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Mechanism of chirality reversal for planar interface domain walls in exchange-coupled hard/soft magnetic bilayers

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The mechanism of chirality reversal for a planar interface domain wall in a hard/soft magnetic bilayer has been identified by combining magnetoresistance measurements, modeling, and direct magnetic domain observations. The reversal occurs through IDW nucleation and lateral domain wall propagation. Over an unpredicted wide range of applied magnetic fields, the chirality transition takes place by an unwinding followed by a rewinding of the IDW. The chirality transition mechanism of phase transition could be identified from a micromagnetic analysis of the lateral magnetic domain wall orientation. Up to three magnetization phases coexist in the uniaxial material during reversal.

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I. INTRODUCTION

The control of nonuniform magnetic orders which occur at surfaces,1 domain walls in thin films2 and strips,3 and magnetic vortices in disks and rings4,5 is one of the key issues in the optimization of magnetic nanostructures. In particular, chiral magnetic orders such as vortices6 are appealing as they could be used to store binary information and experiments have been devoted to the identification of the direction of magnetization curling in such structures. Recently, the possibility of a controlled switching of the vortex core polarization, i.e., the vortex chirality, has been demonstrated.7

Prototypical chiral magnetic orders are also found in thin-film exchange-spring magnets.8,9 These structures are composed of exchange-coupled hard and soft magnetic layers. The hard magnetic phase provides the pinning which stabilizes the magnetization of the soft magnetic phase in a particular orientation via the exchange coupling across the interface. Upon application of an external magnetic field, the soft layer magnetization rotates to line up with the field while being pinned at the interface. This results in a rotation angle that increases with increasing distance from the hard material. A spiral magnetic order called interface domain wall material. A spiral magnetic order called interface domain wall

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Twisted soft layer magnetization

FIG. 1. (Color online) Possible states of magnetization in exchange-spring hard/soft TbFe/GdFe samples. (a) Spiral spin configuration $\sigma^+$ where the magnetization $m_{GdFe}$ rotates along the sense of field rotation. (b) Twisted soft layer magnetization $\sigma^-$ with spiral configuration of opposite chirality. (c) Spin state $\sigma^0$ in which the GdFe moments are aligned along the direction of interfacial pinning (see text for details). A clockwise (CW) rotating magnetic field $H_{rot}$ is assumed in the sketches. The spin states $\sigma^+$, $\sigma^-$, and $\sigma^0$ are labeled in (a)–(c). The senses of rotation of $m_{GdFe}$, CW or counterclockwise (CCW), are indicated.
interfacial pinning [Fig. 1(c)]. It arises from the combined effects of the interface exchange interaction and a uniaxial anisotropy in the plane of the film which stabilizes the $\sigma^0$ state during the unwinding process. Thus, for moderate fields, transitions from $\sigma^+$ to $\sigma^0$, and then to $\sigma^-$, were found. The equilibrium magnetic configurations $\sigma^+$, $\sigma^0$, and $\sigma^-$ are reproduced quantitatively by a spin chain model, containing no free parameter. However, the prediction of irreversible transitions between the magnetic configurations is out of the scope of this model. The moderate field regime is not even expected from 1D micromagnetic simulations since not only is the calculated energy of the $\sigma^-$ configuration lower than that of $\sigma^0$, but the height of the energy barrier between $\sigma^+$ and $\sigma^0$ is larger than the height of the energy barrier between $\sigma^+$ and $\sigma^-$. 

II. EXPERIMENT AND RESULTS

To shed light on the micromagnetic mechanism of chirality reversal, we combined low-temperature anisotropic magnetoresistance (AMR) measurements and direct magnetic domain observations by magneto-optical Kerr microscopy\(^6\),\(^17\) in an optical cryostat. The complementary experiments were carried out at 20 K, under very similar conditions, on the same amorphous hard/soft Tb$_{45}$Fe$_{55}$ (50 nm)/Gd$_{60}$Fe$_{30}$ (50 nm) ferrimagnetic bilayer sample. Details on sample preparation are given in Ref. 15. Prior to measurements, the latter was cooled down from room temperature in a large magnetic field of several kOe applied along the easy axis of the soft GdFe layer. This field cooling procedure induced in the hard TbFe layer a high remanent magnetization homogeneously fixed along the easy direction. In the following, the orientations of the domain walls at the various transitions are analyzed and the mechanism of chirality transition is deduced.

