Topologically confined vortex oscillations in hybrid [Co/Pd]₈-Permalloy structures

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We report on a reciprocal magnetic interaction mechanism in micrometer-sized hybrid Co/Pd-Permalloy square elements. Time-resolved scanning transmission X-ray microscopy using X-ray magnetic circular dichroism contrast together with micromagnetic simulations demonstrate that there exists a mutual imprint of vortices in the Permalloy and in the stripe domains of the Co/Pd. This results in a hybrid magnetic domain structure leading to a domain confined gyroscopic vortex precession. These observations open the exciting possibility for topological control of vortex core motion. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4873937>]

Hybrid magnetic bilayer films, where one layer has perpendicular anisotropy and the other has in-plane anisotropy, have an interface region where the competing anisotropies control the magnetic structure. While the domain structure and magnetic behavior of the individual layers of these hybrid films are well understood, their combination can lead to a more complex three-dimensional magnetic domain structure.^{1,2} These hybrid structures open up the possibility of diverse applications including exchange coupled composites^{3,4} for bit patterned media, which provide the possibility to reduce the switching field while maintaining a high thermal stability; high output spin torque oscillators;^{5,6} or as a hybrid waveguide material in magnonics^{7,8} leading to alternative modes of spin wave propagation. In this work, we focus on the potential of hybrid films as controlled vortex oscillators. In order to realize this potential, it is vital to understand in detail how the mutual interaction between the two layers modifies the domain structure. Existing experimental studies^{9–11} on continuous hybrid films have only provided indirect measurements of mutual domain interactions and concentrated mainly on the altered domain configuration in the layer with in-plane anisotropy.

In this Letter, we report on direct observations of domain structure imprint and mutual interaction in [Co/Pd]₈-Permalloy (Py) hybrid anisotropy films patterned into 1.5 μm square elements. Here, the Py (Ni₈₀Fe₂₀) layer has an in-plane anisotropy, and the Co/Pd multilayer has a perpendicular anisotropy with the easy axis of magnetization in the two layers being different in both magnitude and direction. We employ Scanning Transmission X-ray Microscopy (STXM)^{12,13} with X-ray Magnetic Circular Dichroism (XMCD),¹⁴ where the ability to tune the X-ray energy to element specific absorption edges allows the individual layers to be imaged. In the transmission geometry, the measured signal is integrated over the whole

volume of the element rather than just the surface. This makes STXM a useful tool to observe magnetic domains in the individual layers of hybrid anisotropy films. The dynamic response of the domain structure was explored with time resolved STXM experiments through application of a radio frequency (rf) magnetic field.¹⁵ Additionally, we performed micromagnetic simulations with the aim of gaining further insight into the static and dynamic magnetic configurations, as well as the mutual interaction of these hybrid anisotropy patterned elements.

In order to realise the experiment, a multi-stage fabrication process was developed to create patterned elements on X-ray transparent membranes. The samples consisted of 1.5 μm square [Co/Pd]₈-Py elements [Fig. 1(a)] fabricated on (Si₃N₄/Si)-membrane templates using electron beam lithography and sputtering. The perpendicular anisotropy layer [Co(0.3 nm)/Pd(0.9 nm)]₈ was deposited on a seed layer¹⁶ of Ta(1.5 nm)/Pd(1.5 nm). A Permalloy layer of 20 nm thickness, with in-plane anisotropy, was deposited

FIG. 1. (a) Hybrid magnetic thin film structure showing the magnetization orientation (represented by arrows) of idealized (non-interacting) magnetic layers. (b) Schematic of sample layout used for STXM imaging with square magnetic hybrid structures overlaid with a 10 μm wide Cu-stripline (dark grey) and adjacent Pt meander temperature sensors. The applied rf current passing through the stripline induces a magnetic field with a dominant in-plane component capable of exciting the structures under the stripline.

