Stabilization of helical magnetic structures in thin multilayers

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Based on micromagnetic simulations, we report on a novel helical magnetic structure in a soft magnetic film that is sandwiched between and exchange-coupled to two hard magnetic layers. Confinement between antiparallel hard magnetic moments, a helix with a turn of 180° is stable without the presence of an external magnetic field. The magnetic stability is determined by the energy minimization and is a result of an internal field created by exchange interaction and anisotropy. Since the internal field stores magnetic energy, the helix can serve as an energy-storing element in spin-based nanodevices. Due to the significantly different magnetic resonance frequencies, the ferromagnetic and helical ground states are easy to distinguish in a broadband ferromagnetic resonance experiment.

Robust and energetically efficient magnetic structures that employ the spin degree of freedom to store and process information are at the heart of modern spin-based technology. Many experiments have been performed to investigate the interaction of spins with charges or external fields, using different device geometries like mechanically or lithographically fabricated point contacts, nanopillars or tunnel junctions. It has recently been shown that the transmission and processing of information without electric currents or external fields can be achieved via the spin degree of freedom subjected to exchange, Ruderman-Kittel-Kasuya-Yosida (RKKY) or long-range dipolar interactions. When structural boundaries fix the magnetization, these interactions can topologically stabilize configurations like spin helices. Though a large variety of devices with desirable parameters can be artificially fabricated down to the sub-nanoscale, the creation of helices with stable magnetic properties can, however, be an experimental challenge.

Here, we propose an approach for creating novel helical magnetic structures in thin multilayer systems. We show that such structures initially twisted in an external magnetic field, stay stable even without the presence of the field. In contrast to rare earth materials where a helical order is governed by the RKKY interaction, the magnetic stability is determined by the energy minimization and is a result of an internal field created by exchange interaction and anisotropy. Since the internal field stores magnetic energy, the helix can serve as an energy-storing element in spin-based nanodevices. Due to the significantly different magnetic resonance frequencies, the ferromagnetic and helical ground states are easy to distinguish in a broadband ferromagnetic resonance experiment.

Our approach is described within a one-dimensional micromagnetic model utilizing the MicroMagnum code that computes the Landau-Lifshitz-Gilbert (LLG) equation. The effective magnetic energy \( E_{\text{eff}} \) in the LLG equation is the sum of the exchange \( E_{\text{exch}} \), demagnetization \( E_{\text{demag}} \), anisotropy \( E_{\text{anis}} \), and external magnetic \( E_{\text{ext}} \) energies. In the present study, we consider a trilayer with lateral dimensions of 10 × 10 µm² size with fixed thickness. The film is discretized into 1-nm thick platelets, and each platelet is assumed to have an uniaxial easy magnetization axis along the in-plane x-direction (see Fig. 1(a)). To realize a helical magnetic order, we model a layered system, where the individual layers differ in thickness \( d \), magnetization saturation \( M_s \) and magnetic anisotropy \( K \). As shown in Fig. 1(a), the system consists of three magnets:

1. A hard magnetic FePt film \( (d_1 = 10 \text{ nm}, \ M_{s1} = 11.0 \times 10^5 \text{ A/m}, \ K_1 = 4.4 \times 10^5 \text{ J/m}^2) \)
2. A soft magnetic Fe film \( (d_2 = 90 \text{ nm}, \ M_{s2} = 8.0 \times 10^5 \text{ A/m}) \)
3. A soft magnetic Fe film \( (d_3 = 90 \text{ nm}, \ M_{s3} = 8.0 \times 10^5 \text{ A/m}) \)

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Under the applied external field, the magnetic moments in FePt and relax the trilayer. The field is then set to zero and the structure is again relaxed. The net magnetic moments in FePt and relax the trilayer. The field is applied an external magnetic field \(B\) leading to magnetic moments in FePt and soft Fe film show a helical order with a turn of 180° magnetic configuration where the magnetic moments in the soft Fe film relax into a stable configuration where they continuously change their direction.

The reason for the stability of the magnetic helices at \(B_{\text{ext}}=0\) is an internal effective magnetic field in the soft layer. To create the internal field, following conditions have to be fulfilled: (i) an external field that introduces energy into the system; (ii) and (iii) magnetic moments at the ends of the structure are aligned antiparallel and are fixed, respectively. Under the action of the external field, the magnetization of the hard Fe film can be twisted by 180° whereas the magnetization of the hard FePt film stays unchanged due to the large anisotropy. When the external field is removed, the magnetization of the hard Fe film does not reverse since its anisotropy is large compared to the exchange interaction that tends to unwind the exchange spring and is weaker with distance from the hard FePt magnet underneath. Confined between antiparallel magnetizations, the magnetic moments in the soft Fe film relax into a stable configuration where they continuously change their direction from parallel to antiparallel, i.e. exhibiting a helical order. At the energy equilibrium the internal field is created that stores exchange and anisotropy energies via \(E_{\text{eff}}=E_{\text{exch}}+E_{\text{anis}}\), and is equal to the energy difference of the local minima \(E_{\text{min},i}\), \(E_{\text{min},180}\) (i.e. \(i=0,180\)) (see Fig. 2(b)). With \(E_{\text{eff}},E_{\text{exch}},E_{\text{anis}}\) and \(E_{\text{dem}}\) plotted as functions of \(B_{\text{ext}}\) that was applied to magnetize the films (see Fig. 2(c)), we find that \(E_{\text{exch}}\) makes the main contribution to \(E_{\text{eff}}\). This means that the exchange interaction is mostly responsible for the creation of the internal effective magnetic field.

