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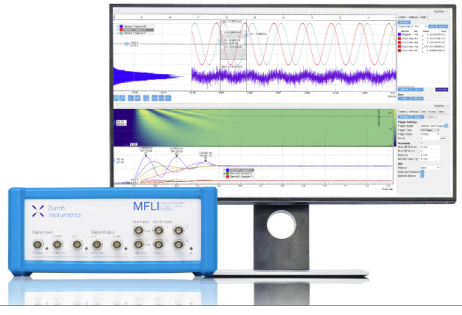
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ABSTRACT

We report on a wide variety of magnetic states in Co/Cu multilayered nanocylinders grown by electrodeposition with different thicknesses of both elements. The remnant magnetic states in individual Co layers have quantitatively been determined at the nanoscale by micromagnetic reconstruction of the magnetic phase shift image obtained by electron holography. We demonstrate that the magnetization in the Co layers can present either uniform or vortex states. Also, different magnetic configurations can be observed within the same nanocylinder. In the case of vortices, the direction of the core can rotate almost at 90° from the nanocylinder axis for layers with an aspect ratio close to 1. We show that the occurrence of each magnetic configuration depends on the aspect ratio of the layers, the direction of magnetocrystalline anisotropy, and, in some cases, the interlayer dipolar coupling. Such a wide variety of magnetic states is observed due to lower values of the Co magnetic constants (magnetization, exchange, anisotropy) with respect to bulk, typical of the electrodeposition process in a single bath, and to the local geometrical variation of the layers. We also calculated the phase diagram of the remnant magnetic states in a single layer for various amplitudes and orientations of the magnetocrystalline anisotropy and different directions of the saturation field. In particular cases, these phase diagrams, in addition to statistics of occurrence of each kind of magnetic configurations in the multilayer and the application of a saturation field in different directions, allow for recovering information on the preferential orientation of the crystalline anisotropy.

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I. INTRODUCTION

The understanding and observation of magnetic configurations in 3D nanostructures is a major topic in nanomagnetism. As recently pointed out in a review by Fernandez-Pacheco *et al.*,[1] 3D magnetism opens some new paths for magnetic sensors, high-density data storage, or magnetic domain wall based devices. In particular, domain walls in cylindrical nanowires, i.e., nanocylinders (NC), and nanotubes[2] are particularly attractive for developing Racetrack memory[3] as they can be manipulated with velocities above the usual Walker limit encountered in nanostripes.

Despite the strong interest in these novel cylindrical nanostructures, the magnetic configurations in multilayered systems with such geometry have been poorly studied up till now while they present multiple advantages for many magnetic applications. Besides the possibility of having high giant magnetoresistance[4] at room temperature, they can be basic blocks for synchronized spin torque nano-oscillators.[5] They are also interesting for developing thermoelectric applications[6] or novel magnonic devices.[7] In order to realize such applications, controlling the magnetic states of the different magnetic layers is a crucial step. However, variations of structural, geometrical, and chemical properties of the layer have a direct impact on its magnetic configuration and, therefore, on device performance. For example, it has been demonstrated that the remnant state in NC of uniform chemical composition can show different configurations due to variations of the magnetocrystalline anisotropy or NC diameter.[8–16] In multilayers, interlayer dipolar coupling further complicates the understanding of the

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magnetic state as metastable states in the individual layers can be stabilized. It is then a key point to have a deeper knowledge of the interplay between magnetic states and local properties in multilayers in order to control the properties of the potential devices.

Several techniques can be used for elaborating multilayered nanowires. Among them, the electrodeposition method has been widely employed as it is particularly efficient to get tens of multilayers and is quite easy to set up. However, multilayers are generally grown from a single bath containing all chemical ions to be deposited. As a consequence, the codeposition of at least one of the chemical species in the other is very difficult to avoid[17,18] inducing local variations of the chemistry of the layers, which might change the magnetic properties of the targeted material. Special care on the growth conditions then has to be given to get reproducible devices, besides a fine structural, chemical, and magnetic analysis on the artificial alloy.

To achieve this, one of the main challenges is the observation and determination of magnetic configurations at the nanometer scale in relation to the variation of the structural parameters. In this work, we combined different electron microscopy techniques and micromagnetic simulations for a deeper understanding of the magnetic states in Co/Cu multilayered nanocylinders. We used off-axis electron holography (EH) to study the remnant magnetic states and the structural parameters of different NCs varying the Co and Cu thicknesses with a spatial resolution of 2 nm. This is about 30 times better than pioneering studies[19,20] of magnetic states in multilayered wires by EH and almost 5 times better than recent experiments.[10] Complementary structural and chemical properties were determined by conventional and high-resolution (HR) electron microscopy, energy filtered transmission electron microscopy (EFTEM), and electron energy loss spectroscopy (EELS). Our methodology based on the quantitative comparison between the experimental and calculated magnetic phase shift image (MPSI) allows discriminating between different possible magnetic states. This work completes our previous report on the magnetic configurations in a $Co_{25\,nm}/Cu_{15\,nm}$ electrodeposited nanocylinder.[21] Here, we focus our attention on the influence of the dipolar coupling and aspect ratio of the different layers on the remnant states. All observed magnetic configurations are explained as a function of the intrinsic parameters of the layers. In particular, magnetocrystalline anisotropy, which is intrinsically related to the local structure of the layer, is found to play a major role.

II. EXPERIMENTAL METHODS

Nanocylinders were grown by electrodeposition in commercial polycarbonate membranes. Their diameters range between 70 and 90 nm. In order to study the effect of the aspect ratio and dipolar coupling on the magnetic states, four series of samples with different nominal Co and Cu thicknesses have been realized, namely, $Co_{25\,nm}/Cu_{15\,nm}$, $Co_{25\,nm}/Cu_{45\,nm}$, $Co_{50\,nm}/Cu_{50\,nm}$, and $Co_{100\,nm}/Cu_{100\,nm}$. The Co/Cu NCs were grown in a pulsed mode in a single bath solution containing 0.43 mol/l of $CoSO_4{\cdot}H_2O$, 0.01 mol/l of $CuSO_4$, and 0.58 mol/l of H_3BO_4. The potential of the electrical pulses used for the deposition of the Co and Cu layers were −1.0 V and −0.3 V, respectively. Removing as much as possible of the polycarbonate membrane is a crucial step for electron holography experiments allowing an increase in the signal/noise ratio of the magnetic image. Multiple washing of the samples in dichloromethane was then performed after the electrodeposition process to remove the polycarbonate from the NCs. The final step consisted of depositing the clean NCs on a holey carbon grid before electron microscopy studies.

Bright field (BF), high-resolution, EFTEM, and EELS experiments were realized for structural and chemical studies using a Tecnai F20 microscope operating at 200 kV, fitted with an objective lens aberration corrector (CEOS) and a GIF Tridiem to acquire elementary maps of Cu and Co using the three window method[22] and filtering the signal coming from the Co-L edge (778 eV) and Cu-L edge (931 eV).

Off-axis electron holography (EH) experiments were performed on the same NCs using a dedicated HF3300C Hitachi TEM fitted with a cold emission gun providing high spatial and temporal coherence for interferometric studies. Dedicated Lorentz modes combined with the B-core corrector were developed to achieve a 0.5 nm spatial resolution in a field-free magnetic environment. All the holograms were recorded in a 2-biprism configuration[23] to avoid artifacts linked to Fresnel fringes and to set separately the interference area size and the fringe spacing. The fringe spacing has been set to 1 nm in this study. Phase and amplitude images were extracted from the holograms using homemade software based on classical Fourier analysis (FFT). The size of the digital mask used in the FFT was chosen to obtain a spatial resolution of 2 nm on the phase and amplitude images. The magnetic and electrostatic contributions to the phase shift were separated by switching the sample upside down. The magnetic phase shift image (MPSI) corresponds to the component of the magnetic induction **B** perpendicular to the electron beam direction and projected over the beam path. Prior to the EH observation of the remnant magnetic states, the NCs were saturated with a magnetic field of 1 T produced by an external electromagnet. A first observation was performed with a saturation field ($\mu_0\mathbf{H_s}$) applied in a direction parallel (PL configuration) to the NC axis before a second observation after saturation perpendicular (PP configuration) to the NC axis. The precision of the alignment between the NC axis and the field is estimated to be lower than 10°. For all set of samples except $Co_{100\,nm}/Cu_{100\,nm}$, about 15 NCs were observed in order to discuss the statistic of the appearance of the different magnetic configurations.

