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Towards electron holography of magnetic fields in nanometer-sized crystals in the transmission electron microscope

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Abstract

Magnetic fields in sub-50-nm nanocrystals can presently be characterized using the technique of electron holography in the transmission electron microscope with a spatial resolution of between 5 and 10 nm. The technique involves using an electron biprism to overlap a high-energy electron wave that has passed through an electron-transparent specimen with another part of the same electron wave that passed only through vacuum. Analysis of the resulting interference pattern provides direct access to the phase shift of the specimen wave, which can then be used to obtain the in-plane component of the magnetic induction in the specimen projected in the electron beam direction. Over the past ten years we have used electron holography to study magnetic remanent states and magnetization reversal mechanisms in chains, rings and two-dimensional arrangements of nanoparticles that have sizes of between 20 and 100 nm. We have also recently developed a mathematical approach that can be used to measure the magnetic moments of isolated or closely-spaced nanoparticles, either in projection or in three dimensions, from recorded phase images. Here, we discuss how the technique can be extended in the future in order to allow magnetic fields in individual nanocrystals that have dimensions of between 2 and 20 nm to be measured quantitatively with a spatial resolution that approaches 1 nm. We also present preliminary results that illustrate how the technique can be combined with environmental transmission electron microscopy to study the evolution of magnetic interactions in real time during the oxidation, reduction and self-assembly of magnetic nanoparticles in situ in the electron microscope. We illustrate several of these developments using examples taken from studies of Fe and Co nanoparticles that have different arrangements, sizes and spacings.