Ferrimagnetic stripe domain formation in antiferromagnetically-coupled Co/Pt–Co/Ni–Co/Pt multilayers studied via soft x-ray techniques

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We investigate the macroscopic and microscopic magnetic reversal in perpendicular anisotropy antiferromagnetically (AF) coupled $[\text{Co}/\text{Pt}]_{N-1}/\text{Co}-\text{Ru}-[\text{Co}/\text{Ni}]_{M-1}/\text{Co}-\text{Ru}-[\text{Co}/\text{Pt}]_{N-1}/\text{Co}$ multilayers (ML) using soft x-ray spectroholography and local, as well as area-integrated, soft x-ray hysteresis loop techniques. For $N=25 \gg M=3$ we find ferrimagnetic stripe domains in remanence due to the combination of strong dipolar fields from the thick Co/Pt MLs with a strong AF-interlayer exchange coupling of the thin Co/Ni ML in the center, which reverses its polarity three times during a magnetic field reversal. Furthermore, local hysteresis loops reveal distinct random spin-flip avalanches, thus indicating the existence of local magnetic pinning sites due to the insertion of the center Co/Ni stack. © 2011 American Institute of Physics. [doi:10.1063/1.3583454]

Artificially tailored magnetic multilayers (MLs) allow excellent control over their magnetic properties and thus are important model systems for studying the reversal behavior of complex magnetic layered structures, such as used in devices. Depending on parameters such as layer thickness, number of repeats, and type of individual layer material the resulting ML can exhibit ferromagnetic, antiferromagnetic or ferrimagnetic properties. Phase diagrams for various ML-systems exist and predict unusual magnetic configurations.^{1–5} In this context the importance of characterization methods capable of resolving the horizontal and vertical magnetic configuration has been emphasized. Here, we use perpendicular anisotropy Co/Pt and Co/Ni MLs to form a layered magnetic system that reveals a remanent state consisting of ferrimagnetic stripe domains (chessboard state) as predicted earlier.^{6,7}

Figure 1(a) illustrates the sample structure. Two stacks of $[\text{Co}(4)/\text{Pt}(7)]_{24}/\text{Co}(4)$ are antiferromagnetically (AF)-coupled to the opposite sides of a $[\text{Co}(4)/\text{Ni}(10)]_2/\text{Co}(4)$ stack via Ru(9) interlayers. Samples are magnetron sputter deposited. A 20 nm Pt underlayer provides (111) texture and a 2 nm Pt cap protects against oxidation.⁸ Due to the vertical AF-coupling the Co/Ni stack prefers an antiparallel orientation to the two adjacent Co/Pt stacks. Panel (b) presents a superconducting quantum interference device (SQUID) hysteresis loop of the sample. The low field portion of the loop corresponds to the formation of stripe domains driven by the strong demagnetization fields of the thick Co/Pt ML stacks.^{2,9} However, these stripe domains are ferrimagnetic

with the center Co/Ni stack aligned antiparallel to the adjacent Co/Pt stacks. This ferrimagnetic stripe domain reversal saturates at a field of ~ 2.5 kOe, where the system has transformed into a laterally uniform ferrimagnetic structure. Higher fields are able to overcome the AF-coupling and force the center Co/Ni stack into the external field direction. Saturation is reached at 8 kOe.

Element-specific x-ray techniques allow analyzing the magnetic reversal in detail. Figure 2 presents hysteresis loops obtained via x-ray magnetic circular dichroism (XMCD) at the Co (778 eV) and Ni (853.9 eV) L_3 edges. Signals at the Co-edge are mainly sensitive to the Co/Pt stacks, while the much thinner Co/Ni stack can be monitored at the Ni-edge. Following the ascending hysteresis loop branch starting at negative saturation (marked i in Fig. 2), we observe a reversal of the center Co/Ni stack via uniform reversible rotation between -7 and -1 kOe due to the strong AF-coupling via the Ru interlayers, which leaves the sample in a uniform ferrimagnetic down-up-down state (ii). At about -1 kOe lateral anti-phase domains with a vertically ferrimagnetic (up-

FIG. 1. (Color online) (a) Sample structure and ferrimagnetic state of the AF-coupled Co/Pt–Co/Ni–Co/Pt ML system with corresponding thickness values in Ångström to the left. (b) SQUID hysteresis loop of the AF-coupled sample, the marked area indicates the separate reversal of the center Co/Ni stack at higher fields.