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directly on to the final Pd layer and a 1 nm Al protective capping layer was deposited on top of the film stack. In order to be able to apply an rf magnetic field to excite the patterned elements, an additional lithographic step was used to overlay the elements with an evaporated 200 nm thick copper stripline. The sample temperature was measured using platinum meander sensors fabricated close to the patterned elements. The central membrane area was covered by a 150 nm thick AlN heat-sink layer to distribute the thermal load generated during rf excitation. In the final step, the Si_3N_4 -membrane window was opened by wet etching in a potassium hydroxide (KOH) solution. The complete sample layout is shown schematically in Fig. 1(b).

The STXM experiments were carried out at the PolLux beamline (X07DA) at the Swiss Light Source. A high resolution Fresnel zone plate with 15 nm outer zone width focused the X-rays onto the sample, which was raster scanned. In order to observe magnetic contrast, the X-rays were tuned to either the Co L_3 edge (778 eV) or the Ni L_3 edge (852 eV), which allowed XMCD measurements of the Co/Pd or Permalloy layers to be made independently. The transmitted X-rays were detected using a fast avalanche photodiode (APD) capable of single photon counting, enabling magnetization changes to be recorded in the nanosecond time regime. The sample was tilted to an angle of 30° with respect to the incoming beam (Fig. 1(b)). The tilting is commonly used to image systems with in-plane components of magnetization, and for our samples allows both in-plane and perpendicular magnetization components to be imaged simultaneously which is key in avoiding alignment errors. Images were acquired in either a static or dynamic mode of operation. For static images, the magnetic contrast from XMCD measurements was enhanced by dividing images acquired using left and right hand circular polarisation.^{13,15} During dynamic image acquisition, a 15 dBm rf current was applied to the Cu stripline, creating a sinusoidal Oersted field¹⁷ to excite the domain structure. Synchronising the excitation signal to the synchrotron ring-clock allows dynamic imaging at defined phase angles relative to the rf magnetic field. Therefore, adjusting the phase of the rf excitation with respect to the synchrotron ring-clock provides images at any arbitrary point on the field cycle. We use a differential imaging technique for time resolved imaging, which gives the difference of two consecutive magnetic contrast images with a 180° phase shift. This technique reduces almost all “non-magnetic” and “non-dynamic” contrast contributions.¹⁵

Applying an rf excitation leads to an increase in the sample temperature which is measured by determining the resistance of the platinum meander sensors. Acquisition of data in the dynamic mode typically takes several minutes to ensure images with sufficient signal-to-noise ratio. During this time, the temperature remains constant at approximately 180°C .

The static STXM-XMCD images of these hybrid structures are shown in Figs. 2(a) and 2(c). The data show that domains in the Co/Pd layer are modified from the expected pure stripe pattern with the emergence of locally near circular structures indicated with white arrows. In the Py layer, an indistinct black/white contrast is observed rather than the expected Landau pattern. This diffuse domain structure is due to the fact that the measurement integrates over the

FIG. 2. Static [(a) and (c)] and dynamic [(b) and (d)] XMCD images of a $1.5\ \mu\text{m}$ hybrid square structure with 20 nm Py layer showing the vortex core interacting with the underlying Co/Pd circular stripe domain. The local effect of the coupling is indicated by arrows, where the core polarity is matched to the circular stripe domains. The opposite contrast shown in (b) and (d) confirms the magnetic origin of the data. (e) Three-dimensional schematic indicating a vortex pair with reversed polarities, represented by arrows, circulating in opposite directions and coupled to the Co/Pd circular domains.

entire thickness of the Py layer where the magnetization gradually changes from out-of-plane at the interface, to close to in-plane at the top of the layer.¹¹

In order to experimentally investigate the dynamic response of the hybrid patterned element, an oscillating magnetic field at an rf excitation frequency of 250 MHz and 15 dBm input power was applied to the stripline. This frequency coincides with the excitation values reported in the literature²¹ for Py elements with similar dimensions. Dynamic images in Figs. 2(b) and 2(d) show two distinct excitation spots; one with black and one with white contrast indicating opposite polarity magnetizations. As a result of the pixel-by-pixel imaging (image resolution 80×80 pixel) and time integration (20 ms/pixel) in our measurements, the