To recover the magnetic configurations observed in the MPSI, we performed micromagnetic simulations of the magnetic remnant states and compute the corresponding simulated MPSI. We first sum the magnetization **M** and dipolar field $\mathbf{H_d}$ to calculate the induction field $\mathbf{B} = \mu_0(\mathbf{M} + \mathbf{H_d})$. Then, the corresponding MPSI was numerically computed by integrating the components of **B** parallel to the object plane along the electron path (y direction in our experiment and simulations) using the following expression:

$$\phi_M(\boldsymbol{R}) = -\frac{e}{\hbar}\iint \mathbf{B}_\perp(\mathbf{r}_\perp, y)\mathrm{d}\mathbf{r}_\perp \mathrm{d}y, \tag{1}$$

where ϕ_M is the magnetic phase shift, $\boldsymbol{R}$ is the three-dimensional (3D) position vector, e is the elementary electron charge, $\hbar$ is the reduced Planck constant, $\mathbf{B}_\perp$ is the perpendicular magnetic component to the electron path (i.e., parallel to the object plane), and $\mathbf{r}_\perp$ is the position vector in the object plane (the x-z plane here).

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Micromagnetic simulations were realized using the 3D OOMMF package,[24] in a universe of $180 \times 180 \times 180\ nm^3$ for the single layer phase diagram and $2400 \times 600 \times 600\ nm^3$ for multilayers. The cell size is $3 \times 3 \times 3\ nm^3$, close to the spatial resolution of the experimental MPSI and below the exchange length of cobalt (≈5 nm with our experimental values of magnetization and exchange given below). All 3D remnant magnetic states presented below were calculated after saturation with a 1 T magnetic field applied parallel or perpendicular to the NC axis and a misalignment of 10° to reproduce the uncertainty of the experimental conditions. The average structural parameters deduced from TEM experiments, such as orientation, thickness, and diameter of the layers were implemented in OOMMF with a homemade script. In order to reproduce as much as possible the real geometry of the Co layers and, in particular, the orientation of the layers with respect to the NC axis, we applied the following procedure. We first defined a disk with nominal thickness and very large lateral dimensions with respect to the NC diameter. Then, a cylinder with a nominal diameter of the NC obtained by TEM measurements is passed through the layer. The layer was tilted around the y- and x-axis with angles deduced from the TEM analysis. Only the volume determined by the intersection of the initial layer and the cylinder was considered as the Co part. We then adjusted all the parameters (tilt angles, thickness) until the apparent thickness and orientation of the layer in the TEM image were respected. At the end of this process, a complex geometry similar to a cylinder with two tilted surfaces was recovered. In our simulations, the electron path corresponds to the +y to −y direction as shown in Fig. 1.

The magnetic parameters of the simulations are the magnetization amplitude Ms, the exchange constant A, and the direction θ_k and amplitude K_u of the magnetocrystalline anisotropy $\mathbf{H_k}$. For the latter, our model considers only uniaxial crystal anisotropy. This assumption relies on the polycrystalline nature of the Co layers averaging the anisotropy. For every simulation, the starting values of Ms, A, and K_u are 1200.10^3 A/m ($\mu_0 M_s$ 1.5 T), 22.10^{-12} J/m, and 130.10^3 J/m^3 ($\mu_0 H_k$ 1.5 T), respectively. These values are the ones obtained from our previous experiments on $Co_{25\,nm}/Cu_{15\,nm}$.[21] Finally, the value of M_s corresponds to the average value measured using EH experiments on single Co NCs grown in the same electrochemical bath (not shown here). After the first simulation, the parameters are adjusted until the qualitative and quantitative agreement with the experimental MPSI. With this method, we recover the 3D magnetic configuration of the layers as well as the underlying magnetic parameters.

III. STRUCTURAL ANALYSIS

A bright field (BF) TEM image of a typical Co/Cu multilayered NC with 50 nm/50 nm nominal thicknesses is shown in Fig. 2(a). It presents an average diameter of 85 ± 2 nm. It is obvious that the different layers are difficult to observe by conventional TEM techniques as the difference of contrast between Co and Cu is quite weak. In order to precisely determine the position and the shape of the different layers, we performed EFTEM experiments over the same area. Figures 2(b) and 2(c) present the corresponding elemental maps of Co and Cu, respectively. Figure 2(d) is the combination of the previous maps where the alternation of Co and Cu

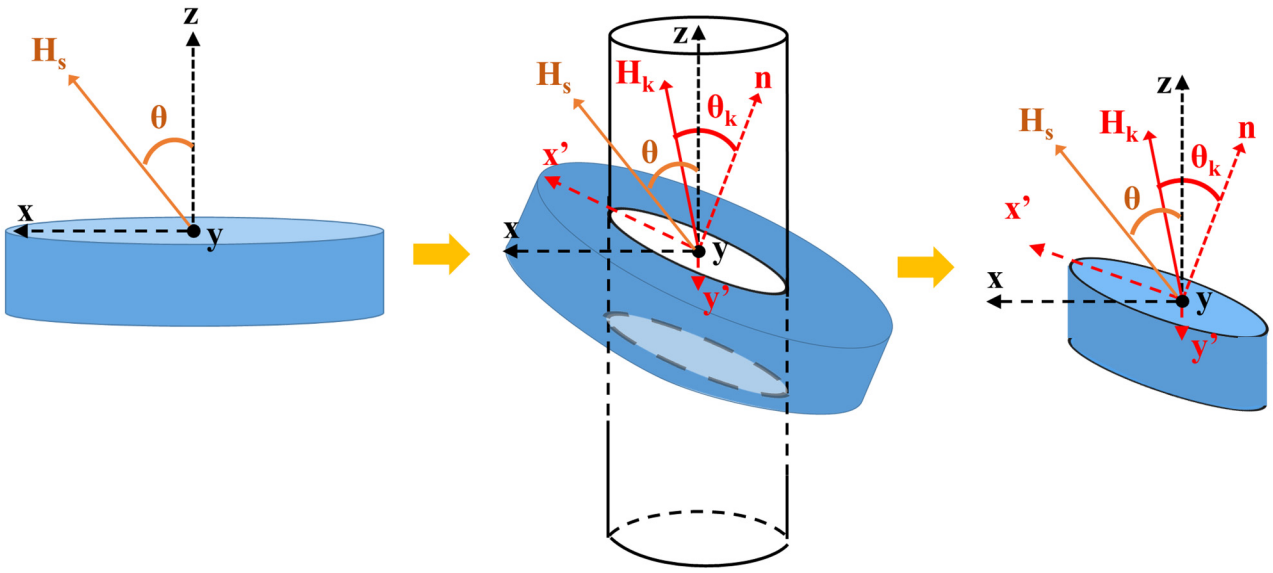


FIG. 1. Scheme of the procedure to define the geometry of one layer in the micromagnetic simulations. **n** is the unit vector perpendicular to the plane of the layer. x′y′n corresponds to the orthogonal rotated frame after rotation of the layer around the y- and x-axis. θ_k is the relative angle between **n** and the direction of the magnetocrystalline anisotropy field $\mathbf{H_k}$. $\mathbf{H_s}$ is the external saturation magnetic field.

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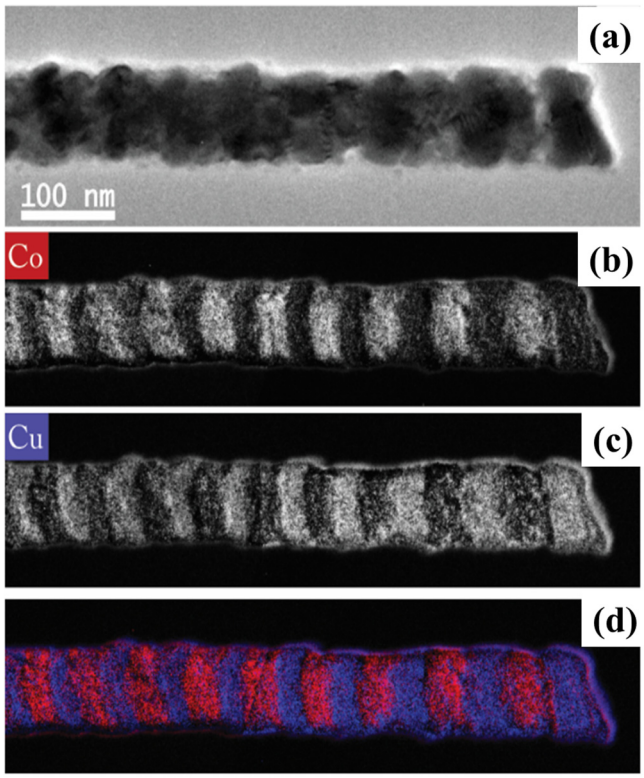


FIG. 2. (a) Bright field transmission image of a Co/Cu nanocylinder. EFTEM images of the same NC recorded at the cobalt (b) and copper (c) edge. (d) Cobalt (red) and copper (blue) map as the result of the superimposition of (b) and (c).

layers is clearly seen in red and blue, respectively. We observe that some of the layers are rotated a few degrees with respect to the expected position (90° with respect to the wire axis). While Co impurities are barely visible in the Cu layers, a non-negligible amount of Cu seems to be present in the Co layers.

