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Magnetic vortex observation in FeCo nanowires by quantitative magnetic force microscopy

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An approach is presented that allows quantifying the three dimensional magnetization pattern of a magnetic nanoobject from measured two dimensional Magnetic Force Microscopy (MFM) data. This is based on a MFM deconvolution approach, which quantitatively determines the effective surface charges, on a micromagnetic calculation of the total magnetic charges at and below the sample surface, and on a projection of the lower lying charges onto the sample surface for a comparison of the such obtained effective surface charges with the experimentally determined ones. Thus, by making use of the depth sensitivity of MFM and by applying a quantitative contrast analysis, we are able to reconstruct the inhomogeneous magnetization state at the end of individual cylindrical Fe52Co48 nanowires arranged in a triangular array. As a result, we prove the existence of a magnetic vortex state at their ends. © 2014 AIP Publishing LLC.

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Imaging and understanding the magnetic structure of nanoobjects is an increasingly important issue as device sizes are continuously reducing. The present study examines the magnetization state at the end of cylindrical FeCo nanowires embedded in a triangular array. Although various kinds of magnetic nanowire arrays have been extensively studied over the last two decades (see, e.g., Refs. 1–5 and references therein), information about the magnetic status of a single wire embedded in an array is still difficult to obtain. That holds even more for the local magnetization state at the wire ends, which is expected to be not identical with the bulk magnetization.6 Magnetic Force Microscopy (MFM) is already widely used for qualitative imaging of magnetic microstructures with a resolution down to 10 nm.7 In comparison with other methods capable of highly resolved magnetic imaging such as spin-polarized scanning tunneling microscopy, electron holography, or scanning electron holography with polarization analysis, MFM has the great advantage of simple instrumentation and very little requirements for sample preparation. However, the quantification and hence correct interpretation of measured MFM data is still challenging. To overcome this drawback, the MFM signal can either be analysed based on simplifying tip-sample interaction models8,9 or the MFM system can be calibrated by a tip transfer function approach, preferably in Fourier space.7,10,11 However, until today both approaches were only applied to resolve two-dimensional magnetization patterns. In this letter, we present a method, which includes the depth sensitivity in the quantitative analysis of the measured MFM data and herewith extends the quantitative evaluation to the third dimension, making it possible to resolve the magnetization structure within the volume of the investigated cylindrical nanowires.

FeCo nanowires were electrochemically grown in anodized aluminum oxide (AAO) templates.12 A well ordered triangular arrangement of cylindrical nanowires with a diameter $d$ of about 70 nm, an inter-pore distance $D$ of about 100 nm and a length $L$ of 6 µm was obtained (Figs. 1(a) and 1(b)). The magnetization measurements were carried out with a Digital Instruments 3100 magnetic force microscope in tapping/lift mode. The MFM tip used for the presented measurements is a magnetically coated cone shaped tip fabricated by team nanotech (HRMFM-ML3). All MFM measurements presented in this article are performed at a lift height of 15 nm and a cantilever oscillation amplitude below 30 nm. The source of the measured MFM signal is the force gradient between the magnetic tip and magnetic sample. It can be theoretically described by a correlation integral of the tip’s stray field gradient and the sample magnetization over

![FIG. 1. (a) SEM top view and (b) cross section of the Fe52Co48 filled Al2O3 template. (c) MFM overview of the FeCo nanowire array in the as-prepared zero field state.](image-url)
the whole sample volume. Using a calibrated tip is a necessary requirement for the quantitative reconstruction of the magnetization present in a magnetic sample. An easier handling of the resulting volume integral is possible when considering only the interaction along the vertical (z)—direction and transforming it into Fourier space, where the problem reduces to a multiplication operation as given by

\[
\frac{\partial \tilde{F}_z}{\partial z}(\mathbf{k}, z) = -\mu_0 \frac{\partial \tilde{H}_\text{tip}}{\partial z}(\mathbf{k}, z) \tilde{\sigma}_\text{eff}^*(\mathbf{k}), \tag{1}
\]

