Imaging magnetic vortex configurations in ferromagnetic nanotubes

M. Wyss,1 A. Mehlin,1 B. Gross,1 A. Buchter,1 A. Farhan,2,3 M. Buzzi,4 A. Kleibert,4 G. Tütüncüoglu,5 F. Heimbach,6 A. Fontcuberta i Morral,5 D. Grundler,7 and M. Poggio1

1Department of Physics, University of Basel, 4056 Basel, Switzerland
2Laboratory for Micro- and Nanotechnology, Paul Scherrer Institute, 5232 Villigen, Switzerland
3Laboratory for Mesoscopic Systems, Department of Materials, ETH Zürich, 8093 Zürich, Switzerland
4Swiss Light Source, Paul Scherrer Institute, 5232 Villigen, Switzerland
5Laboratory of Semiconductor Materials, Institute of Materials, School of Engineering, École Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland
6Lehrstuhl für Physik funktionaler Schichtsysteme, Physik Department E10, Technische Universität München, 85747 Garching, Germany
7Laboratory of Nanoscale Magnetic Materials and Magnonics, Institute of Materials, School of Engineering, École Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland

Abstract

We image the remnant magnetization configurations of CoFeB and permalloy nanotubes (NTs) using x-ray magnetic circular dichroism photo-emission electron microscopy. The images provide direct evidence for flux-closure configurations, including a global vortex state, in which magnetization points circumferentially around the NT axis. Furthermore, micromagnetic simulations predict and measurements confirm that vortex states can be programmed as the equilibrium remnant magnetization configurations by reducing the NT aspect ratio.
The study of magnetic nanostructures is motivated by their potential as elements in dense magnetic memories, logical devices\(^1\), magnetic sensors\(^2\), and as probes in high-resolution imaging applications\(^3\text{-}^5\). For these reasons, a number of nanometer-scale geometries have been investigated both theoretically and experimentally, including magnetic dots, rings, wires, and tubes. Of particular interest are nanomagnets with stable flux-closure magnetization configurations and both fast and reproducible reversal processes. In the context of magnetic memory, speed and reliability are determined by the latter, while ultimate density can be enhanced by the former. High density is favored by flux-closure configurations because they produce minimal stray fields, thereby minimizing interactions between nearby memory elements\(^6\).

Ferromagnetic nanotubes (NTs) are a particularly promising morphology, given their lack of a magnetic core. At equilibrium, the hollow magnetic geometry is expected to stabilize vortex-like flux-closure configurations with magnetization pointing along the NT circumference. In contrast, in magnetic nanowires (NWs), the exchange energy penalty for the axial singularity in the center of a vortex configuration tends to favor non-flux-closure states. In a NT, the lack of this axial singularity – or Bloch point structure – also allows for a fast magnetization reversal process that begins with vortices nucleating at its ends and propagating along its length\(^7\text{-}^9\). Theoretical studies of ferromagnetic NTs have predicted an equilibrium flux-closure configuration, the so-called global vortex state, as well as other equilibrium configurations including a uniform axial state and a mixed state\(^9\). In a global vortex state, the entire NT’s magnetization is circumferentially aligned, while the mixed state combines vortex-like ends, minimizing magnetostatic energy, and an axially aligned center, minimizing exchange energy. Calculations suggest that for short NTs, opposing vortex states, in which two vortices of opposing chirality are separated by a Néel domain wall, may also be stable\(^10\). The dependence of the NT’s equilibrium magnetization configuration on geometry, as well as details such as the relative chirality of the end-vortices, have been considered both analytically and numerically\(^10\text{-}12\). In particular, it has been predicted that the most technologically relevant magnetization configuration – the global vortex state – can be programmed as the stable remnant configuration by a small NT aspect ratio.

Experimental evidence for vortex configurations in NTs has so far been limited to magnetic force microscopy images of single NTs reported by Li et al\(^13\). There, the authors interpret a nearly vanishing MFM contrast and a small remnant magnetization as an indi-
cation of a global vortex state. Streubel et al. use x-ray magnetic dichroism photoemission electron microscopy (XMCD-PEEM) to investigate rolled-up permalloy (Py) membranes, which are 3-µm in diameter. The authors report azimuthal domain patterns that are commensurable throughout the windings and attribute the effect to magnetostatic coupling between windings. Inter-winding exchange coupling, however, is not present. Here we use XMCD-PEEM to image magnetic configurations in individual magnetic NTs, which are an order of magnitude smaller. These NTs are prepared as continuous magnetic shells around nano-templates, allowing for both magnetostatic and exchange coupling. We find remnant global vortex states and show that aspect ratio can be used to program the occurrence of different remnant states, including mixed, opposing vortex, and global vortex states.

