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Visualization of vortex core polarity in NiFe nanodots by tilted Fresnel images

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A R T I C L E I N F O

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A B S T R A C T

We illustrate an approach which allows determining the out-of-plane component of the vortex core (polarity) in NiFe nanodots using Fresnel imaging in Lorentz electron microscopy. Using tilted Fresnel images, contribution of the polarity is introduced into the Fresnel image. However, this contribution is relatively small and a difference image from two symmetrically tilted Fresnel images must be used to eliminate the strong contribution from the in-plane curling magnetization and non-magnetic contrast. The sense of the polarity appears as a bipolar white–black contrast in the difference image on the tilt axis. A vortex core with a diameter of 16.5 ± 2.5 nm is experimentally measured. Image tilting, displacement and geometrical distortion may disturb the difference image, and hence subtraction of the difference image must be aligned by cross-correlation. The method is also justified by a study of the observed contrast characteristic due to misalignment. The method is confirmed to be superior to similar approach with direct interpretation of information and more information subtracted.

1. Introduction

Recently, controlling behavior of magnetic domain walls has been extensively studied due to potential applications for spintronic devices [1–4]. In particular the magnetic vortex is of considerable interest. The magnetic vortex is a magnetic configuration, which consists of an out-of-plane magnetization at its core and in-plane curling magnetization around the vortex core. Therefore, a magnetic vortex can be identified as having a chirality of the in-plane flux closure (clockwise or counter-clockwise), and the direction of the out-of-plane component (polarity or polarization). Recently, much of the work in this field [2,4–7] has indicated that the magnetic vortex could be a promising candidate for the near-future non-volatile memory cell. Potentially, a magnetic vortex can be used as a promising memory cell: the sense of the in-plane flux closure can be employed as an information carrier, and the out-of-plane polarization of the magnetic vortex core can also be regarded as “0” or “1” of a bit element [4]. Therefore, understanding the micromagnetic structure and behavior of the magnetic vortex will be useful not only from a fundamental scientific point of view but also for technological applications.

Previously, the vortex core polarity has been determined using magnetic force microscopy (MFM) [1], spin-polarized scanning tunneling microscopy (SP-STM) [8], X-ray dichroism (XMCD) [9], or by electron holography [10]. The MFM is a reliable technique, however, the MFM runs in scanning mode therefore takes a long time for capturing an image (up to few 10 min) and one must be aware that the magnetic field of the tip may affect the magnetic structure of the sample. The SP-STM is able to image magnetic structures with very high resolution but it seems to be difficult to separate the information from magnetization and topography, and limited by very slow working. Of the other techniques XMCD requires a synchrotron source that seems to be hard for applying widely. Junginger et al. [10] have indicated that the polarity of the vortex core could be determined with tilting specimen electron holography but electron holography required an algorithm to recover the phase information from interference pattern. Besides, field view in electron holography seems to be limited and it needs to position the element close to vacuum, which may influence the micromagnetic structure due to stray fields. Recently, Phatak et al. [11] have also described the method to determine the vortex polarity in which the tilted Fresnel image was exploited. In this method, only one tilted Fresnel image was required, however an analytical model of magnetic phase shift must be applied to interpret the polarity direction. The Fresnel images were recorded at high defocus (above 450 μm—so far from linear regime of Fresnel imaging [12]) where the quantitative information would be disturbed by the reduction of image resolution and noise (e.g. low spatial frequency noise [13]).

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In this article, we illustrate a method in which the out-of-plane polarity of the magnetic vortex can be determined using two tilted Fresnel images without an image processing required. Subtraction of difference image from symmetrically tilted Fresnel images allows interpreting directly the information and deriving more information of the vortex core that is supposed to be superior to previous approaches.

2. Method descriptions

$Ni_{80}Fe_{20}$ circular nanodots with a saturation magnetization of $M_s = 860 \times 10^3$ A/m ($B_s = 1$ T) exchange constant $A = 13 \times 10^{-12}$ J/m [14] were selected as the object of this work. An array of $Ni_{80}Fe_{20}$ dots with various diameters was fabricated using electron beam lithography and lift-off technique. The $Ni_{80}Fe_{20}$ film was deposited using thermal evaporation in a base vacuum of 2×10^{-6} mbar. For TEM measurement, the sample was grown on a Si substrate supported by a $100 \times 100\ \mu m^2$ Si_3N_4 with a thickness of 50 nm for electron transparency. Thickness of the dots was measured to be 22.2 ± 1.5 nm using atomic force microscopy.