where \(\tilde{\sigma}_\text{eff}^*\) denotes the complex conjugate of the effective surface charges representing the sample magnetization, \(\frac{\partial \tilde{H}_\text{tip}}{\partial z}\) is the stray field gradient of the tip and \(\frac{\partial \tilde{F}_z}{\partial z}\) the force gradient experienced by the tip and detected in MFM. The tilde denotes the Fourier transforms of the quantities, \(\mathbf{k} = (k_x, k_z)\) represents the lateral frequencies and \(z\) the distance from the sample surface. The term \(\frac{\partial \tilde{H}_\text{tip}}{\partial z}\), which is called tip transfer function (TTF), globally quantifies the tip without including any kind of tip model or further assumptions. The knowledge of the TTF enables the restoration of the magnetic information \(\tilde{\sigma}_\text{eff}\) from the measured image. The TTF itself is determined by a preceding calibration measurement on a suitable reference sample. The calculation of the TTF from the measured data requires a deconvolution procedure, for which a modified Wiener filter was chosen. The programming and data analysis has been performed with the development environment SigMath (developed by one of the authors). Details are provided elsewhere. The basic requirement for a reference sample is to provide a defined, well-known magnetization pattern. For this purpose, we use a CoPt multilayered thin film with perpendicular magnetic anisotropy and the following architecture: Pt(5 nm)/[Pt(0.9 nm)/Co(0.4 nm)]\(_{100}\)/Pt(2 nm). At remanence, where the sample shows a band domain structure, the domain period as seen in the MFM contrast (see Fig. 2(a)) stays uninfluenced by the tip properties as required for the reference sample. Vibrating sample magnetometry measurements revealed a uniaxial anisotropy constant of \(K_u = 517\) kJ/m\(^3\) and a saturation magnetization of \(M_s = 554\) kA/m. With this \(Q_u = K_u/M_s^2\) becomes 2.7, which guarantees a magnetization aligned almost (>92%) fully perpendicular to the sample surface within each domain.

Applying a discrimination level to the obtained MFM image of the reference sample and considering opposite charges of identical magnitude from the upper and lower sample surface allows constructing the effective surface charge pattern \(\sigma_{\text{eff}}(x, y)\) at its upper surface. Dividing the Fourier transform of the measured force gradient \(\frac{\partial \tilde{F}_z}{\partial z}(\mathbf{k}, z)\) by the Fourier transform of the complex conjugate of this binary image \(\tilde{\sigma}_\text{eff}^*(\mathbf{k}, k_z)\) results in the TTF in a certain distance \(z\) away from its apex. The inverse Fourier transform results in \(\frac{\partial \tilde{H}_\text{tip}}{\partial z}\), which is additionally circularly averaged to reduce noise (Fig. 2(b)). Further details of the calibration procedure, which include the subtraction of the lever canting in the MFM image (12° in our instrument) and the influence of a finite domain transition, are outlined by Meyer et al.

Prior to the quantitative analysis of the nanowire array’s magnetization state (Fig. 1(c)), the negligible mutual influence of the tip and sample magnetization at the measurement distance (\(z_{\text{lift}} = 15\) nm) has been verified. To that end, MFM images have been calculated for larger nominal measurement distances by the known experimental decay of the MFM signal in Fourier space and compared with measured data. The marginal differences validate the negligible mutual influence and in the same time prove the complete characterization of the tip’s magnetic coating.

The particular challenge of quantitative MFM in the case of nanowires arises from the fact, that a three dimensional magnetization structure is to be deduced from a single two dimensional MFM measurement. It is not possible to unambiguously solve this problem without additional constraints. A forward approach has been developed for which a reasonable guess of the effective surface charges is taken and subsequently convolved with the TTF. The measured image is compared with the calculated images until a match is found. Two surface charge models have been considered, which are discussed in the following.

The wires have an aspect ratio of \(L_z/d = 93\) and the shape anisotropy \(K_{\text{ab}} = 1/4 (\chi \mu_0 M_s^2) [1 - 3N_z] = 1130\) kJ/m\(^3\) (with \(N_z = 0.00036\)) is about two orders of magnitude larger than the crystalline anisotropy of bcc-Fe (\(K_1 = 48\) kJ/m\(^3\)). Furthermore, the wires are polycrystalline with grain sizes of 30 nm, which renders the magnetocrystalline anisotropy of the grains an overall random contribution. All this suggests a predominantly homogeneous magnetization along the wire axis and a homogeneous effective surface charge distribution of the order of \(M_s\) across the wire surface. In a first step, the charge profile for a single wire was set constant to the magnetization value of the FeCo nanowires of 1900 kA/m. Two discrete orientations of the wire magnetization are expected, either pointing upwards (dark MFM contrast, parallel to the tip) or downwards (bright MFM contrast, anti-parallel to the tip). An exemplary MFM overview image of the investigated array can be found in Fig. 1(c). To come closer to the MFM image of the array, the wire arrangement in the simulation was based on the geometrical data of the porous alumina matrix and the particular direction of each wire magnetization was assigned according to the given MFM image section. The measured data of such an MFM image and the corresponding simulated MFM image are shown in Figs. 3(a) and 3(b), respectively. The arrows and numbers on the left indicate different line profiles through the images. The comparison of the simulated and measured (red and black) line profiles shows a convincing qualitative agreement but also a clear overestimation of the present effective surface

**FIG. 2.** (a) MFM image of the band domain state in the Co/Pt multilayer used for the tip calibration (b) circular averaged \(\frac{\partial \tilde{F}_z}{\partial z}\) of the used HRMFM tip in a distance of \(z = 30\) nm (15 nm topographic scan +15 nm lift height) away from the tip apex.
charges in the nanowires. As a consequence, the simple model of a homogeneous surface charge distribution has to be improved.