We study CoFeB and Py NTs consisting of a non-magnetic GaAs core surrounded by a 30-nm-thick magnetic shell with a hexagonal cross-section, as shown in Figure 1 (a). The NTs have a vertex-to-vertex diameters $d$ between 200 and 300 nm and lengths $l$ from 0.5 to 12 µm. We obtain specific lengths and well-defined ends by cutting individual NTs into segments using a focused ion beam (FIB). After cutting, we use an optical microscope equipped with precision micromanipulators to pick up the NT segments and align them horizontally onto a Si substrate. Scanning electron micrographs (SEMs) of the 19 CoFeB and 25 Py NTs studied (see Supporting Information) reveal continuous surfaces, which are free of detectable and whose roughness is less than 5 nm. The fabrication process and choice of materials avoids magneto-crystalline anisotropy. Recent magneto-transport experiments suggest that a growth-induced magnetic anisotropy may be present in the CoFeB NTs. Dynamic cantilever magnetometry measurements of NTs from the same growth wafers as used here provide $\mu_0M_S = 1.3 \pm 0.1$ T and $0.8 \pm 0.1$ T for the CoFeB and Py NTs, respectively, where $\mu_0$ is the permeability of free space. The magnetic shell material is covered by a few-nanometer-thick native oxide, which affects the NT magnetization only at cryogenic temperatures through antiferromagnetic exchange coupling. In Py NTs, Buchter et al. observed such coupling below a blocking temperature of 18 K.

XMCD-PEEM measurements are performed at the Surface/Interface: Microscopy (SIM) beamline of the Swiss Light Source (SLS) at the Paul Scherrer Institut (PSI). Experiments are carried out at room temperature and in remnance. Circularly polarized x-rays tuned to the $L_3$-edge of Fe propagating along $\hat{k}$ impinge on the Si sample substrate with an incident
Figure 1. (a) Schematic drawing of a NT cross-section with incident x-rays, photoexcited electrons, and expected XMCD-PEEM contrast for the depicted vortex configuration. The brown central region depicts the non-magnetic GaAs template material, the gray region the magnetic NT, and the red region the native oxide. (b) SEM of a CoFeB NT with a Au alignment marker visible on the right of the image. (c) PEEM image with grayscale contrast corresponding to $I_{\text{PEEM}}$ and (d) XMCD-PEEM image with red (blue) contrast representing positive (negative) $I_{\text{XMCD}}$. The dashed line shows the position of the NT.

angle of $16^\circ$, as shown schematically in Figure 1 (a). The apparatus allows the rotation of the sample about the substrate normal with respect to $\hat{k}$, which is fixed. XMCD-PEEM images are obtained by taking the difference of PEEM images obtained with x-rays of opposite chirality $\sigma^+$ and $\sigma^-$ normalized to their sum: $I_{\text{XMCD}} = (I_{\sigma^+}^+ - I_{\sigma^+}^-)/(I_{\sigma^+}^+ + I_{\sigma^-}^-)$, where $I_{\sigma}^\pm$ represents the emission intensity of photoelectrons, which is proportional to the local absorption cross-section of $\sigma^\pm$ polarized x-ray illumination. The spatial resolution of the images is about 100 nm.

