3D Reconstruction of Magnetic Textures in Nanomagnets by Electron Holographic Tomography

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Magnetic nanostructures display a large variety of three-dimensional (3D) inhomogeneous spin textures depending on the imposed geometric boundary conditions. For example, magnetic nanowires (NWs) have attracted intensive investigations because of their potential use as domain wall (DW) conduits for memory and sensing applications [1]. The fundamental understanding of nanomagnetism requires quantitative magnetization mapping techniques resolving textures down to the nanometer scale in 3D.

Here we report on the tomographic reconstruction of the all Cartesian components of the magnetic induction by a combination of off-axis electron holography (EH) and dual tilt-axis tomography in the transmission electron microscope (TEM). Here, the former allows to reconstruct projections of magnetic flux densities and the latter facilitates the reconstruction of the 3D distribution of the Cartesian component parallel to the respective tilt axis from a tilt series of projections. In the straight forward approach, each phase image in the tilt series around x (and y) is differentiated in a direction perpendicular to the tilt axis, and standard tomographic reconstruction algorithms are employed to calculate the 3D distribution of B_x (and B_y). The third component B_z is evaluated by numerically integrating div $\boldsymbol{B} = 0$. To further reduce the reconstruction error we also discuss a simultaneous reconstruction algorithm of all $\boldsymbol{B}$-field components based on the relation between the magnetic four-potential and the electron wave's phase shift.

Going one step further, we discuss strategies to retrieve the 3D magnetization distribution $\boldsymbol{M}$ from the reconstructed 3D magnetic flux density by means of scalar potential micromagnetics. That is we separately reconstruct the solenoidal part of $\boldsymbol{M}$ from $\boldsymbol{B}$, wheras the conservative part is obtained by minimizing the micromagnetic free energy.

Using this approach we reconstruct the remnant magnetic configuration of an electro-deposited Co/Cu multilayered nanowire (NW) (Fig. 1) [3]. The 3D structural and chemical distribution was obtained simultaneously from the mean inner potential (MIP) tomogram (Fig. 1c) reconstructed from the electric phase shift of the NW. Thus, we could correlate magnetization states (circular or parallel) of the individual Co disks and we discuss the competing coupling mechanisms within and between the magnetized Co layers (Figs. 1e-j). The powerful approach presented here is widely applicable to a broad range of 3D magnetic nanostructures and may play a considerable role in the advancement of novel spintronic nonplanar nanodevices.

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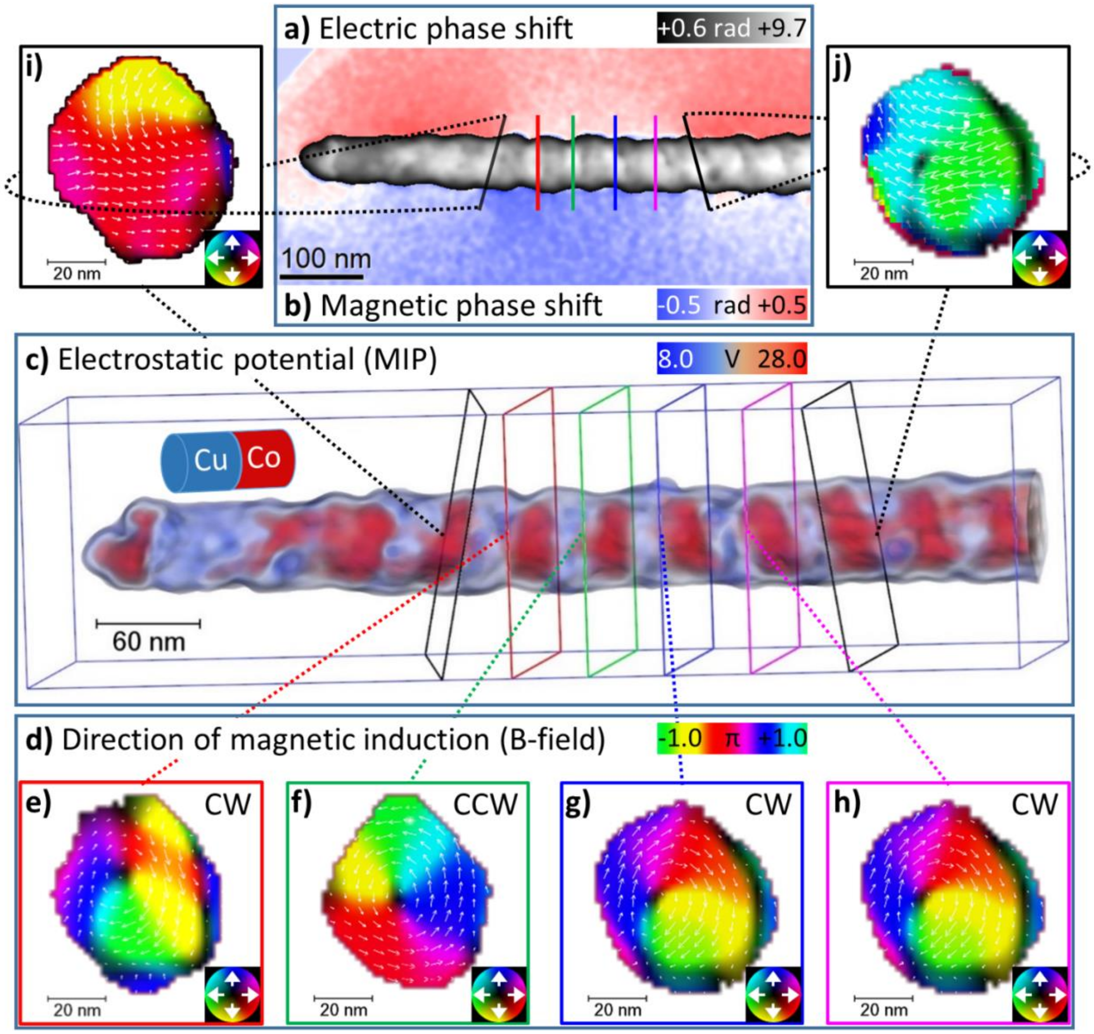

Figure 1. 3D reconstruction of a Co/Cu multilayered nanowire (NW) by EHT. (a) The electric phase shift (grey scale) is proportional to the projected potential of the NW. (b) The magnetic phase shift (red-white-blue) is proportional to the magnetic flux illustrating the stray field of the NW. (c) The color scale of the electrostatic potential displays the 3D morphology of the Cu and Co segments in blue and red based on their different mean inner potentials. (d) Direction of the 3D magnetic induction representing the magnetic configuration within the Co cylinders, i.e., (counter-) clockwise ((C)CW) vortex states (e-h). The outer Co segments (i,j) do not show a vortex configuration; instead they are magnetized almost homogeneously in mutually opposite direction. This explains why a magnetic stray field leaks out of the NW at these positions as observed in the magnetic phase shift (b).