Figure 2 displays AMR measurements and results from the 1D model for a clockwise rotating magnetic field of $H_{\text{rot}}=220$ Oe, together with magnetic domain observations. For the experiments the rotation field velocity was about 20 deg/min. An almost perfect agreement between the model and the AMR data is obtained over a wide range of field angles. By comparing the results of the simulations with the resistivity data [Fig. 2(a)] it is found that the IDW starts to wind in the direction of the magnetic field rotation (clockwise winding, $\sigma^0$ state), then unwinds to form a $\sigma^0$ configuration and finally rewinds to the counterclockwise twisted $\sigma^+$ state.\(^{16}\) As already mentioned, the transition angle cannot be predicted from our micromagnetic approach. Kerr microscopy images have been taken at various field angles [Figs. 2(b)–2(m)] during these transitions. The magneto-optical signal is obtained from the topmost 20–30 nm of the GdFe film. Both subsequently occurring chirality transitions, from $\sigma^+ \rightarrow \sigma^0$ and then from $\sigma^0 \rightarrow \sigma^-$, are clearly identified. Note that both magnetization processes occur in a narrower angle range as compared to the AMR data. This discrepancy is likely due to the difference in the surface areas probed by the two techniques (200×200 $\mu$m$^2$ for Kerr imaging and 5×10 $\mu$m$^2$ for AMR). As illustrated in Figs. 2(c)–2(g), the $\sigma^+ \rightarrow \sigma^0$ transition is dominated by lateral domain nucleation, followed by lateral domain wall (LDW) motion. No domain activity occurs in the angle range where only the $\sigma^0$ state is observed [Figs. 2(h) and 2(i)]. The $\sigma^0 \rightarrow \sigma^-$ transition takes place in a similar way to the $\sigma^+ \rightarrow \sigma^0$ one [Figs. 2(j)–2(l)]. However, the domain density during reversal is much higher. The reduced domain contrast is a direct consequence of the alignment of the magnetization relative to the magneto-optical sensitivity direction. The formation of the ripple-like domains is attributed to the fact that the $\sigma^0$ and $\sigma^-$ states have similar energies at the critical angle,\(^{16}\) which facilitates...
FIG. 3. (Color online) (a) Change in sample resistance (symbols) and modeling results (lines) for a rotating field of $H_{\text{rot}}=230$ Oe. (b)–(e) Evolution of the magnetic domain structure during the chirality transition process displayed in (a). The inset of (c) shows a schematic representation of the zigzag $\sigma^0/\sigma^-$ walls formed as the $\sigma^-$ phase expands inside the $\sigma^0$ domains.

The nucleation of many domains. Significantly, the LDWs are aligned along particular orientation angles, $\alpha^0$ and $\alpha^-$, respectively (see Fig. 2). As we will further discuss later, these are determined by the demand for zero net magnetic charge on the LDW.

The magnetization processes for a slightly larger rotating field of $H_{\text{rot}}=230$ Oe are displayed in Fig. 3. From the resistivity measurements, the development of the $\sigma^+$ configuration can be clearly identified. However, unlike before, in the process of switching from the $\sigma^+$ state to the $\sigma^-$ state, the sample resistance never reaches the high value characteristic of a laterally uniform $\sigma^0$ state. Domain observations reveal the mechanism of reversal. As in the lower field example, domains of $\sigma^0$ configuration nucleate and grow by LDW propagation [Fig. 3(b)]. Note the equivalence in domain wall (DW) orientation angle $\alpha^0$ by comparing Figs. 2(c)–2(g) and Figs. 3(b) and 3(c). Yet, as seen in Fig. 3(c), a third phase rapidly nucleates inside the $\sigma^0$ domains. From the magneto-optical contrast and more importantly the LDW orientation angle, close to $\sigma^0$ in Figs. 2(j)–2(l), this third phase is identified as being in the $\sigma^-$ state. This demonstrates the possible coexistence of all three phases $\sigma^+$, $\sigma^0$, and $\sigma^-$ with a remarkable organization: The $\sigma^-$ domains are surrounded by the intermediary $\sigma^0$ phase, which is contained by the original $\sigma^+$ phase. As the field is rotated further, the chirality change proceeds by a two-step $\sigma^+\rightarrow\sigma^0$, and $\sigma^0\rightarrow\sigma^-$ process, which eventually leads to the predicted $\sigma^-$ state. In the course of this process, zigzag $\sigma^0/\sigma^-$ DWs are formed next to the $\sigma^+/\sigma^0$ DWs [see inset of Fig. 3(g)]. With the identification of the simultaneous occurrence of three chirality phases, we will now focus on the $\sigma^0$ to $\sigma^-$ transition at large field.