A SEM of a representative 11.3-µm-long CoFeB nanotube is shown in Figure 1 (b). A PEEM image of the same NT shows $I_{\text{PEEM}} = (I_{\sigma^+}^+ + I_{\sigma^-}^-)/2$ with the NT long axis $\hat{n}$ aligned
perpendicular to the x-ray beam appears in Figure 1 (c). Due to the resonant excitation of
the Fe $L_3$-edge, PEEM contrast from the NT surface appears as the brightest feature. The
dark stripe on the right of the NT is a shadow effect resulting from the grazing incidence of
the incident x-rays and their partial attenuation by the NT. A bright region to the left of
the NT appears due to x-rays reflected by the smooth surface of the NT. A dotted outline
shows the position of the NT in the corresponding XMCD-PEEM image in Figure 1 (d), as
determined by overlaying SEM, PEEM, and XMCD-PEEM images of the same NT. $I_{\text{XMCD}}$
within the outline stems from a region on top of the NT within 3 to 5 nm of the surface and
is proportional to the projection of its local magnetization along $\hat{k}$. $I_{\text{XMCD}}$ in the shadow
on the right of the outline – on the non-magnetic Si surface – depends on the imbalance
in the intensity of $\sigma^\pm$ x-rays transmitted through the magnetic material, rather than any
surface magnetization$^{17}$. The contrast in the shadow region is therefore sensitive to the
magnetization of the volume traversed by the x-rays, with opposite sign compared to surface
contrast (see Methods). The lack of surface and shadow $I_{\text{XMCD}}$ contrast corresponding to
the central part of the NT in Figure 1 (d) indicate negligible magnetization oriented parallel
to $\hat{k}$ (perpendicular to $\hat{n}$). On the other hand, at the NT ends, strong surface and shadow
contrast indicates magnetization oriented parallel to $\hat{k}$ (perpendicular to $\hat{n}$).

XMCD-PEEM images with $\hat{k} \perp \hat{n}$ (perpendicular XMCD-PEEM contrast) are shown in
Figures 2 (a) and (c) for Py and CoFeB NTs with lengths of 6.9 $\mu$m and 7.2 $\mu$m, repectively.
Contrast similar to that of Figure 1 (d) shows magnetization oriented perpendicular to $\hat{n}$ near
the ends of the NTs. Further information is gleaned by rotating the sample stage relative to
$\hat{k}$ and performing the same measurements with $\hat{k} \parallel \hat{n}$ (parallel XMCD-PEEM contrast), as
shown in Figures 2 (b) and (d). In this case, strong surface contrast in the central part of
the NT indicates magnetization parallel to $\hat{n}$. Decreased contrast at the NT ends confirms a
magnetization oriented perpendicular to $\hat{n}$, as suggested by the measurements with $\hat{k} \perp \hat{n}$.
Despite the strong shadow contrast from the ends in Figure 2 (c), the corresponding surface
contrast is weak. This lack of contrast is likely due to oxidation of the NT surface. Given the
limited probing depth related to the surface contrast and the fact that the shadow contrast
originates from the magnetization within the NT, in such cases we rely on $I_{\text{XMCD}}$ in the
shadow to determine the NT’s magnetic configuration.

Specific magnetization configurations in a magnetic nanostructure produce characteristic
XMCD-PEEM signatures for a given orientation of $\hat{k}$. Following the procedure described by
Figure 2. XMCD-PEEM images of a 6.9-µm-long Py NT with (a) $\hat{k} \perp \hat{n}$ and (b) $\hat{k} \parallel \hat{n}$ and of a 7.2-µm-long CoFeB NT with (c) $\hat{k} \perp \hat{n}$ and (d) $\hat{k} \parallel \hat{n}$. Dashed outlines indicate the positions of the NTs. (e) - (h) represent 2-µm-long $I_{\text{XMCD}}$ linecuts along the corresponding colored dashed lines in (a) - (d). In the linecuts, the background intensity is indicated by the level of the horizontal dashed lines and vertical dashed lines delineate the boundaries of the NT. (i) and (j) show simulated remnant magnetic states for a NT with $l = 2.1 \, \mu\text{m}$ and $d = 245 \, \text{nm}$. Both configurations are mixed states with an axial central domain and vortex ends of either (i) opposing chirality – consistent with (a) and (b) – or (j) matching chirality – consistent with (c) and (d). The color-scale corresponds to normalized magnetization along $\hat{y}$. Arrow heads indicate the local magnetization direction.