Therefore, the magnetization structure of a single nanowire has been deduced from micromagnetic simulations with the object-oriented micromagnetic framework (OOMMF).\(^{14}\) A wire with similar dimensions (diameter: 70 nm and length: 1 \(\mu\)m) to that of the experiment was discretized into \((2 \times 2 \times 2)\)-nm\(^3\) cells. According to the material properties of FeCo, the exchange constant and saturation magnetization were set to \(A = 26 \times 10^{-12}\) J/m and \(M_s = 1900\) kA/m. Starting from a fully saturated wire with \(M\) along the wire axis, the magnetization was relaxed until the maximum torque across all spins drops below \(\frac{dm}{dt} = 0.01\) /ns.

In single domain nanowires of given geometry and material parameters, the magnetization forms a magnetic vortex at the nanowire’s end with large in-plane components, which rotate around the wire axis in a flux closure arrangement (Fig. 4(a)). Avoiding poles both at the upper surface and the sides of the wire leads to a large reduction of stray field energy, which counteracts the additional cost in exchange energy. This magnetization structure is also known as a transient state in the magnetization reversal via localized curling.\(^{15}\) With increasing distance from the wire ends the moments align gradually parallel to the wire axis (the \(z\)-component of the magnetization increases) and show a homogeneous magnetization throughout the wire (\(M_z = M_s\), Fig. 4(b)). In order to include the vortex in the MFM image simulation, it has to be exactly quantified utilizing the given simulation results. Therefore, the vortex is described in terms of effective surface charges \(\sigma_{eff}(x, y)\). Magnetic surface charges are defined as \(\sigma = \mu_0 n \cdot M\), where \(n\) is the outward directed surface normal and volume charges are given by \(\rho = -\mu_0 \text{div} M\). Since MFM is a depth sensitive method, it is not sufficient to analyze only the charges generated by the discontinuity at the surface itself. As the magnetization’s \(z\)-component is inhomogeneous along the \(z\)-axis (see Fig. 4(b)), internal charges have to be taken into account,
since they also contribute to the MFM signal, even though they possess smaller influence being further away from the tip than the actual surface charges (see sketch in Fig. 5). Using the known exponential decay behavior of stray fields and the corresponding charges, the effective surface charge is calculated by summing up the surface charges and the volume contributions (Fig. 4(d))

$$\tilde{\sigma}_{eff}(k) = \tilde{m}^0_z(k) + \sum_{n=2}^{N} (\tilde{m}_z^n(k) - \tilde{m}_z^{n-1}(k)) \cdot e^{-kn\Delta z} \quad (2)$$

with the average magnetization $\tilde{m}_z^n = \frac{1}{2}(\tilde{m}_z^{n-1} + m_z^e)$ within a defined cell volume $A\Delta z = AL/N$ depending on the chosen degree of discretization $N$. The term $\tilde{m}_z^n(k) - \tilde{m}_z^{n-1}(k)$ describes the $z$-contribution of the volume charges. The level of sufficient discretization is given by $N$ at which $\tilde{\sigma}_{eff}$ runs into saturation. The volume of interest is limited to the known exponential decay behavior of stray fields and the existence of a magnetic vortex at the ends of the imaged nanowires. Thus, including the depth sensitivity of MFM by taking the volume contributions of the magnetic charges into account turns out to be crucial for a correct understanding of the measured MFM signal. The combination of micromagnetic calculations and appropriate quantitative MFM data analysis proves the existence of a magnetic vortex at the ends of the imaged nanowires. A question which might be interesting to address in the future, is, whether the presence of the vortex state has measurable implications on the magnetization reversal mechanism and can thus be probed by angular dependence of coercivity.

Summarizing, we developed a method, which enables the three dimensional reconstruction of a magnetization pattern of magnetic nanoobjects from two dimensional MFM measurements. The method requires the application of a quantitative MFM procedure including a preceding tip calibration. In an application of the proposed method, we reveal the vortex formation at the end of FeCo nanowires.

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