To quantify the amount of the Cu impurities in the Co layers, EELS spectra have been recorded on different Co/Cu multilayered NCs (see supplementary material in Ref. 21). The extracted data confirm a very low Co amount in the Cu layers but give a Cu amount of about 15% in the Co part. This result has already been obtained in other works[25–27] and is due to the lower Co deposition potential (−1.0 V) compared to that of Cu (−0.3 V). As a consequence, a small amount of Cu is codeposited during the Co deposition if a single bath method is used in the electrodeposition process.

Statistical analysis was performed from the EFTEM images on tens of layers observed in the different wires that give a distribution of apparent thickness for each set of samples. In Table I, the relation between the nominal and measured thicknesses of the layers with the corresponding standard deviation is shown. The nominal thickness is defined as the one expected from the duration of the Co and Cu voltage pulses. The distribution indicates that the standard deviation increases with the increase of the NC thickness. However, the

TABLE I. Nominal and measured thicknesses for different sets of Co/Cu NCs with the corresponding standard deviation extracted from the statistical TEM analysis.

Nominal thickness Co/Cu (nm/nm)	Average measured thickness Co/Cu (nm/nm)	Standard deviation (nm/nm)	Mean diameter (nm)	Standard deviation of the mean diameter (nm)
25/15	24/14	4/8	65	10
25/45	22/46	5/14	74	7
50/50	42/46	13/17	68	8
100/100	90/110	24/44	69	10

mean thickness of the electrodeposited layers remains in good agreement with the nominal thicknesses. The mean diameter for each set of samples and the standard deviation are presented in Table I. The NC diameter varies between 50 nm and 90 nm regardless of the thickness of the layers. These values are 2–3 times larger than the nominal pore size labeled by the manufacturer (30 nm). The difference between the real and the nominal pore size given by the manufacturer has been already observed.[28] Different explanations exist[29,30] as, for instance, the variation of the cross section of the pores in the membrane pores that are not cylindrical.

High-resolution (HR) TEM images demonstrate the polycrystalline structure of Co and Cu layers with grains randomly oriented presenting a mean size of 7 ± 2 nm [Fig. 3(a)]. The polycrystalline character of the Co and Cu layers is confirmed calculating the FFT of HRTEM images as presented in Fig. 3(b). The analysis of the ring diameters and spacing indicates polycrystalline cubic (fcc) phases for Co and Cu as expected when some Cu is inserted into the Co layer,[31,32] which was confirmed by EFTEM and EELS analysis. Similar characteristics as the ones presented in Fig. 3 are found for all multilayered Co/Cu NCs whatever the Co and Cu thicknesses are.

IV. MAGNETIC PROPERTIES OF A SINGLE LAYER

In order to understand which magnetic configurations can be expected in our complex geometries and how they appear in the MPSI, we first present micromagnetic simulations of the phase diagram in a single layer, i.e., without taking into account the dipolar interaction between neighboring Co layers. To reproduce the geometrical uncertainty of our real system, simulations were performed considering a tilt of 15° and 5° around the y- and x-axis, respectively, with z being the NC axis. The values of Ms, A, and K_u are 1200.10^3 A/m ($\mu_0 M_S$ 1.5 T), 22.10^{-12} J/m, and 130.10^3 J/m^3, respectively. These values correspond to the one obtained to reproduce the magnetic configurations observed in Fig. 2 of Ref. 21. In the following, we will use θ and φ as the azimuthal and the longitudinal angles, respectively (spherical coordinates) in the xyz reference frame. θ_k and φ_k are the azimuthal and the longitudinal angle, respectively, in the rotated x′y′n frame related to the tilted surface of the layer (see Fig. 1). Here, we took different orientations of $\mathbf{H_s}$ either parallel (θ = 10°, φ = 10°) or perpendicular (θ = 80°, φ = 10°) from the wire axis. Two different orientations θ_k of the crystal

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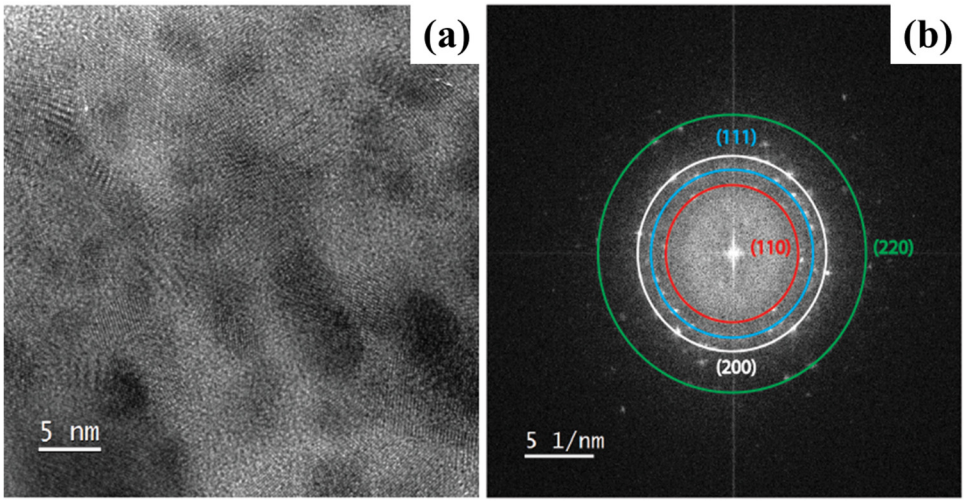


FIG. 3. (a) High-resolution TEM image and (b) FFT pattern of a Co layer calculated from (a).

anisotropy $\mathbf{H_k}$ with respect to the normal of the layer **n** has also been considered. However, all orientations (θ_k and φ_k) of the crystal anisotropy were not tested to limit the simulation time. So we arbitrarily considered θ_k to be equal either to 10° or 80° with $\varphi_k = 20°$. The results of these simulations are presented in Fig. 4.

Basically, we can observe four different states that are color coded in Fig. 4. We will not focus on the transition states [orange in Fig. 4(c)] that appear in particular cases we did not experimentally observe. The blue and turquoise colors correspond to uniform magnetic configurations, with the magnetization pointing either in the Co layer plane (in-plane "IP" state) or along the NC axis, i.e., z direction (out-of-plane "OP" state), respectively. The green and red colors represent the vortex states with the core pointing either perpendicular (VOP state) to the layer plane or roughly in the layer plane (VIP state, the angle between the direction of the core and **n** being at least >45°). It is worth noting that micromagnetic simulations show the appearance of vortices for thicknesses down to 25 nm. For perfect layers, i.e., with surfaces perfectly perpendicular to the z-axis (flat disks), the limit thickness to get vortices is at least 30 nm. The fact that vortex states are favored in our particular geometry demonstrates the importance of being as close as possible to the real geometry of the sample in micromagnetic simulations at very small scales.

The occurrence of the different states is related to the aspect ratio (thickness/diameter) of the layer and the competition between the shape and magnetocrystalline anisotropies with the direction of the applied saturation field $\mathbf{H_s}$. For example, these diagrams emphasize the importance of the direction of both $\mathbf{H_k}$ and $\mathbf{H_s}$. When $\mathbf{H_k}$ rotates from out-of-plane axis to in-plane axis, the area corresponding to the IP state grows as expected. Interestingly, $\mathbf{H_k}$ also influences the orientation of the vortex core. As shown in Figs. 4(a) and 4(c), for small values of θ_k and an aspect ratio close to 1, the vortex core rotates toward the layer plane, with a typical angle between **n** and the vortex core >60°, in order to decrease the magnetocrystalline energy. Indeed, when the core rotates, a bigger portion of the magnetic volume aligns with $\mathbf{H_k}$. As observed in Figs. 4(c) and 4(d), such a feature almost disappears for $\theta_k = 80°$. Typically, we verified that it strongly reduces when θ_k is above 30°.

We also observed a strong effect of the $\mathbf{H_s}$ direction on the remnant states. Indeed, for both orientations of θ_k, we obtained an increase in the area corresponding to vortices when $\mathbf{H_s}$ is applied perpendicular to the layer plane. Interestingly, for particular aspect ratios, the system can switch from IP to VOP states by tuning $\mathbf{H_s}$. This behavior, already observed in our previous report,[21] shows that the application of a saturation magnetic field in different directions might be a tool to recover information on the intrinsic parameters of the nano-objects.