individual position of the vortex core as a function of time was not resolved precisely, but rather localized black/white clouds are seen that correspond to the integrated gyroscopic motion during the image acquisition.¹⁵ The black/white contrast associated with the vortex core precession results from the fact that two vortex cores with opposite polarity (with moments pointing out of/in to the image plane) have been formed. In Fig. 2(e), a 3D visualisation, based on the data in Figs. 2(a) and 2(b), of the interaction between the Co/Pd domain pattern and the vortices in the hybrid anisotropy element is shown. The different polarities of the vortex cores in the dynamic image (Fig. 2(b)) and the corresponding central domains with the same orientation of magnetization in the Co/Pd circular domain pattern in Fig. 2(a) demonstrate the mutual interaction between the different layers of the hybrid film. Changing the phase of the rf excitation by 180° relative to the synchrotron clock causes the image contrast to reverse, unambiguously confirming true vortex core motion with two vortices with opposite vortex core polarity in Fig. 2(d).

To gain more insight into these magnetic hybrid structures, we use micromagnetic simulations to simulate a static and dynamic domain structure of a 1.5 μm square element. The Landau-Lifshitz-Gilbert equation was solved for the system using a hybrid finite element/boundary element method,¹⁸ with a linear basis function and an adaptive mesh from 5 to 12 nm. The model assumed an interfacial exchange coupling between the magnetic layers with the following boundary condition at the interface $A_{\text{Py}}\partial\theta/\partial z = A_{\text{Co/Pd}}\partial\theta/\partial z$ that is derived from the minimization of the Gibbs free energy with respect to θ , the polar angle of the orientation of the polarization.^{19,20} We have included the Oersted field due to the non-uniform current path through the different materials in our simulations. Spin current interactions have shown only marginal contributions and so are omitted in this study. The material parameters used in the simulations are obtained from magnetic measurements of related samples and from literature. The magnetic measurements were performed at a temperature of 180 °C reflecting experimental conditions during rf excitation: the Co/Pd multilayer was treated as a single material with electrical conductivity $\sigma_{\text{Co/Pd}} = 3 \text{ MS m}^{-1}$, exchange stiffness $A_{\text{Co/Pd}} = 10 \text{ pJ m}^{-1}$, saturation magnetization $M_{\text{Co/Pd}} = 400 \text{ kA m}^{-1}$, an out-of-plane magnetocrystalline anisotropy $K_{\text{Co/Pd}} = 250 \text{ kJ m}^{-3}$, and a damping constant $\alpha_{\text{Co/Pd}} = 0.02$. The corresponding material parameters for the Py layer were $\sigma_{\text{Py}} = 3 \text{ MS m}^{-1}$, $A_{\text{Py}} = 13 \text{ pJ m}^{-1}$, $M_{\text{Py}} = 800 \text{ kA m}^{-1}$, $K_{\text{Py}} = 0 \text{ kJ m}^{-3}$, and $\alpha_{\text{Py}} = 0.02$. The surrounding Cu stripline had a conductivity of $\sigma_{\text{Cu}} = 4.5 \text{ MS m}^{-1}$. All simulation results of initial remanent states were obtained following saturation in the out-of-plane direction. For individual square elements of Py, one observes a Landau state^{21–23} representing a single vortex and for Co/Pd multilayers a stripe domain state²⁴ is observed. In our hybrid anisotropy films, we observe a more complex domain structure which arises from the mutual interaction between the two layers.²⁵ The circular like domain patterns of the Co/Pd layer are a result of competing energy contributions. Simulations with different shapes and squares with different dimensions demonstrate that the circular domain structure is more dominant for smaller squares (400–800 nm), whereas larger ones (1000 nm–1500 nm) give rise to maze-like domains, circular

domains, and other domain topologies. Additional symmetry (circular) is imposed through the mutual imprint once a Landau pattern is formed in the Py structure.

