In situ measurement of magnetic fields at the nanoscale using off-axis electron holography and environmental transmission electron microscopy

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Electron holography is a specialized technique, which can be used to record the phase shift of the electron wave that has passed through a thin specimen in a transmission electron microscope (TEM) that is equipped with a field emission gun and an electron biprism. The subsequent interpretation of the recorded phase shift allows magnetic fields in materials and in working devices, projected in the electron beam direction, to be visualized and quantified with a spatial resolution approaching 1 nm. The latest generation of ultra-stable electron microscopes is equipped with high brightness electron sources, aberration correctors and sophisticated software for the automation of experiments and offers the possibility of achieving a phase sensitivity of $2\pi/1000$ with sub-nm spatial resolution. This level of performance now promises to allow magnetic states in ferromagnetic crystals that are as small as 5 nm to be visualized directly and quantitatively. Electron holography can also be used to measure the magnetic moment of a nanocrystal of arbitrary shape and magnetization state from a phase image by making use of the relationship between the volume integral of the measured magnetic induction and the true magnetic moment. Our calculations suggest that it may be possible to measure magnetic moments with magnitudes of below 100 μ_B, both in projection and in three dimensions, if the effects of dynamical diffraction, charging of the specimen due to electron beam irradiation and the presence of adsorbates on the specimen surface are minimized. We are currently also combining electron holography with environmental TEM to study the reduction of single crystalline 15 nm Fe oxide cubes to single crystalline Fe at elevated temperature in hydrogen *in situ* in the electron microscope, and their subsequent reoxidation to polycrystalline Fe oxide. The magnetic properties of the cubes are measured using electron holography after each stage of reduction and oxidation. I will discuss both the insight that these measurements provide into the physics of magnetic states in nanocrystals that are close to the transition between superparamagnetic and single domain behavior, and the degree to which the high-energy electron beam may affect the details of chemical reactions observed in the ETEM.