Conventionally, no information of the magnetic induction parallel to the electron beam is provided by the LTEM because no Lorentz force occurs ($\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$, with **E** and **B** are electrostatic field and magnetic induction in the specimen, respectively). Therefore, there is no contribution of the vortex polarity in the Fresnel images when the sample is perpendicular to the beam (un-tilted). However, by tilting the specimen at an angle, θ, to the horizontal plane, the vortex core will be as a result not parallel to electron beam and this creates an in-plane component contribution on the horizontal plane ($B_z \sin\theta$). Therefore, in this case the vortex core will contribute to the contrast of the Fresnel image. In fact, the contribution of the vortex polarity in the tilted Fresnel image is relatively small compared to a strong contrast of the in-plane curling magnetization component and is not prominent in a single Fresnel image (see Section 3, Fig. 2(c)). Nevertheless the main contribution to the contrast, which is provided by the curling in-plane components, can be subtracted by calculating a difference image of two Fresnel images produced by symmetrically tilting the specimen. As a result, the contrast of the vortex polarity can be visible in a nearly zero background. In experiment the observed contrast due to the polarity in the

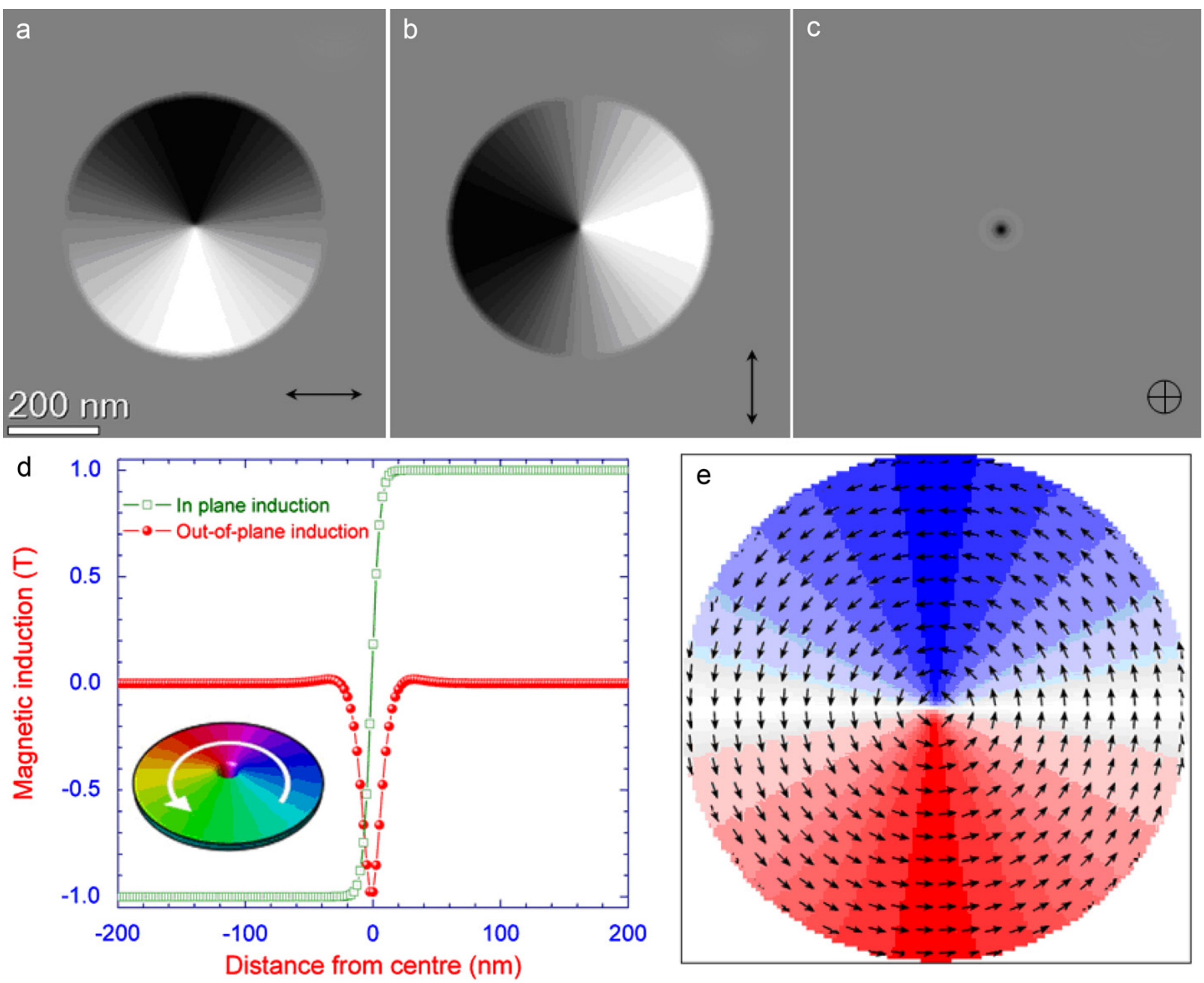

Fig. 1. Magnetic configuration of the simulated 600 nm diameter $Ni_{80}Fe_{20}$ with thickness of 20 nm: M_x, M_y, M_z components of the vortex core (a–c) as the gray-scale images, the profiles of the in-plane and out-of-plane components around the vortex core (d) and spin pattern of vortex (e). Magnetization profiles here were measured along the diameter of the dot.