Jamet et al., which takes into account the progressive absorption of the x-ray beam through the sample cross-section\textsuperscript{16}, a vortex configuration in our NTs should result in perpendicular XMCD-PEEM contrast of the form shown in Figure 1 (a). This contrast is characterized by both strong surface and shadow contrast (due to the component of the magnetization aligned parallel to $\hat{k}$) and a change of sign in the x-ray shadow. Figures 2 (e) and (g) show line-cuts through the perpendicular XMCD-PEEM image at the NT ends that match this expectation. Figures 2 (f) and (h) show line-cuts of parallel XMCD-PEEM images through the same region along $\hat{n}$. The reduction in the surface contrast near the end of the NT relative to the central region is also consistent with decreasing on-axis magnetization due to a vortex end state. The complementarity of vanishing and strong contrast in the central part
Figure 3. XMCD-PEEM images with $\hat{k} \perp \hat{n}$ and $\hat{k} \parallel \hat{n}$ of short NTs. (a) 1.3-µm-long Py NT found in a global vortex state. (b) 0.73-µm-long Py NT in an opposing vortex state. (c) 1.06-µm-long CoFeB NT in a global vortex state. (d) 0.83-µm-long CoFeB NT in an opposing vortex state. Simulated equilibrium states of ferromagnetic NTs ($l = 610$ nm, $d = 245$ nm) in (e) a global vortex state and in (f) an opposing vortex state. The color-scale corresponds to the normalized magnetization along $\hat{y}$. Arrow heads indicate the local magnetization direction.

of the NT in the perpendicular and parallel XMCD-PEEM images, respectively, provides strong evidence for an axially aligned central region. Taken together, these images point to a mixed state configuration, where magnetic moments in the central part of the NT align along its long axis and curl into vortices at the ends. The relative signs of the perpendicular XMCD-PEEM contrast at the ends of the NT shown in Figure 2 (a) (2 (c)), indicates that the NT is in a mixed state with end vortices of opposing (matching) chirality.

For NTs of either material longer than 2 µm, we find remnant mixed states with vortices of both opposing and matching chirality, as in Figure 2 (see Supporting Information). For NTs shorter than 2 µm, different magnetization configurations emerge. Figure 3 (a) shows both perpendicular and parallel XMCD-PEEM images of a 1.30-µm-long Py nanotube. In the perpendicular image, nearly all magnetic moments point perpendicular to $\hat{n}$ and show the signature of a global vortex state with a single chirality. In the parallel image, a small area of axial moments is visible in the surface contrast, indicating either a slightly tilted vortex configuration or imperfections at the surface of the magnetic shell. Figure 3 (b) shows
XMCD-PEEM contrast from a 0.73-µm-long Py NT, in which the magnetization points mostly perpendicular to the NT axis. The remnant magnetization configuration, however, does not display a vortex of a single chirality, but rather two vortices of opposing chiralities separated by an axial Néel domain wall. This central wall produces vanishing shadow contrast (white) in the perpendicular image, while showing strong positive (red) surface and negative (blue) shadow contrast in the parallel image, as expected for magnetization aligned along \( \hat{n} \). We therefore conclude that this NT is in an opposing vortex state. Results for CoFeB NTs of similar sizes are shown in Figure 3 (c) and (d). Figure 3 (c) shows contrast from a 1.06-µm-long NT in a remnant global vortex state, whereas (d) shows a 0.83-µm-long NT in a remnant opposing vortex state.

In order to corroborate the XMCD-PEEM measurements, we carry out numerical simulations of NT magnetization using the software package $Mumax^3$\textsuperscript{25}. This package employs the Landau-Lifshitz micromagnetic formalism using a finite-difference discretization. We then compare the numerically expected equilibrium configurations and the experimentally observed remnant configurations as a function of vertex-to-vertex diameter \( d \) and length \( l \). Experimental results are extracted from perpendicular and parallel XMCD-PEEM images of each measured NT (see Supporting Information). Simulations are consistent with our XMCD-PEEM measurements in that long NTs are calculated to have remnant mixed state configurations, as depicted in Figure 2 (i) and (j), and short NTs remnant global vortex or opposing vortex states, as depicted in Figure 3 (e) and (f). The simulations also reproduce subtleties of the magnetization configuration in the NTs, including the length of the vortex ends and its dependence on \( d \) (see Supporting Information). The average length of the vortices along \( \hat{n} \) is measured to be 320 nm for CoFeB NTs and 360 nm for Py NTs.

