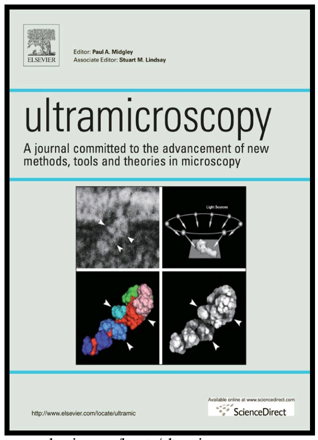

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Model-based magnetization retrieval from holographic phase images

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Abstract

The phase shift of the electron wave is a useful measure for the projected magnetic flux density of magnetic objects at the nanometer scale. More important for materials science, however, is the knowledge about the magnetization in a magnetic nano-structure. As demonstrated here, a dominating presence of stray fields prohibits a direct interpretation of the phase in terms of magnetization modulus and direction. We therefore present a model-based approach for retrieving the magnetization by considering the projected shape of the nano-structure and assuming a homogeneous magnetization therein. We apply this method to FePt nano-islands epitaxially grown on a $SrTiO_3$ substrate, which indicates an inclination of their magnetization direction relative to the structural easy magnetic [001] axis. By means of this real-world example, we discuss prospects and limits of this approach.

Keywords: off-axis electron holography, magnetic imaging, FePt nano-structured film

Introduction

The magnetic induction at the nanoscale can be measured in projection by means of the phase of the electron wave as reconstructed by electron holography [1, 2, 3]. It is well known that iso-lines in magnetic phase images can be interpreted as projected field lines of the magnetic induction [4]. However, in most cases, fringing fields depending on the geometry of nano-structures prohibit a direct interpretation of the phase image in terms of magnetization [5, 6], which is a more important quantity in solid state physics and materials science for the investigation of *e.g.* magnetic interactions between various magnetic nanostructures [7, 8, 9]. For some cases, magneto-statics can be directly applied to the phase image yielding magnetic momenta [10] or known shape-dependent demagnetization factors can be employed to return the magnetization of magnetic particles [11]. In general, a separation of the magnetization from fringing fields in phase images requires micro-magnetic simulations based on the exact structure and parameters, such as saturation magnetization and exchange constant, which necessitates large computational efforts even for the small system size [12, 13, 14, 15]. Furthermore, even highest signal and spatial resolution in magnetic holography usually performed in field-free space is not sufficient to observe all subtle mirco-magnetic effects [13]. Therefore, in many cases, it is more efficient to utilize magnetostatic calculations instead [16, 17].

In this paper, we present a simple model-based approach to retrieve the magnetization from experimental phase images. This bears on a decomposition of an arbitrary magnetic nano-structure into independent components, which possess individual homogeneous magnetizations. For each component, the phase shift due to magnetization and fringing fields is then computed as a function of geometry and thickness distribution as well as its magnetization vector. Considering the analytic solution for the phase shift of a homogeneously magnetized cuboid (see e.g. [18]), we adopt the geometry of each component by parting the respective thickness distributions into a set of equally magnetized cuboids with suitable dimensions. The sum of the phase shifts of all cuboids returns a magnetization model for a certain nano-structure component as a function of two free parameters: the modulus and the direction of the magnetization vector. Thus, each component can be treated as a magnetically homogeneous entity with varying magnetization vector. The sum over the phase images of all components yields a calculated phase image as a function of the magnetizations vectors of all independent components. This allows to directly fit these vectors to the experimental phase image by determining the least square root.

We demonstrate the performance and limits of this method on L10-ordered FePt nano-islands epitaxially grown on (001) single-crystalline $SrTiO_3$ (STO) substrates. In a

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