In order to determine the different magnetic configurations of the layers, we first need to define how they appear in the MPSI. It is first important to remember that the images recorded in off-axis EH correspond to the 2D projection of the magnetic induction field **B** perpendicular to the electron beam and integrated over the entire path. This 2D projection can lead to misinterpretations in the determination of the remnant states. To give simple examples, we present in Fig. 5 the MPSI of different simulated magnetic configurations. The simplest configuration corresponds to the case of the IP state for which the magnetization is uniform in the layer plane and oriented perpendicular to the direction of the electron path. The IP state of each Co layer favors an antiparallel coupling (AP state) between them due to interlayer dipolar coupling. In such a case, the MPSI will appear as presented in Fig. 5(a). Following the isophase lines, corresponding to the color lines in the figure, which follow the direction of the $\mathbf{B}_\perp$ components, we observe a magnetization in the Co layers perpendicular to the NC axis (corresponding to the z-axis in Fig. 5) which alternately changes its direction from a Co layer to the other. This variation of direction induces the change of color in each layer.

Figures 5(b)–5(e) show the variation of the MPSI for a perfect vortex state observed for different orientations of the layer. Figures 5(b) and 5(c) correspond, respectively, to a perfect alignment of the layer in relation to the NC axis and to a rotation around the y-axis. In these cases, the only non-null averaged

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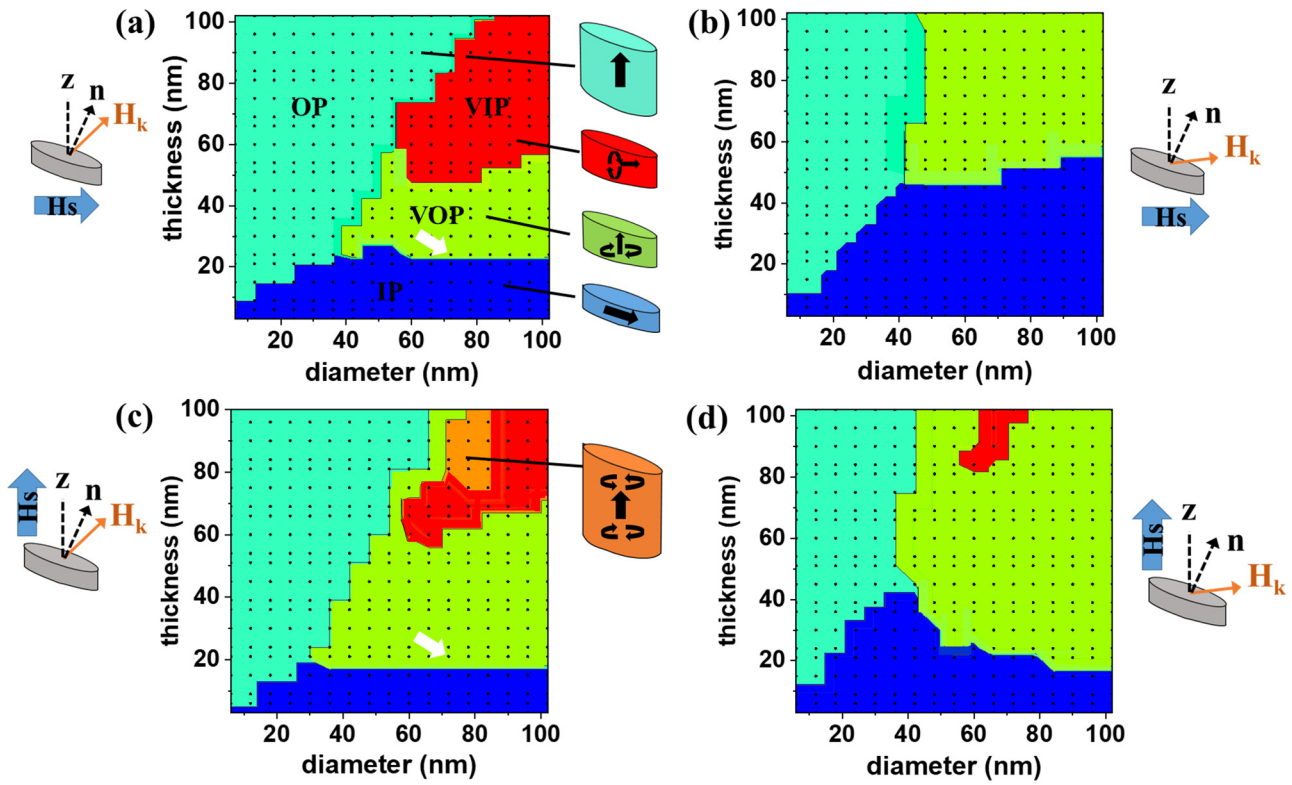


FIG. 4. Remnant state phase diagrams of a single tilted layer for different orientations of $\mathbf{H_k}$ and $\mathbf{H_s}$. θ_k is equal to 10° in (a) and (c) and 80° in (b) and (d). The different magnetic configurations are color coded in the diagrams and schematically represented with the same color code beside in (a) and (c). The black points in the diagram correspond to the simulated data. IP, in plane; OP, out of plane; VIP, vortex in plane; VOP, vortex out of plane. The white arrow in (a) and (c) shows the parameters used for the simulation of the multilayers system in Ref. 21.

component of the magnetization perpendicular to the electron path is the core of the vortex inducing a strong gradient of the phase shift at the center of the layer in the MPSI. The vortex core is recognized by following the isophase lines in the center of the layer. The situation is very different in Figs. 5(d) and 5(e). The layer in Fig. 5(d) is a 35 nm thick layer tilted around the x-axis (≈15°), while the one in Fig. 5(e) corresponds to a 55 nm thick layer that is not tilted at all. The direction of the vortex core is different between these configurations, pointing either perpendicular (VOP state) or parallel (VIP state) to the layer plane. However, they both appear qualitatively similar with a circular shape of comparable thickness in the MPSI after the 2D projection. In the 55 nm thick layer [Fig. 5(e)], the vortex core points in the direction of the electron path and the magnetic phase shift is only due to the rotating component of the vortex at the origin of the observed circular shape. In the tilted 35 nm thick layer [Fig. 5(d)], the electrons travel slightly across the plane of the layer allowing recovering a small part of the rotating components of the vortex. Therefore, the only possibility to differentiate between both states is to measure the amplitude of the corresponding phase shift at particular points, which is very different as shown in Fig. 5(f). This example demonstrates the importance of the quantitative analysis of the MPSI in order to determine the exact magnetic configurations.

V. MAGNETIC PROPERTIES OF MULTILAYERS

The situation is, of course, more complex in multilayered systems where Co layers can magnetically interact through the dipolar field. In Ref. 21, we have studied the remnant magnetic states in $Co_{25\,nm}/Cu_{15\,nm}$ multilayers. We found that whatever the direction of $\mathbf{H_s}$ is, about 70% of the layers showed the IP state leading to an antiparallel coupling (AP state) of the magnetization from one layer to the other, such as in Fig. 5(a). For $\mathbf{H_s}$ applied parallel to the NC axis, we observed a change of the magnetic configuration from AP to VOP states for only about 20% of the Co layers. Such a transition in multilayers was quantitatively simulated with the set of parameters used to calculate the phase diagram of Figs. 4(a) and 4(c) (see white arrows). For thicknesses around 25 nm, such transitions are not allowed in a single layer as the VOP state is stable. This demonstrates that the interlayer dipolar coupling in a multilayered system with thin nonmagnetic spacer such as $Co_{25\,nm}/Cu_{15\,nm}$ favors the IP states with an antiparallel coupling