Despite the agreement, the relative chirality of the end vortices predicted by the simulations does not match our observations. For long NTs in remnant mixed state configurations, the energy difference between a configuration with matching or opposing chirality vortices is calculated to be small compared to the precision of the simulation; therefore each is predicted to be equally likely. In the real NTs, although the distribution is equal across all NTs, it is unequal for a single material: 3 opposing and 8 matching mixed states appear in CoFeB NTs, while 9 opposing and 4 matching appear in Py NTs. As aspect ratio is reduced, simulations indicate that the relative chirality of the end vortices leads to energy differences larger than the thermal energy. As the central region of axial magnetization disappears, opposing
chirality should first be favored, resulting in a stable opposing vortex state. Upon further reductions in aspect ratio, the simulations eventually favor matching chirality, resulting in a stable global vortex state. For short NTs of both CoFeB and Py, however, the measured distribution of relative vortex chirality as a function of \( l \) and \( d \) does not follow the numerical predictions (see Supporting Information). These discrepancies suggest that imperfections may be decisive in energetically favoring one configuration over another. Simulations show that the equilibrium chirality is sensitive to variations in NT thickness as well as geometrical imperfections, such as slanted rather than flat ends introduced by the FIB cutting process. Given that such imperfections are known to be present, we assume that they play a role in determining the relative chirality of end vortices.

If we consider NTs measured to have equal chirality vortices, we find that the NT aspect ratio dictates whether the remnant state is a global vortex state, consistent with the simulations. In Figure 4 (a) and (b), NTs measured to be in either a mixed or global vortex state are plotted as a function of \( l \) and \( d \) together with the numerical expectation. We distinguish between a global vortex state and a mixed state with an axially aligned central domain and equal chirality vortices. The presence of the central domain can be quantified by an order parameter \( M_n/|M| \) corresponding to the relative amount of magnetization that is axially aligned. By plotting this order parameter for numerical simulations of NTs with different lengths and diameters, a clear boundary between the mixed state and global vortex state emerges, as shown in Figure 4 (a) and (a). The same classification is carried out on the measurements, with the global vortex state determined by the absence of a well-resolved axial domain in the XMCD-PEEM images. The measured dependence of magnetic configuration on geometry not only agrees closely with the numerical simulations, but is also qualitatively consistent with analytical predictions for cylindrical ferromagnetic NTs by Landeros et al.\(^9\)

If we consider NTs with opposing chirality, a similar phase boundary can be defined between a mixed state configuration with opposing end vortices and an opposing vortex state incorporating a Néel wall (see Supporting Information). The transition from an axial central domain, found in the mixed state, to the Néel domain wall can be quantified by the presence of inflection points in plots of \( M_n/|M| \) along \( \hat{n} \). Unfortunately, the available spatial resolution of XMCD-PEEM is not sufficient to clearly determine the inflection points and therefore to distinguish between these two states.

In order to test the robustness of the remnant magnetization configurations, for some
Figure 4. Phase diagrams for (a) CoFeB and (b) Py NTs as a function of $l$ and $d$ considering only equal chirality magnetization configurations. The numerically calculated order parameter $M_n/|M|$ is plotted in the color scale and defines the boundary between the mixed and global vortex state. Red (white) points show measurements of real NTs in global vortex (mixed) states as measured by XMCD-PEEM (see Supporting Information). Black points show NTs that switched remnant configuration after we applied 40 mT along $\hat{n}$.

NTs, we take a second set of XMCD-PEEM images in remnance after applying 40 mT along $\hat{n}$ *in situ* to saturate the NTs. In 11 cases, the measured remnant configuration is observed to be identical to the one initially measured, while in 6 cases the relative chirality of the end vortices changes. According to the simulations, in these 6 cases, the dimensions of the NTs are such that a matching or opposing chirality does not significantly affect its magnetic energy (see Supporting Information). These include long NTs in mixed states and NTs
calculated to be close to the phase boundary between where opposing or equal chirality is favored (black points in Figure 4 (b)). Sample imperfections may trigger the chirality change in such NTs.

In conclusion, we use XMCD-PEEM to image the remnant magnetization configuration of CoFeB and Py NTs for a variety of lengths. Our study reveals that short NTs can occupy a stable global vortex state in remnance. Consistent with an analytical theory by Landeros et al.\textsuperscript{9} and our own numerical simulations, the NT aspect ratio is found to play a crucial role in stabilizing the global vortex state. XMCD-PEEM images of the equilibrium magnetization configurations show that the relative chirality of vortex ends in real NTs is less controlled than expected from simulations. As a result, short NTs are found not only in remnant global vortex states, but also in opposing vortex states, which include a Néel wall between two opposing vortices. Additional simulations suggest that sample imperfections including variations in thickness and deviations from a perfect geometry are responsible for this discrepancy. Still, our magnetic images of global vortex states show that the most important properties predicted for idealized ferromagnetic NTs have been realized in real structures. They also demonstrate the programming of the equilibrium magnetic configuration of a ferromagnetic NT via geometry, a result consistent with long-standing theoretical predictions.