In order to explore the observed mutual domain imprinting, we simulate the domain structure in the two layers using the methodology described above. Figs. 3(a)–3(d) show the remanent state after relaxing from an initial out-of-plane saturation. The perpendicular domain structure in the Co/Pd layer [Fig. 3(b)] penetrates into the Py layer [Fig. 3(d)]. Similarly, the in-plane domain structure that dominates in the Py layer [Fig. 3(c)] maps into the Co/Pd layer [Fig. 3(a)]. In addition, multiple vortex cores (white (black) spots) in the Py [Fig. 3(d)] have the same polarity as the underlying Co/Pd domains [Fig. 3(b)]. The reason for this is the strong coupling between the in-plane and out-of-plane domain structures, which induces metastable pinning site potentials, as a consequence of the mutual spin structure interaction. The simulated static domain configurations Figs. 3(b) and 3(d) capture the mutual spin imprinting effect as observed in the static experimental domain images shown in Figs. 2(a) and 2(c). In particular, the simulations confirm that vortices form in the Py layer over the locally circular stripe domain patterns in the Co/Pd layer, and this can be understood in terms of energy minimization since this represents the lowest energy configuration.

In the dynamic simulations, the domain structure in both the Co/Pd and Py layers undergoes significant changes when the rf current is applied to the stripline with an rf field strength of 74 Oe. The snapshots are taken after 20 ns of excitation with five complete current cycles (amplitude 36 mA, period 4 ns) applied. During the excitation most vortices were driven out of the system and only a central one remained. The previous Co/Pd domain pattern [Fig. 3(b)]

FIG. 3. Static simulated remanent magnetic states of a 1.5 μm square taken at the bottom of the Co/Pd layer ($z = -9.6 \text{ nm}$) and the top of the Py layer $z = +20 \text{ nm}$ (see Fig. 1(a)). (a)–(d) Mutual domain imprint is clearly evident by comparing (b) and (d). Here the Co/Pd stripe domains are visible in the Py layer and the in-plane Py domain structure is seen in the Co/Pd layer [compare (c) vs. (a)]. The emergence of a locally circular domain structure is visible in (b) and a complex magnetization pattern resembling Landau state forms above it in the Py (c). White (Black) spots in (d) indicate vortex core positions in the model. The dynamic simulations (e)–(h) show a snapshot of the domain pattern that evolves from the static domain configuration [(a)–(d)]. The curling stripe domains (b) are rearranged around the centre of the square (f) where the vortex is located as shown in (g) and (h). Note that care should be taken when correlating with the experimental images, which have contributions from both in-plane and out-of-plane components since the sample is at an angle of 30° to the X-ray propagation direction. The trajectory of the vortex motion in the dynamic simulations is shown by the circular arrow.

transformed into a domain pattern with a strong circular symmetry [Fig. 3(f)] close to the center of the square, which couples to a single vortex in the Py-layer [black spot in Fig. 3(h)]. The gyroscopic vortex core motion also influences the in-plane domain structure in the Py changing it into a more Landau-like pattern [compare 3(c) and 3(g)]. Furthermore, a mutual domain imprint of the newly created domain structure can be seen.

The simulations show that the domain pattern in the Co/Pd layer is modified by the vortex core in the Py layer as it orbits around its equilibrium position (center of the square), which gives rise to the circular symmetry in the Co/Pd domain pattern. This interaction between the two layers offers the possibility of creating vortex oscillators in which the underlying Co/Pd domain pattern defines, through its locally circular domain structure, the gyration radius of the core. The Co/Pd domain structure forms potential wells in the energy landscape determining the radius of gyration. Hence, using the appropriate eigenfrequency, the vortex core gyration in the Py layer is governed by the underlying Co/Pd domain structure.

In conclusion, we demonstrated the excitation of mutually imprinted domains in patterned, micrometer-sized Co/Pd-Py hybrid anisotropy elements using continuous microwave excitation at 250 MHz and 15 dBm power. The mutual influence of the domain structures is reflected in an imprint of the Co/Pd stripe domain structure in the Py. We observe both in experiment and simulation that there is a position match between the locally circular stripe domains of the Co/Pd layer and the excitation spots corresponding to vortex core precession in the Py-layer. Micromagnetic simulations reproduce the key effects found in the experiments: imprint of the stripe domains from the Co/Pd layer into the Py layer and demonstrate how the vortex in Py layer “writes” its orbital motion onto the Co/Pd layer. This opens the possibility to control the path and amplitude of the vortex core, which can be exploited in high power rf magnetic vortex oscillators and could provide additional functionality in such devices.

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