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FIG. 2. (Color online) (a) XMCD hysteresis loops of the AF-coupled Co/Pt-Co/Ni-Co/Pt ML system obtained at the Co (solid symbols) and Ni (open symbols) L_3 absorption edges. For comparison the Ni edge signal has been scaled to the same strength as the Co edge signal. The insets show corresponding remanent spectroholography images of the stripe domain structure at the Co (top) and Ni edge (bottom). (b) Schematic illustration of the magnetic configuration [(i)–(v)] during a field reversal for the regions marked in (a).

down-up) structure (iii) form as indicated by the opposite direction of the hysteretic reversal at the Co and Ni edge around remanence. At about 2.5 kOe the ferrimagnetic stripe domains saturate leaving the sample in the opposite uniform ferrimagnetic up-down-up state, i.e., all the stacks have reversed their polarity via ferrimagnetic stripe domains (iv). Higher magnetic fields trigger another uniform rotation of the Co/Ni stack, thus approaching complete saturation of the sample at about 7 kOe (v). Note that the saturation states (i) and (v) are not fully reached in the XMCD loops. Additional spectroholography images^{10,11} of a 830 nm diameter circular area recorded at the two different absorption edges directly reveal the ferrimagnetic nature of the stripe domain phase at remanence [see inset of Fig. 2(a)]. For the images we used exposure times of 800 s for the Co L_3 and 3200 s for the Ni L_3 edge, respectively. The small amount of 2 nm of buried Ni only provides a weak scattering signal. Thus, in the hologram reconstruction the domain configuration shows reduced contrast, but is still clearly recognizable as being anticorrelated with the contrast at the Co edge. This contrast inversion confirms the experimental realization of a ferrimagnetic chessboardlike stripe domain state (iii) as predicted for similar systems.^{6,7} By choosing the intermediate Co/Ni ML very thin compared to the adjacent Co/Pt MLs the magnetostatic interaction between the Co/Ni and Co/Pt MLs is reduced,¹² and the appearance of the ferrimagnetic stripe domain phase becomes energetically favorable. In contrast for antiferromagnetic [Co/Pt]/Ru MLs as studied in Refs. 2 and 9 the ratio between Ru-AF-interlayer exchange coupling and dipolar interactions between the equally thick stacks always favors a nearly ferromagnetic alignment of lateral stripe domains with only a small relative phase shift between adjacent AF-coupled blocks as theoretically predicted in Ref. 13.

For further characterization of the sample we use the microscopic field of view (FOV) of the holography mask to obtain in-focus XMCD local hysteresis loops (LHLs) at the Co-edge.¹⁴ Figure 3(a) illustrates the steplike and irreproducible nature of the microscopic reversal process of the AF-coupled sample. The inset enlarges the nucleation region with a corresponding macroscopic Kerr-loop added for comparison.¹⁵ In Fig. 3(b) we show that the average of six LHLs of our FOV displays less microscopic features and approaches the shape of the corresponding macroscopic

FIG. 3. (Color online) (a) Three consecutive LHLs of the AF-coupled Co/Pt-Co/Ni-Co/Pt ML system obtained at the Co L_3 absorption edge. The inset magnifies the section around the negative field nucleation point together with the corresponding macroscopic hysteresis loop. (b) Comparison of the macroscopic Kerr loop with an average over six consecutive LHLs (Ref. 15).

