies adapted to measure nanomagnetism, yet each technique has strengths and limitations. Lorentz TEM, for example, projects images of the average magnetic field inside a specimen while exposing it to an external field or temperature, but it is insensitive to the field component along the beam path. Limitations can be overcome by using more than one technique. Here we discuss the use of specialized electron microscopies, STEM holography and scanning electron microscopy with polarization analysis (SEMPA), to understand the 3D structure of nanomagnetic spin textures such as skyrmions.

STEM holography [1,2] is an interferometric 4D-STEM technique where electrons in the beam are coherently divided into a superposition of two or more separate probes and then scanned over the specimen. If one probe passes through vacuum while the other transmits through the specimen, the resulting phase shift can be measured by recording the interference pattern formed in the far-field at the detector. That is, the bright field discs of the two probes overlap at the detector, forming interference fringes (Fig. 1). Unlike defocus- and deflection-based magnetic imaging techniques such as Lorentz TEM or DPC which are sensitive to phase gradients within the specimen, STEM holography is directly sensitive to the phase relative to the reference beam. With this, STEM holography can be used to directly measure the component of the magnetic vector potential parallel to the beam.

SEM with polarization analysis (SEMPA) [3] is a surface-sensitive technique that can image all three vector components of the surface magnetization. Special detectors can measure the average spin polarization of secondary electrons. Each detector returns information about two components of the magnetization vector; one returns in-plane (Mx and My) and the other returns one in-plane (Mx) and the out-of-plane component (Mz). Therefore, two consecutive scans provides complete, quantitative imaging of the in-plane and out-of-plane magnetic nanostructure as well as normal SE contrast.

We combine both techniques on the same Fe/Gd multilayer material to understand the 3D structure of magnetic skyrmions. STEM holography and Lorentz TEM provide images of the skyrmion magnetic field projected through the thickness of the specimen, and SEMPA provides images of the magnetization at the surface. We find that whereas crystalline specimens can host magnetic skyrmions with whorl-like magnetic fields that extend uniformly through the thickness of the material, here we observe a more intricate magnetic structure. TEM indicates that in the bulk of the material, the magnetic flux wraps around the core like a vortex, yet SEMPA indicates that near the surface the magnetic flux points radially [4], such that the 3D structure is akin to that of a vortex ring. The behavior of these magnetic features under applied currents and fields is influenced by such 3D structure, so multimodal magnetic microscopy can inform technology development of magnetic skyrmions [5].

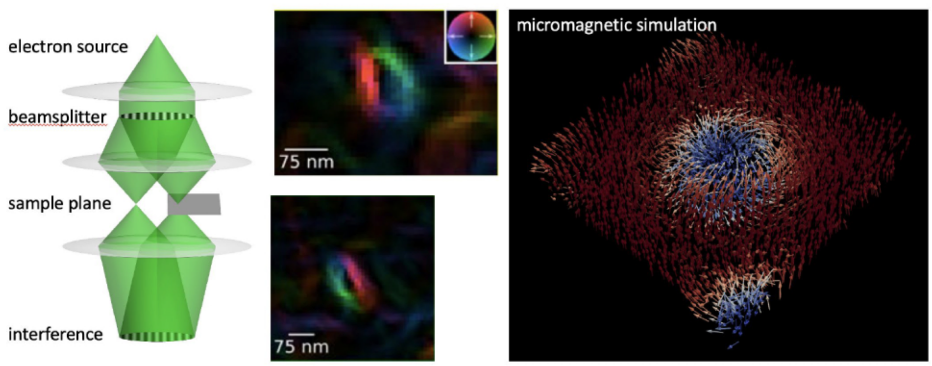

Fig. 1. (Left) Schematic of STEM holography optical setup in which one electron probe transmitting through the sample and a reference probe passing through vacuum interfere at the detector. (Upper right) Images of the in-plane magnetization in a Fe/Gd multilayer thin film. Images are derived from direct phase images using STEM holography. A color wheel inset describes how the magnetic direction is encoded in color. In both cases shown, the magnetic field wraps azimuthally around the core of the feature – a Bloch-type magnetic wall. (Lower right) A micromagnetic simulation of the material illustrates the 3D structure of skyrmions, with azimuthally pointing (Bloch-type) magnetization at the center of the material and radially pointing magnetization (Neél-type) at the top and bottom surfaces.

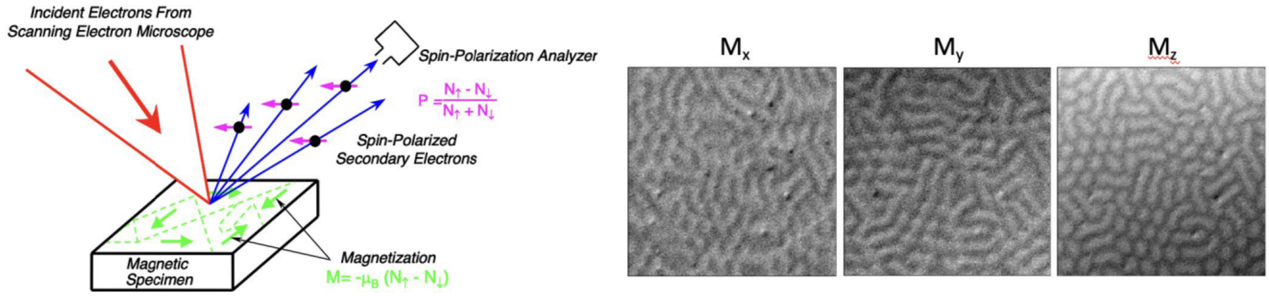

Fig. 2. (Left) Schematic of SEMPA in which the spin polarization of secondary electrons is measured by an analyzer. (Right) Images of the three vector components of the magnetization at the surface of an Fe/Gd multilayer (2.2 micron field of view). Magnetization at the surface of the material points radially.

References

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