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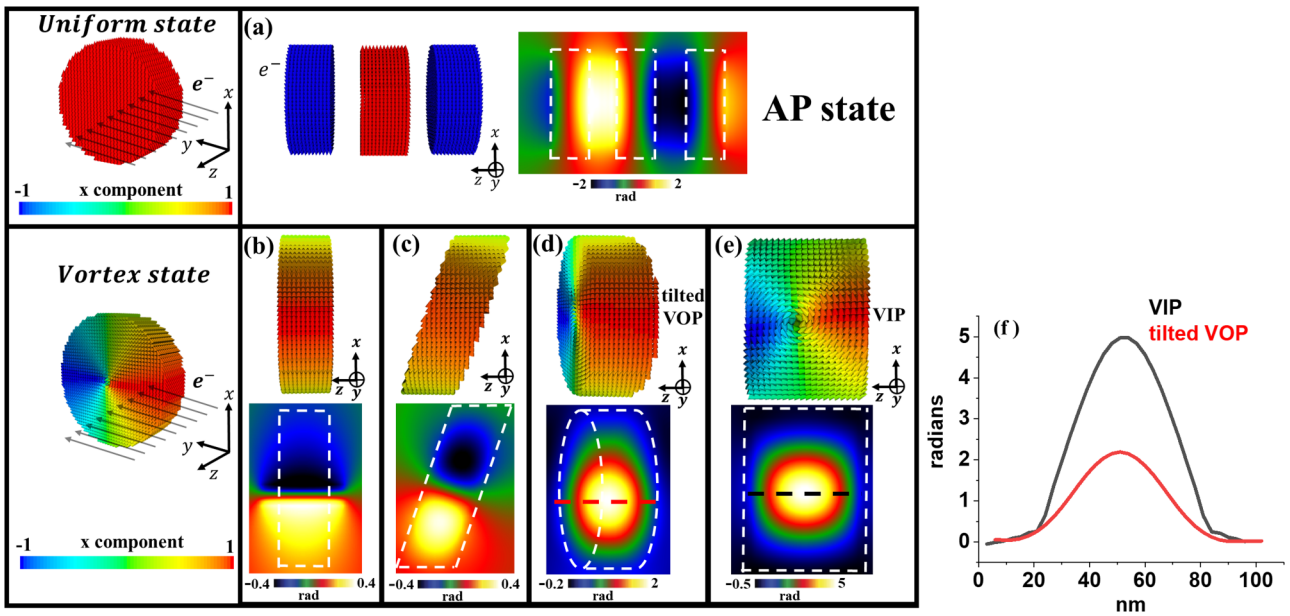


FIG. 5. MPSI of different magnetic states for the electron path along the y direction. (a) MPSI for three layers with uniform IP states with an antiparallel coupling (AP state). The layers are 20 nm thick and their diameter is 70 nm. (b)–(e) MPSI images calculated for a magnetic vortex state observed in four different layers with different orientations and thicknesses. The diameter of the layers is 84 nm. The thickness of the layers is 30 nm for (b) and (c), 35 nm for (d), and 55 nm for (d). (b) Orientation of the layer as expected perpendicular to the NC axis (corresponding to z). Layers tilted around the y (c) and x (d) axis. (e) Layer of 55 nm thickness not tilted showing a vortex with the core pointing in the y direction (VIP state). (f) Phase shift amplitude at the positions defined by the colored dotted line in (d) and (e). The white dotted boxes in the MPSI are guide for the eyes and correspond to the contours of the Co layers.

of the magnetizations (AP state). Another demonstration of the importance of the interlayer coupling was the observation in some rare cases of the OP state in $Co_{25\,nm}/Cu_{15\,nm}$ multilayers for NCs with a diameter of about 70–80 nm. Such configurations were reproduced in the simulation of multilayers considering $\theta_k < 20°$ in each layer and $K_u \approx 200 \times 10^3$ J/m^3 but was impossible to recover in a single layer.

A. $Co_{25\,nm}/Cu_{45\,nm}$ multilayered nanocylinders

In the present article, we have first studied $Co_{25\,nm}/Cu_{45\,nm}$ multilayers to investigate the effect of the dipolar coupling. In these NCs, we did not observe any effect of the direction of $\mathbf{H_s}$ on the remnant state. This can be seen in Fig. 6 showing the MPSI obtained at remanence in a NC with a diameter of about 80 nm. In particular, we neither found the AP to VOP transition nor the OP state. The reduction of the interlayer dipolar coupling with respect to the $Co_{25\,nm}/Cu_{15\,nm}$ multilayers is accounted for explaining this difference with the $Co_{25\,nm}/Cu_{15\,nm}$ multilayers. Indeed, micromagnetic calculations performed on two 25 nm thick Co layers with a 45 nm spacer (Cu thickness) show that the dipolar coupling energy in the AP state is roughly divided by 3 as compared to a 15 nm spacer. Let us note that for such Cu thickness, the $1/r^3$ dependence of the dipolar energy is not recovered as the "punctual magnetic

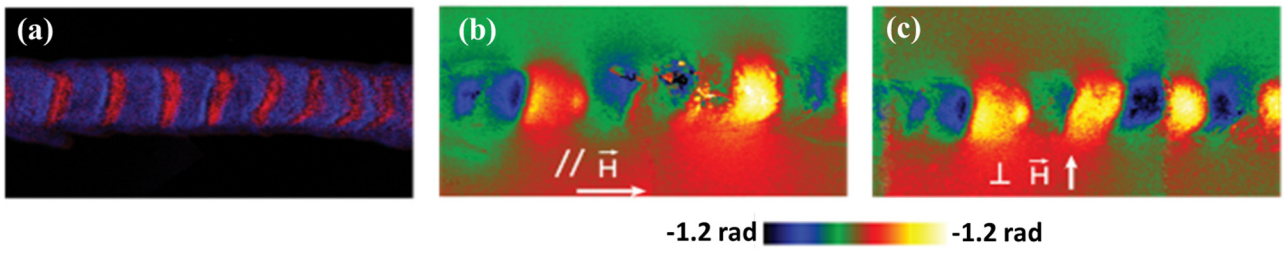


FIG. 6. (a) EFTEM image of a 80 ± 2 nm diameter $Co_{25\,nm}/Cu_{45\,nm}$ nanocylinder showing the copper (blue) and cobalt (red) layers. MPSI at remanence after 1 T saturation field applied parallel (b) or perpendicular (c) to the wire axis.

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dipole" approximation does not hold. Therefore, the dipolar coupling is no longer sufficient to stabilize the OP state or to favor the transition between AP to VOP states. However, as experimentally observed, the magnetization is not randomly distributed in the Co layer plane proving that the dipolar coupling is still sufficient to induce the AP configuration between layers.

Therefore, in this system, we can assume that the magnetic behavior of the layers is mainly governed by the shape and magnetocrystalline anisotropies. Also, information on the direction of $\mathbf{H_k}$ in the individual layer has to be recovered using the phase diagram in Fig. 4. Typical magnetic configurations encountered in this set of samples are shown in Fig. 7. We noticed that AP and VOP states can coexist in the same NC depending on the position in the wire. For both experimental MPSI in Fig. 7 obtained on 80 nm diameter NCs, we performed micromagnetic simulations to reproduce the corresponding AP and VOP states qualitatively and quantitatively, allowing to differentiate them. For example, while the MPSI in Fig. 7(c) seems to present only AP states, our micromagnetic analysis shows that a canted vortex is visible in the second Co layers. Such a feature appears for isolated vortices for which the core is not centered in the middle of the layer because of the stray field of the surrounding layers. Therefore, the averaged component of the magnetization in the x direction is non-null (the component of the vortex in the +x and −x directions does not fully compensate each other) leading to the measured phase shift profile.

In Fig. 7(d), we recover a situation similar to the case of Fig. 5(c), i.e., a VOP states in layers slightly tilted around the x-axis (about 10°). Then, the vortices appear as a rather circular shape in the MPSI. Simulations performed on 20 layers show that the VOP configurations are reproduced only if $\theta_k \leq 20°$ with an amplitude of at least 130×10^3 J/m^3. This result is in good agreement with simulations performed on a single layer, which show that the lower limit value of K_u to obtain the VIP state for each direction of $\mathbf{H_s}$ is about 100×10^3 J/m^3 (not shown here). To obtain the AP states, it is sufficient that $\theta_k \geq 20°$ whatever the amplitude of K_u.

Statistical analysis performed on more than 50 layers from different wires allows estimating that the AP configuration appears in about 60% of the layers and VOP state in about 40%. This result is quite surprising if we consider that the remnant states of each layer are governed by their intrinsic properties. Indeed, the average magnetocrystalline anisotropy should be randomly distributed from one Co layer to the other to reflect the random orientation of the polycrystals. This should favor the AP and IP states. To highlight this point, we performed micromagnetic simulations of the remnant state in a single layer with a diameter of 72 nm and a thickness of 24 nm as a function of K_u and θ_k. The results are shown in Fig. 8 for both $\mathbf{H_s}$ orientations (parallel or perpendicular to the NC axis). We see that VOP states are stable whatever the direction of $\mathbf{H_s}$ is only if the anisotropy direction is close to the normal of the layer plane. However, the layers we observed can show a small change in thickness, orientation, and even intrinsic magnetic parameters (Ms, A) due to local variations of the Cu impurities leading to different remnant states. But our observations suggest a preferential orientation of the magnetic anisotropy of Co layers along the NC axis in this system.