Kerr-loop as expected. The steplike behavior in LHLs has been observed previously.^{16–18} In Ref. 14 was shown that Co/Pd MLs deposited at increased sputter pressure (6 mTorr) exhibit a similar behavior due to an increased defect concentration. The resulting additional local magnetic pinning sites prevent uniform domain widening and cause a more stepped microscopic reversal via spin-flip avalanches. The current AF-coupled sample has been sputtered at low deposition pressure (3 mTorr). However, the center AF-coupled Co/Ni stack introduces defects that yield similar steplike microscopic reversal as observed for higher deposition pressure but without changing the shape and coercivity of the macroscopic hysteresis loop (compare Ref. 14). Similar to Ref. 14 the irreproducible nature of the LHLs indicates that the increased defect density is not yet sufficient to trigger a return-point memory (RPM) effect.^{19–21}

To monitor the steplike reversal in the AF-coupled sample we record spectroholography images at the Co L_3 edge along a hysteresis loop as shown in Fig. 4. For these measurements the sample is located downstream of the beamline focus to increase coherence and consequently the hysteresis loop itself exhibits lower signal to noise. Initially, the sample is brought to a uniform ferromagnetic state via a field sweep from -2.7 to 2.7 kOe, where the first image confirms a laterally uniform state within the FOV. The second (0.73 kOe) and third (0.45 kOe) image, each recorded directly after a distinct step in the loop, reveal the initial domain nucleation within the FOV as well as the appearance of another domain “branch.” Afterwards the reversal proceeds in a more continuous fashion, i.e., stripe domains contract down to bubble domains and are finally annihilated.

FIG. 4. (Color online) (a) XMCD LHL of the AF-coupled Co/Pt-Co/Ni-Co/Pt ML system obtained at the Co L_3 absorption edge together with a set of holography images obtained along the hysteresis loop. The external magnetic field sweep was paused each time in order to record the corresponding holography images.

In order to reveal possible locations of magnetic nucleation or pinning sites we recorded ten independent remanent domain images, each with 320 s exposure time at the Co-edge after saturation at 7 kOe (Fig. 5). The contrast in each of these images with about 50% of the domains magnetized in each direction is normalized to the interval of 0 (black) and 1 (white). The enlarged average image plotted on the same grayscale as the individual images scales from 0.2 to 0.9 and thus maps correlated areas within the FOV. The high contrast areas indicate the presence of nucleation or pinning sites that tend to favor a reproducible microscopic reversal but without tailoring the macroscopic hysteresis loop shape. Thus introduction of local nucleation or pinning sites can be achieved by increasing the deposition pressure¹⁴ or by insertion of an AF-coupled interlayer. However in the first case the macroscopic loop is altered with a significant coercivity increase, while in the second case the macroscopic loop shape is preserved.

In conclusion we fabricated and characterized a ML sample with a remanent ferrimagnetic stripe domain state by introducing a thin AF-coupled Co/Ni center stack in between two much thicker Co/Pt stacks. The ferrimagnetic nature of the remanent stripe domain configuration was directly confirmed by soft x-ray spectroholography. The center Co/Ni stack reverses its magnetization three times during an external magnetic field sweep. The remanent stripe domain state is the corresponding ferrimagnetic equivalent to the “chessboard state” predicted for artificially layered antiferromagnets^{6,7} and thus a direct experimental evidence

FIG. 5. (Color online) Ten different remanent domain configurations after previous sample saturation. The enlarged average image reveals possible locations of magnetic nucleation or pinning sites.

of the existence of this state. In addition, LHLs reveal a steplike domain evolution on the microscopic scale as directly imaged during a microscopic hysteresis loop. These results indicate that the introduction of the AF-coupled Co/Ni center stack introduces local defects without changing the macroscopic hysteresis loop characteristics, which is in contrast to local defects introduced by increasing the sputter pressure during the deposition process.¹⁴ Finally, a set of remanent state images reveals possible locations of corresponding nucleation or pinning sites that may be responsible for the steplike microscopic reversal. However these sites are not strong enough to trigger any macroscopic RPM effects.^{19–21}

Sample preparation and magnetometry measurements were carried out at the HGST San Jose Research Center. Gold mask deposition and focused-ion-beam milling were performed at SSRL and Stanford University. All x-ray measurements were conducted at beamlines UE52-SGM and UE56-1-SGM at the BESSY-II synchrotron. We would like to thank Professor Dr. Zabel for making the ALICE scattering chamber (BMBF Contract No. 05KS7PC) available and the DOE for support at SSRL.

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