**Methods. Sample Preparation.** Ferromagnetic NTs are made by depositing a thin magnetic film on template GaAs NWs. These templates are grown by molecular beam epitaxy on a Si (111) substrate using Ga droplets as catalysts\textsuperscript{19}. For the CoFeB NTs, CoFeB is then magnetron-sputtered on the NWs, producing an amorphous and homogeneous 30-nm thick shell\textsuperscript{22}. For the Py NTs, a 30-nm thick polycrystalline shell of Ni\textsubscript{80}Fe\textsubscript{20} is deposited by thermal evaporation\textsuperscript{23}. During both depositions, the wafers of upright and well-separated GaAs NWs are mounted with a 35° angle between the long axis of the NWs and the deposition direction. The wafers are then continuously rotated in order to achieve a conformal coating.

**XMCD-PEEM contrast.** \( I_{\sigma^\pm} \) at any location is proportional to both on the intensity of the incident \( \sigma^\pm \) x-rays and their absorption at that location. Absorption of \( \sigma^\pm \) x-rays is proportional to the projection of the magnetic moment along \( \hat{k} \). Therefore, positive (red) or negative (blue) \( I_{\text{XMCD}} \) represents near surface magnetization either parallel or anti-parallel with \( \hat{k} \), respectively. For photoemission excited by x-rays that have previously
passed through magnetic material, however, the absorption in the traversed volume must also be considered\textsuperscript{15–17}. In our images, such magnetic contrast appears in the x-ray shadow of the NT on the non-magnetic substrate. Since the absorption of $\sigma^\pm$ x-rays is proportional to the projection of the magnetic moment along $\hat{k}$, there is also a proportional attenuation of $\sigma^\pm$ x-rays transmitted through the NT and incident in the shadow. The resulting $I^\pm_\sigma$ is therefore proportional to the magnetization of the volume traversed by the x-rays. This proportionality has opposite sign compared to that at a magnetic surface, i.e. positive (red) or negative (blue) $I_{\text{XMCD}}$ results from volume magnetization either anti-parallel or parallel to $\hat{k}$, respectively. Combining these two types of contrast, we extract information about both the surface and volume magnetization of the measured NTs\textsuperscript{15}. The roughly 100 nm spatial resolution of the XMCD-PEEM images depends on the quality of the focus and properties of the sample, including morphology and cleanliness.

\textit{Mumax3 simulations.} We set $\mu_0 M_S$ to its measured value of 1.3 T and 0.8 T and the exchange stiffness to $A_{\text{ex}} = 28 \text{ pJ/m}$ and 13 pJ/m for CoFeB and Py, respectively. In the simulations, space is discretized to 5 nm and thermal fluctuations are not included.

\textit{Supplementary Information (WyssSuppInfo.pdf).} This file included XMCD-PEEM and SEM images of all measured NTs, phase diagrams of relative vortex chirality, phase diagrams of NTs with opposing vortex chirality showing the phase transition between mixed and opposing vortex states, and plots of both simulated and measured vortex length as a function of NT diameter.

\section*{ACKNOWLEDGMENTS}

The authors thank Jaianth Vijayakumar, David Bracher, and Patrick Appel for technical support. We acknowledge the support of the Canton Aargau, the Swiss Nanoscience Institute, the SNF under Grant No. 200020-159893, the NCCR Quantum Science and Technology (QSIT), and DFG in the Schwerpunkt Programm “Spincaloric transport phenomena” SPP1538 via project GR1640/5-2.

\begin{thebibliography}{9}
\bibitem{1} R. P. Cowburn and M. E. Welland, \textit{Science} \textbf{287}, 1466 (2000).
\end{thebibliography}
2 M. M. Maqableh, X. Huang, S.-Y. Sung, K. S. M. Reddy, G. Norby, R. H. Victora, and B. J. H. Stadler, Nano Lett. 12, 4102 (2012).

3 S. Khizroev, M. H. Kryder, D. Litvinov, and D. A. Thompson, Appl. Phys. Lett. 81, 2256 (2002).

4 M. Poggio and C. L. Degen, Nanotechnology 21, 342001 (2010).

5 H. Campanella, M. Jaafar, J. Llobet, J. Esteve, M. Vázquez, A. Asenjo, R. P. d. Real, and J. A. Plaza, Nanotechnology 22, 505301 (2011).