B. $Co_{50\,nm}/Cu_{50\,nm}$ multilayered nanocylinders

The study of $Co_{50\,nm}/Cu_{50\,nm}$ multilayered nanocylinders allowed us to investigate the effect of the aspect ratio. As compared to the 25 nm/15 nm case, the Co layers present an aspect ratio multiplied by two while micromagnetic calculations show that the

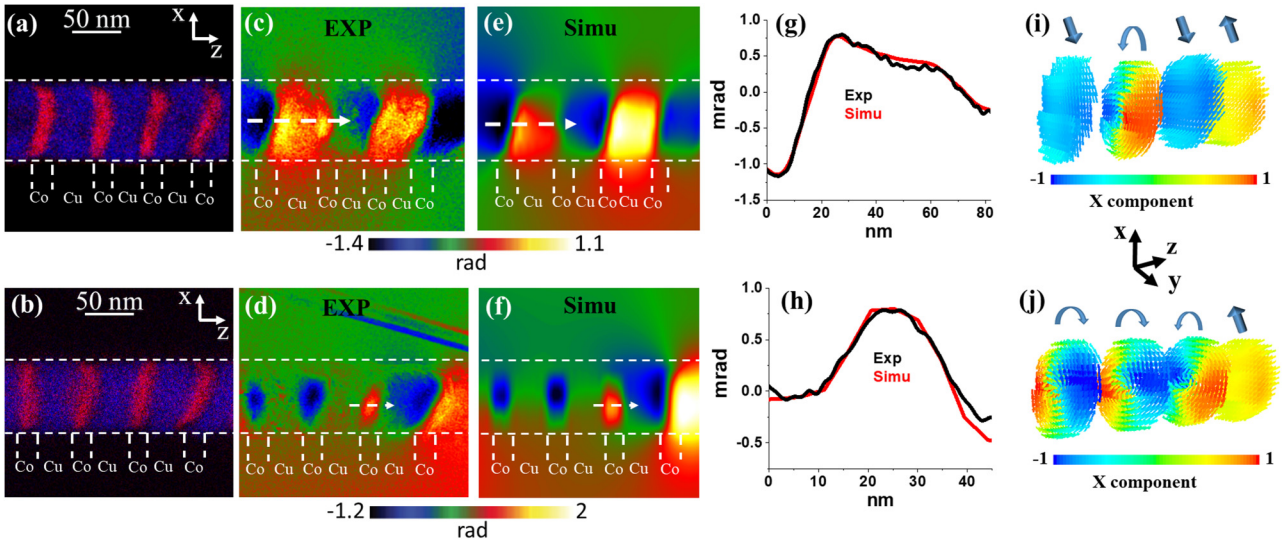


FIG. 7. (a) and (b) EFTEM image of two $Co_{25\,nm}/Cu_{45\,nm}$ NCs with a diameter of 80 ± 2 nm. Experimental [(c) and (d)] and simulated [(e) and (f)] MPSI of the nanocylinders for $\mathbf{H_s}$ applied perpendicular to the wire axis. (g) Experimental and simulated MPSI amplitudes at the position denoted by the white arrow in (c) and (e). (h) Experimental and simulated MPSI amplitudes at the position denoted by the white arrow in (d) and (f). (i) and (j) Corresponding 3D magnetic states in each Co layer.

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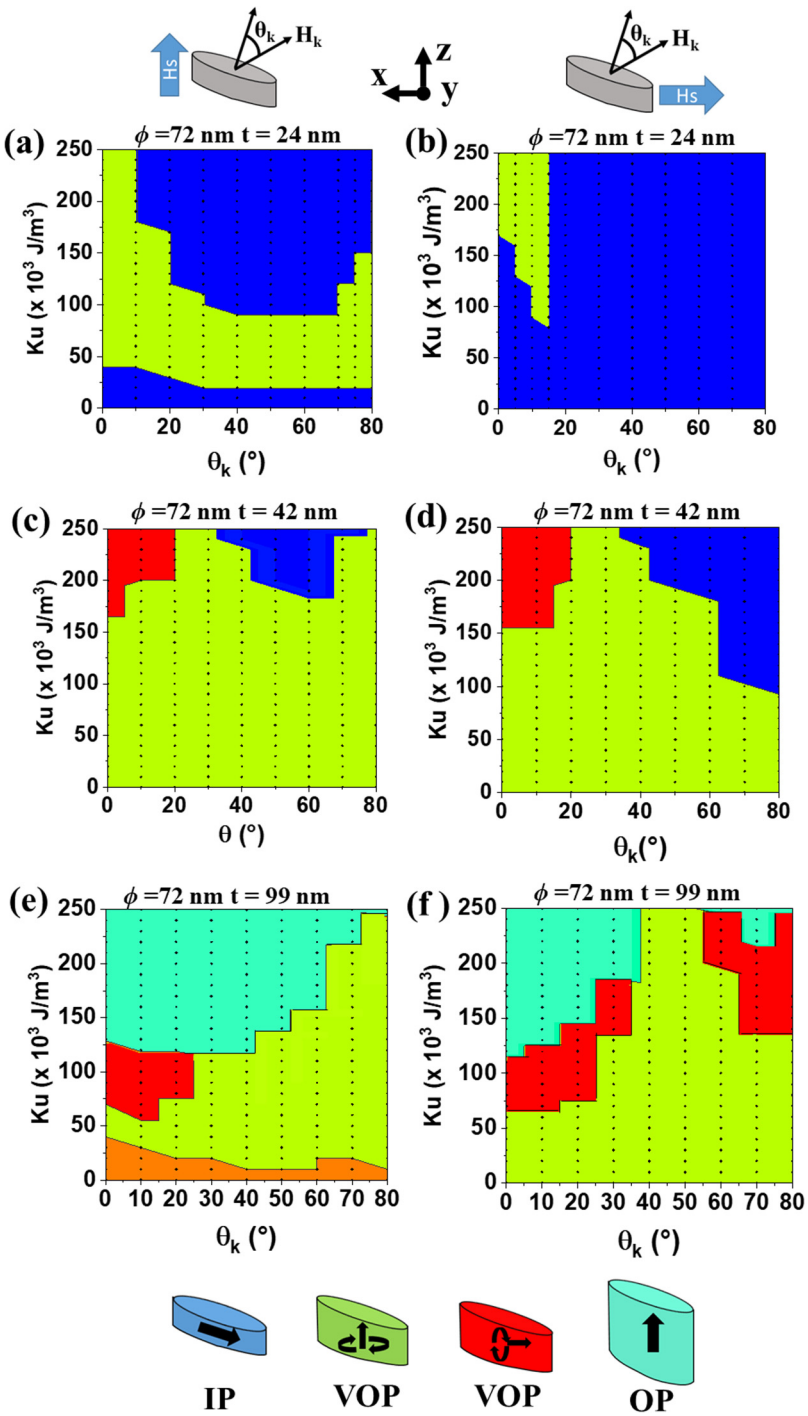


FIG. 8. Phase diagrams as a function of K_u and θ_k for $\mathbf{H_s}$ applied perpendicular ($\theta = 10°$, left column) or parallel ($\theta = 80°$, right column) to the plane of the layer. The thickness (t) and diameter (ϕ) of the layer is given above the diagrams. The layer is tilted by 15° and 5° around the y- and x-axis, respectively. The color code is the same as in Fig. 5, and the different states are reminded at the bottom of the figure.

dipolar coupling energy is roughly constant (≈20% lower than the 25 nm/15 nm case) in the AP state. Once again, no modification of the remnant states with the direction of $\mathbf{H_s}$ is observed. A typical feature of the different magnetic configurations encountered in all wires is presented in Fig. 9 (images recorded on a 84 ± 2 nm diameter NC). The EFTEM experiment shows that all layers present different apparent thickness and orientation, in agreement with the dispersion given in Table I. In order to recover the magnetic states

