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Magnetic Configurations in Three-Dimensional Nanomagnets Explored by Electron Holographic Tomography

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Three-dimensional (3D) magnetic nanostructures exhibit a large variety of inhomogeneous spin textures of non-trivial topology and chirality 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 a quantitative characterization technique resolving magnetic structures down to the nanometer scale. Off-axis electron holography (EH) fulfills this requirement by using the transmission electron microscope (TEM) in an interferometric setup to measure the phase shift of an electron wave that passed through the sample. The phase shift of ferro-magnetic samples consists of an electric (prop. to electrostatic potential) and a magnetic part (prop. to enclosed magnetic flux). To separate these two parts, one can reconstruct two phase images with inverse magnetic fields (e.g., by flipping the sample up-side down in the holder). Computing half of the sum and difference of corresponding image pairs yields the electric and the magnetic phase shift. The latter represents 2D projections of the Cartesian components of the magnetic induction (B-field) oriented perpendicular to the TEM electron beam direction. To characterize the 3D magnetic textures, 2D magnetic induction maps are often not sufficient. To obtain the 3D distribution of the ***B***-field [2], we elaborate on electron holographic tomography (EHT). Here, two tilt series of electron holograms (ideally covering 180°), the second one with specimen magnetization reversed for separation of electric part, are acquired for the tomographic 3D reconstruction of one component of the B-field (the one parallel to the tilt axis). Hence, for a second ***B***-field component two further tilt series, with perpendicular tilt axis, are recorded. The remaining third component is obtained by invoking that the ***B***-field is divergence free.

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 neglecting the respective other derivative), 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 allow non-perpendicular tilt axis and to exploit the complete dataset we also report on a simultaneous reconstruction algorithm of all ***B***-field components based on the relation between the electromagnetic four-potential and the electron wave's phase shift. Moreover, we discuss strategies to retrieve the 3D magnetization distribution from the reconstructed 3D magnetic flux density by means of scalar potential micromagnetics.

We present the 3D reconstruction of 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).

This result was achieved using advanced in-house developed software packages for acquisition, alignment and tomographic reconstruction. 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 [4].

References:

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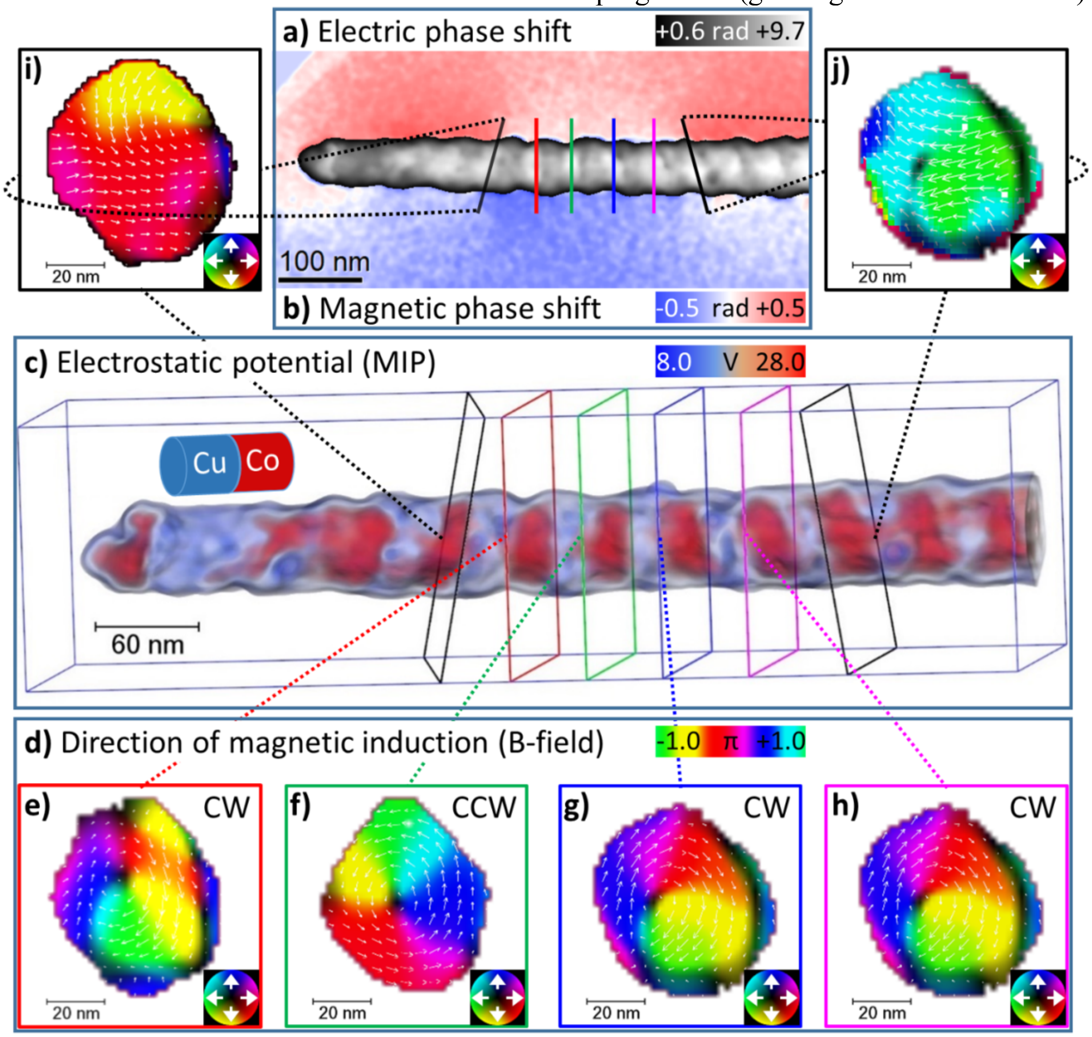

Figure 1. 3D reconstruction of a Co/Cu multilayered nanowire (NW) by EHT. (a) The electric phase shift (grey scale) is proportional to the projected potential of the NW. (b) The magnetic phase shift (red-white-blue) is proportional to the magnetic flux illustrating the stray field of the NW. (c) The electrostatic potential reconstructed by EHT renders the 3D morphology of the Cu and Co segments in blue and red. The contrast is given by the different MIP of Cu and Co. (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 however not show a vortex configuration, but 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).