6 X. F. Han, Z. C. Wen, and H. X. Wei, J. Appl. Phys. 103, 07E933 (2008).

7 N. A. Usov, A. Zhukov, and J. Gonzalez, J. Magn. Magn. Mater. 316, 255 (2007).

8 P. Landeros, S. Allende, J. Escrig, E. Salcedo, D. Altbir, and E. E. Vogel, Appl. Phys. Lett. 90, 102501 (2007).

9 P. Landeros, O. J. Suarez, A. Cuchillo, and P. Vargas, Phys. Rev. B 79, 024404 (2009).

10 A.-P. Chen, J. M. Gonzalez, and K. Y. Guslienko, J. Appl. Phys. 109, 073923 (2011).

11 A. P. Chen, N. A. Usov, J. M. Blanco, and J. Gonzalez, J. Magn. Magn. Mater 316, e317 (2007).

12 A. P. Chen, K. Y. Guslienko, and J. Gonzalez, J. Appl. Phys. 108, 083920 (2010).

13 D. Li, R. S. Thompson, G. Bergmann, and J. G. Lu, Adv. Mater. 20, 4575 (2008).

14 R. Streubel, L. Han, F. Kronast, A. A. Ünal, O. G. Schmidt, and D. Makarov, Nano Lett. 14, 3981 (2014).

15 J. Kimling, F. Kronast, S. Martens, T. Böhnert, M. Martens, J. Herrero-Albillos, L. Tatibanskis, U. Merkt, K. Nielsch, and G. Meier, Phys. Rev. B 84, 174406 (2011).

16 S. Jamet, S. Da Col, N. Rougemaille, A. Wartelle, A. Locatelli, T. O. Menteş, B. Santos Burgos, R. Afid, L. Cagnon, S. Bochmann, J. Bachmann, O. Fruchart, and J. C. Toussaint, Phys. Rev. B 92, 144428 (2015).

17 S. Da Col, S. Jamet, N. Rougemaille, A. Locatelli, T. O. Mentes, B. S. Burgos, R. Afid, M. Darques, L. Cagnon, J. C. Toussaint, and O. Fruchart, Phys. Rev. B 89, 180405 (2014).

18 A. T. Hindmarch, C. J. Kinane, M. MacKenzie, J. N. Chapman, M. Henini, D. Taylor, D. A. Arena, J. Dvorak, B. J. Hickey, and C. H. Marrows, Phys. Rev. Lett. 100, 117201 (2008).

19 D. Rüffer, M. Slot, R. Huber, T. Schwarze, F. Heimbach, G. Tüüncüoğlu, F. Matteini, E. Russo-Averchi, A. Kovács, R. Dunin-Borkowski, R. R. Zamani, J. R. Morante, J. Arbiol, A. F. i. Morral, and D. Grundler, APL Mater. 2, 076112 (2014).
20 T. Schwarze and D. Grundler, Appl. Phys. Lett. 102, 222412 (2013).
21 K. Baumgaertl, F. Heimbach, S. Maendl, D. Rüffer, A. Fontcuberta i Morral, and D. Grundler, Appl. Phys. Lett. 108, 132408 (2016).
22 B. Gross, D. P. Weber, D. Rüffer, A. Buchter, F. Heimbach, A. Fontcuberta i Morral, D. Grundler, and M. Poggio, Phys. Rev. B 93, 064409 (2016).
23 A. Buchter, R. Wölbing, M. Wyss, O. F. Kieler, T. Weimann, J. Kohlmann, A. B. Zorin, D. Rüffer, F. Matteini, G. Tütüncüoglu, F. Heimbach, A. Kleibert, A. Fontcuberta i Morral, D. Grundler, R. Kleiner, D. Koelle, and M. Poggio, Phys. Rev. B 92, 214432 (2015).
24 L. L. Guyader, A. Kleibert, A. F. Rodríguez, S. E. Moussaoui, A. Balan, M. Buzzi, J. Raabe, and F. Nolting, J. Electron. Spectrosc. Relat. Phenom. 185, 371 (2012).
25 A. Vansteenkiste, J. Leliaert, M. Dvornik, M. Helsen, F. Garcia-Sanchez, and B. Van Waeyenberge, AIP Adv. 4, 107133 (2014).