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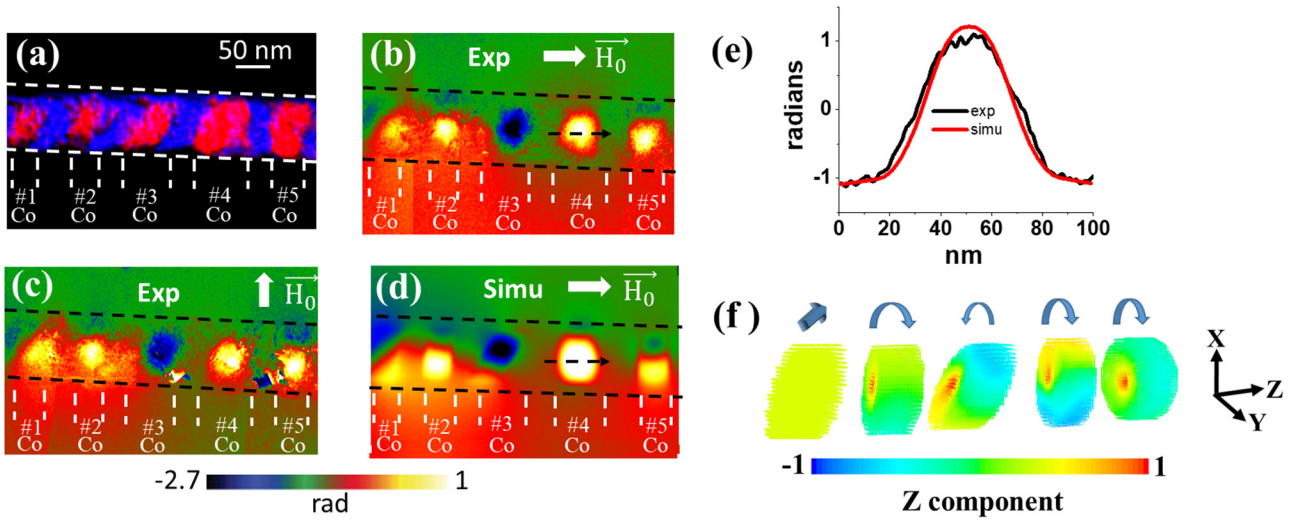


FIG. 9. (a) EFTEM image of a 84 ± 2 nm diameter $Co_{50\ nm}/Cu_{50\ nm}$ nanocylinder. Experimental MPSI for $\mathbf{H_s}$ parallel (b) or perpendicular (c) to the wire axis and simulated MPSI (d) for $\mathbf{H_s}$ parallel to the wire axis. (e) Experimental (black) and simulated (red) amplitude of the MPSI at the position denoted by the dotted arrow in (b) and (d). (f) Corresponding 3D magnetic state for the 5 Co layers.

of all layers, we performed micromagnetic simulations with an individual set of structural and magnetic parameters for each of the 5 Co layers (see Table II). These remnant states have been simulated for $\mathbf{H_s}$ parallel to the wire axis.

The qualitative and quantitative agreement between the experimental and simulated MPSI [Figs. 9(b) and 9(d), respectively] allows one to state that almost all layers present VOP states, even if the vortex cores are not always centered in the middle of the layer as shown in the 3D magnetic configuration in Fig. 9(f). The position of the cores is settled by the complex dipolar coupling between layers related to their variable orientations. This NC gives a clear example of the difficulty related to the 2D projection problem presented in Fig. 5. For instance, at first sight, the Co layer #4 should correspond to a thick layer (≈58 nm) with a VIP state [similar to Fig. 5(d)]. However, we could not fit the experimental phase shift amplitude with this configuration without decreasing the amplitude of the magnetization and the exchange down to 800×10^3 A/m ($\mu_0 M_S$ 1 T) and 12×10^{-12} J/m, respectively. Such a strong difference with the magnetic properties of the other layers is surprising for a thick layer. But a very good quantitative agreement with a VOP state is obtained using the magnetic parameters of neighboring Co layers if considering that the layer is tilted around the x-axis with an angle about 20°.

The presence of almost only VOP states is common to all studied NCs as only 2 IP states were observed over more than 50 layers investigated on different NCs. In particular, the IP state of the Co layer #1 in Fig. 9 was reproduced considering a much lower magnetization than for the other layers. This most probably comes from more Cu in the layer. This was confirmed by the EFTEM profile (not shown here). However, the phase shift amplitude is still about 20% higher than in the experiment. This might be due to a wrong estimation of the diameter of this layer if this one is surrounded by some Cu.

In order to understand further the quasiabsence of IP states, we performed micromagnetic simulations of the remnant state of a tilted single layer as a function of the K_u and θ_k. The diameter of

TABLE II. Structural and magnetic parameters for each layer in the simulation presented in Fig. 9.

	Co1	Cu1	Co2	Cu2	Co3	Cu3	Co4	Cu4	Co5	Cu5
Diameter (nm)	72		72		84		84		84	
Thickness (nm)	33	36	36	39	42	66	39	60	42	45
Tilt y	15		10		35		5		0	
Tilt x	0		10		10		22		10	
Ms (10^3 A/m)	700		1200		1200		1200		1200	
A ($\times 10^{-12}$ J/m)	20		22		22		22		21	
Ku ($\times 10^3$ J/m^3)	200		150		200		150		140	
θ_k (°)	40		5		10		30		10	
φ_k (°)	170		10		65		45		310	

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the layer is 84 nm, and the thickness is equal to 42 nm. The layer is tilted by 15° and 5° around the y- and x-axis, respectively. As can be seen from Figs. 8(c) and 8(d), VOP states are expected whatever the direction of $\mathbf{H_s}$ is only if K_u is weak (below 100×10^3 J/m^3 in the geometry of Fig. 8). This result indicates an averaged magneto-crystalline anisotropy weaker than the one of $Co_{25\,nm}/Cu_{45\,nm}$ NCs, in good agreement with the assumption that a thicker layer contains more grains and then a stronger averaging of $\mathbf{H_k}$.

Finally, when the layers are tilted around the x-axis, information about the chirality of the vortices can be recovered as the component of the magnetization in the layer plane can be measured. For example, the chiralities of the vortices in the Co layers #3 and #4 are opposite [Fig. 9(f)] as shown by the blue to red contrast between the two layers. However, over all the nanocylinders studied, we did not find any clear tendency of a preferential chirality. This is due to the fact that the chirality is partially dependent on the relative angle between $\mathbf{H_s}$ and $\mathbf{H_k}$ directions with $\mathbf{H_k}$ being randomly distributed from one layer to the other.

C. $Co_{100\,nm}/Cu_{100\,nm}$ multilayered nanocylinders

The last system we studied concerned $Co_{100\,nm}/Cu_{100\,nm}$ NCs for which the aspect ratio is >1. Figure 10 shows the two types of magnetic configurations we observed in different NCs, whatever the direction of $\mathbf{H_s}$ is. The NCs presented at the top and bottom of Fig. 10 have diameters of 60 and 90 nm, respectively. In the first case (60 nm diameter), the MPSI shows a uniform feature inside the layer. This distribution of isophase lines is expected in the case of a vortex state with the core aligned in the direction of the NC axis (VOP state) or if the magnetization is uniformly parallel to the NC axis (OP state). The comparison between the experimental and simulated amplitudes calculated for either the OP or the VOP states demonstrates that this magnetic configuration corresponds to the OP state. The best quantitative agreement between experimental and simulated data has been achieved with M_s, A, and K_u equal to 1100×10^3 A/m, 22×10^{-12} J/m, and 130×10^3 J/m^3 as magnetic parameters, respectively. The anisotropy is randomly distributed from one layer to the other within a cone centered on $\mathbf{n}$ with an aperture angle $\theta_k = 10°$.

The MPSI of the second nanocylinder presenting the largest diameter (90 nm) shows a circular shape, typical of a VIP state such as in Fig. 5(d). This has been confirmed by our simulation on 20 layers for which the best quantitative agreement corresponds to a vortex core in the xy plane, roughly at 45° from the y-axis. The simulation parameters are the same as those used previously. The layers have been tilted around the y-axis by 5° only. For such a