FIG. 4. (Color online) (a) Change in sample resistance and modeling results for $H_{\text{rot}}=265$ Oe. (b)–(g) Corresponding magnetic domain evolution around the critical field angle $\psi_c$.

Resistivity measurements at $H_{\text{rot}}=265$ Oe, as shown in Fig. 4(a), suggest a direct $\sigma^\theta$ to $\sigma^-$ chirality conversion, as expected from the 1D model. Domain imaging [Figs. 4(b)–4(g)] reveals a seemingly single step process at the critical angle $\psi_c \sim 157^\circ$, in agreement with the AMR data. As in the previous two cases, the chirality transition is dominated by LDW motion. However, a few dissimilarities in the processes are noticeable from the Kerr microscopy images. First of all, the domain boundaries are more irregular in shape than in the former cases. Also, the magnetization distribution inside the already switched $\sigma^0$ domains displays some inhomogeneities. Importantly, with the average magnetization of the $\sigma^0$ phase being oriented very differently from that of the $\sigma^0$ phase [see sketches in Fig. 2(a)], a strong modification of the LDW orientation is expected in the event of a direct $\sigma^\theta$ to $\sigma^-$ transition. Yet, no such alteration of the LDW angle is found as one moves from the intermediate field regime to the high field one [compare Figs. 2(c)–2(g) and Figs. 4(c)–4(f)].

For clarification, the LDW orientation angles expected for the various possible transitions were modeled. They were...
being extremely confined spatially (Fig. 6). Locally, the intermediary $\sigma^0$ phase may vanish and a $\sigma^+/\sigma^-$ LDW may form. A hybrid LDW then develops, which consists of $\sigma^+/\sigma^0$ and $\sigma^+/\sigma^-$ wall segments having two different characteristic orientations. This hybrid structure is at the origin of the irregular shape of the domain boundaries. Evidently, the assumption of just one well-defined type of LDW along the domain boundaries on which we relied to calculate the LDW orientation angles is not valid in this case, hence the discrepancy between calculated and experimental $\alpha^\pm$ data in Fig. 5. The fact that measured $\alpha^\pm_{\text{domains}}$ approaches the calculated value $\alpha^\pm_{\text{AMR}}$ as the field magnitude increases indicates that the fraction of $\sigma^+/\sigma^0$ wall segments becomes larger, as sketched in Fig. 6. A similar change in the proportions of $\sigma^+/\sigma^0$ and $\sigma^+/\sigma^-$ wall segments is certainly also at the origin of the small but noticeable variation in LDW alignment with varying field angle [see Figs. 4(c)–4(f)]. In the scenario proposed above, the lateral extent of the intermediary $\sigma^0$ phase is beyond the resolution of our magneto-optical microscope.

### III. SUMMARY

In summary, we combined anisotropic magnetoresistance measurements and direct magnetic domain observations to identify the interfacial domain wall chirality reversal mechanisms in thin-film exchange-spring system. Careful analysis and modeling of orientation of the lateral domain boundaries show that domain nucleation and lateral domain wall propagation are playing the key roles in the chirality reversal of *interface planar* domain walls in thin-film exchange-spring system. The chirality reversal takes place in two steps. First domains of uniform magnetization nucleate, leading to an unwinding process, then a rewinding occurs via nucleation of inverted chirality domains. The direct chirality reversal between $\sigma^+$ and $\sigma^-$ is suppressed and the two phases are found to coexist with the $\sigma^0$ phase, forming a network of in-plane and perpendicular domain walls over a large field range. The volume of the intermediate $\sigma^0$ state decreases rapidly with magnetic fields, which inhibits a direct detection of the intermediate phase. The results add significant knowledge on the mechanism of magnetization reversal in exchange-coupled systems and will need to be considered to properly describe the magnetization reversal processes in such systems.

**FIG. 6.** (Color online) Sketches of the magnetic domain boundaries at modestly high fields [see also inset of Fig. 3(c) for comparison]. The resulting average LDW orientation angles $\alpha$ are indicated and marked along the folded LDWs.
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