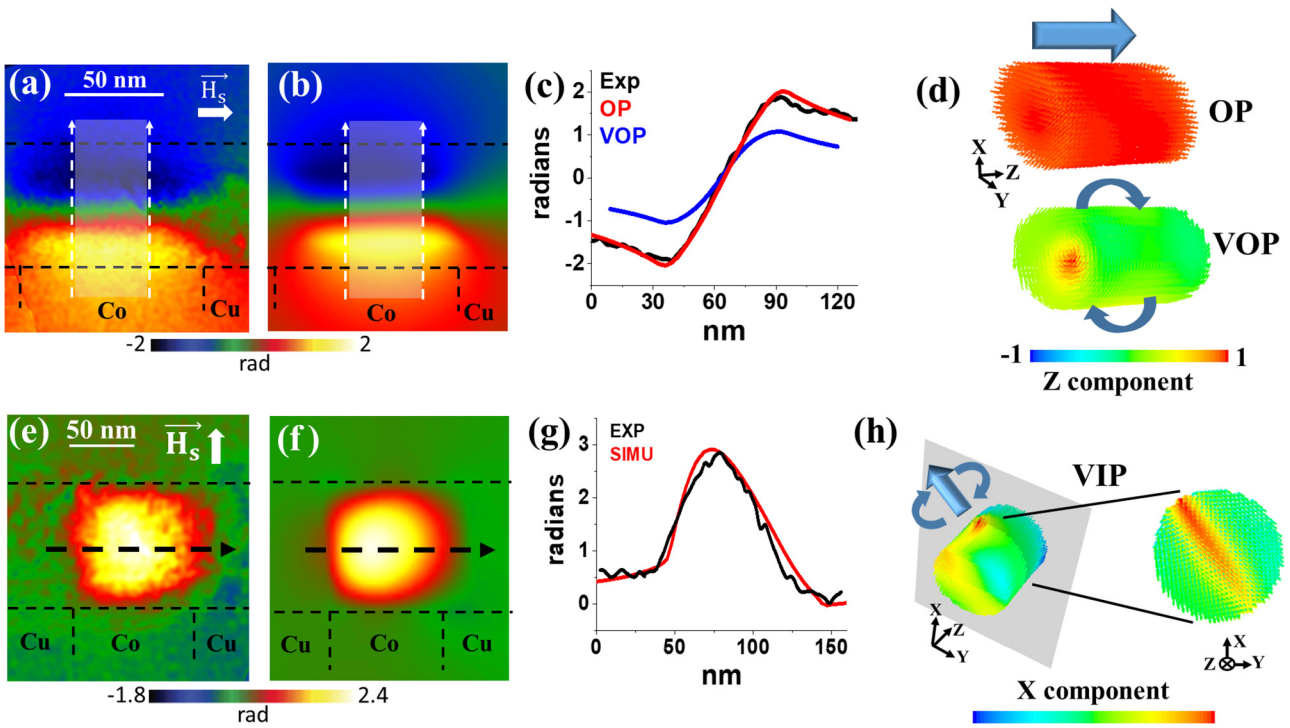


FIG. 10. Experimental (a) and simulated (b) MPSI for a $Co_{100\,nm}/Cu_{100\,nm}$ nanocylinder with a diameter of 60 nm. (c) Phase shift amplitude averaged in the shaded area shown in (a) and (b). The blue curve corresponds to the phase shift amplitude for a VOP state with the same qualitative MPSI. (d) 3D magnetic representation of the OP state corresponding to (b) and the VOP state used to calculate the MPSI amplitude shown in (c). Experimental (e) and simulated (f) MPSI for a $Co_{100\,nm}/Cu_{100\,nm}$ nanocylinder with a diameter of 90 nm. (g) Phase shift amplitude at the position denoted by the black arrow in (e) and (f). (h) 3D magnetic representation of the VOP state with the core of the vortex pointing in the xy plane. The figure at the right is a projection of the gray cut plane shown in the left figure.

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large thickness, the central part of the layer shows a cylindrical symmetry and only the surfaces are still tilted. Therefore, the potential problem of the orientation of the Co layer, as discussed in Fig. 9, in the understanding of the remnant state in the MPSI does not interfere. However, tilted surfaces still play a role as they favor the nucleation of vortex states.

We only observed the OP state in the studied NCs with diameters ranging between 50 and 70 nm. To understand this observation, we have then calculated the phase diagram as a function of K_u and θ_k for a Co layer with diameter and thickness of 72 nm and 99 nm, respectively. The results are shown in Figs. 8(e) and 8(f). Let us note that in this thickness range, the boundaries between the different regions of the diagrams vary rapidly with the diameter of the layer. However, some tendencies can be obtained. First, it appears that OP or VIP states are stable whatever the direction of $\mathbf{H_s}$ is only if the direction of $\mathbf{H_k}$ is close to the normal of the surface ($\theta_k = 10°$). The difference in the occurrence of each state is, therefore, related to the K_u value. The VIP state seems to be a transient state between the VOP and OP states. For example, for the particular aspect ratio of Figs. 8(e) and 8(f), the OP state is stable for high values ($>100.10^3$ J/m^3) of K_u. In this case, the magnetocrystalline energy counterbalances the cost in dipolar energy. When decreasing the value of K_u, the magnetization has to adopt a vortex structure to decrease the dipolar energy. The core of the vortex aligns perpendicularly to $\mathbf{H_k}$ in order to minimize the magnetocrystalline energy as most of the magnetic volume is kept aligned with $\mathbf{H_k}$.

Based on Figs. 8(e) and 8(f), we could expect to observe more VOP and VIP states in $Co_{100\,nm}/Cu_{100\,nm}$ NCs as the thick Co layers exhibit more grains, resulting in lower K_u values due to the random distribution of the grains. As already mentioned, we observed the opposite case for NCs with diameters between 50 and 70 nm. To understand this discrepancy between the single layer and the multilayer systems, we performed simulations on 20 $Co_{100\,nm}/Cu_{100\,nm}$ layers of 60 nm diameter. For each layer, $\mathbf{H_k}$ is randomly distributed in a cone centered on $\mathbf{n}$ and with an aperture angle θ_k of 10° or 80°. In the absence of crystal anisotropy ($K_u = 0$), the VOP state is the most stable configuration for all layers whatever $\mathbf{H_s}$ is. For $\theta_k = 80°$ and $Ku \neq 0$, VOP states are still stable for both directions of $\mathbf{H_s}$. However, the OP state becomes the most stable configuration whatever the direction of $\mathbf{H_s}$ is as soon as values of K_u as low as 50×10^3 J/m^3 with θ_k close to $\mathbf{n}$ are used. This is partially in agreement with the single phase diagram. The main differences are, first, the reduction of the value of K_u to recover the OP state and, second, the fact that we did not observe anymore the creation of VIP states stable for both directions of $\mathbf{H_s}$ in the multilayered structure. The explanation relies on the strong interlayer dipolar coupling that favors the alignment of the magnetization along the NC axis to reduce the dipolar energy. These simulations on multilayers are then in good agreement with the assumption of weak K_u values for very thick layers, for which the shape anisotropy and interlayer coupling stabilize the OP states. However, further investigation and statistics on these systems are required to state on this point.

VI. CONCLUSION

Co/Cu multilayered nanocylinders have been grown by electrodeposition in commercial polycarbonate membranes. We developed a methodology to study with a spatial resolution of few nanometers the magnetic states of these systems. To achieve this, we have combined electron holography and structural and chemical TEM studies with micromagnetic simulations. Simulations of the phase diagram of the remnant magnetic states of a single layer predicted four possible magnetic states depending on the aspect ratio of the layer, the application of a saturation field, and the direction of magnetocrystalline anisotropy. The magnetization can be either uniform within the layer or adopt a vortex structure with different orientations of the core. Such variations of magnetic states can be observed because of the low values of the Co magnetic constants with respect to bulk, typical of the electrodeposition process in a single bath.

We observed all these states by studying nanocylinders with different aspect ratios of the Co and Cu layers. We demonstrated that information on the crystal anisotropy, and then potentially on the local structure of the Co layers, can be recovered by applying a saturation magnetic field in different directions. Our observation seems to prove that the amplitude of the magnetocrystalline anisotropy decreases when increasing the thickness of the Co layer, in agreement with an averaging due to the random distribution of the crystallographic grains. However, the interlayer dipolar coupling can strongly modify the remnant state of a system as compared to the case of a single layer. For instance, we demonstrated that an antiparallel coupling of uniform states in very thin Co layers is favored, even for Cu thickness up to 40 nm. But in very thick layers with an aspect ratio close to 1, the dipolar coupling stabilizes the magnetization along the direction of the NC axis.

While electrodeposited nanocylinders are a nice playground for fundamental studies because of the wide variety of states, their use for potential applications requires further control of the structural properties of the layers. As an example, we often observed different configurations within the same nanocylinder due to the local variations of geometry and/or chemical composition. This might be a problem for applications such as spin torque oscillators. Indeed, the geometry and chemical composition of the layers must be the same for all layers in order to ensure the same resonance frequency and precession amplitude, and to allow phase locking between layers. Several strategies could be tested. To reduce the dispersion in the layer geometry, different templates should be tested, such as porous alumina membranes, which are known to have a small dispersion of the diameter along the pore and reduced roughness as compared to polycarbonate. For single bath deposition, the concentration of the normal metal to deposit has to be as low as possible to reduce interdiffusion and codeposition into the ferromagnetic material.

Finally, we also discussed experimental difficulties to discriminate between different magnetic states when observed by electron holography due to the uncertainty in the real geometry of the layers. 3D tomography is a solution to solve this problem,[33] allowing at the same time a much better determination of the magnetic constants of the layers.

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