The multilayers can store energy \(\Delta E=4.6\times10^{-20}\) J that is about eleven times more than the thermal activation energy \(k_B T=4.1\times10^{-21}\) J with \(k_B=13.8\times10^{-24}\) J/K being the Boltzmann constant and \(T=300\) K being the temperature. The same value of \(\Delta E\) can be obtained when one ermal field, the layer stack can relax into ground states with different energy minima when the field is removed. As schematically illustrated in Fig. 2(b), energy barriers \(E_{\text{bi}} (i=1,2)\) separate two global minima \(E_{\text{min},0}\) at \(\phi=0°\) and \(E_{\text{min},180}\) at \(\phi=180°\) and one local minimum \(E_{\text{min},90}\) at \(\phi=90°\) with \(\phi\) being the angle between the mid magnetic moment in the soft Fe film and the -x-axis. If \(E_{\text{ext}}<E_{\text{b1}}\) or \(E_{\text{ext}}>E_{\text{b2}}\), the system relaxes into a stable state with the global energy minimum at \(\phi=0°\) or \(\phi=180°\), respectively. In these states the magnetic moments of the films are aligned parallel (\(\phi=0°\)) or antiparallel (\(\phi=180°\)) to those of the initial state. In case of \(E_{\text{b1}}<E_{\text{ext}}<E_{\text{b2}}\), the system relaxes into the metastable state with the local energy minimum at \(\phi=90°\). We find that this state corresponds to a magnetic configuration where the magnetic moments in the soft Fe film show a helical order with a turn of 180° and are pinned between the antiparallel magnetizations of the hard FePt film and the hard Fe film at the ends (see Fig. 1(c)). We observe the relaxed helical configuration after the magnetic moments were twisted in external fields in the range of 13 to 38 mT as mapped out by the gray area in Fig. 2(b).

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FIG. 2. (color online) (a) Hysteresis loop of the trilayer. Dashed lines indicate a region of applied fields where the structure is in the exchange spring state shown in Fig. 1(b). The gray area maps out a field range where the system is in the helical state shown in Fig. 1(c) after the external field is removed. (b) Schematic drawing of energy barriers the helical state shown in Fig. 1(c) after the external field. The gray area maps out a field range where the system is in the exchange spring state shown in Fig. 1(b). Dashed lines indicate a region of applied fields where the structure is in the exchange spring state shown in Fig. 1(b).

The internal field also replaces the external field, therefore the increase of FMR frequencies compared to those in the ferromagnetic case at $B_{\text{ext}} = 0$ is expected.

The internal field also modifies the spatial profiles of magnetic excitations. Figures 3(c) and (d) show amplitudes of the lowest frequency resonance, plotted as functions of the thickness for the FM and the HM case, respectively. The excitations are known as perpendicular standing spin waves (PSSW). It can be seen in Fig. 3(c) that the lowest frequency excitation is mainly localized in the Fe layers with a maximum at the thickness $d = 60$ nm. In contrast to the FM case, the lowest frequency excitation in the helix has two maxima at $d = 30$ nm and $d = 86$ nm separated by a minimum at $d = 60$ nm. This is a result of the twist of the mid magnetic moment perpendicular to the fixed layer magnetization, hence parallel to the hard axis of the trilayer. In order to excite magnetic moments along the hard axis, a stronger magnetic pulse is required. Therefore, the amplitude of excitations gradually reduces (increases) from maximum to minimum (from minimum to maximum) as magnetic moments rotate from 0° to 90° (from 90° to 180°).

In conclusion, we show a pathway to create a helical spin order in thin hard FePt/soft Fe/hard Fe films, which is stable at zero applied external fields. The magnetic sta-
FIG. 3. (color online) FMR spectra of the trilayer in the (a) ferromagnetic and (b) helical state. Due to the internal magnetic field, resonance frequencies in the helix are higher compared to those in the ferromagnetic case. A spatial profile of the lowest frequency excitation is shown in (c) for the ferromagnetic and in (d) for the helical state. In all cases, \( B_{\text{ext}} = 0 \).

...helicity is determined by the energy minimization and depends on the thickness of the films, the relative strengths and directions of the anisotropies, as well as the exchange coupling between the magnetic layers. We observe the helical turn of 180° in the soft film, confined between the antiparallel magnetic moments of hard layers. Due to the internal field created mainly by exchange interaction, the helix stores magnetic energy. In case of the helix, FMR frequencies of the magnetization precession are higher compared to those when films show a ferromagnetic order at \( B_{\text{ext}} = 0 \). In particular, the ratio of the lowest resonance frequencies \( f_{\text{HM,1}}/f_{\text{FM,1}} \) is approximately two. The spatial profile of the lowest frequency excitation shows two maxima separated by a minimum, which is in contrast to a single maximum in the middle of the trilayer in the ferromagnetic case.

By measuring broadband FMR spectra with a vector network analyzer \(^{14}\), one can indirectly detect the helical order in an experiment. The direct observation can be performed via magnetic superstructure reflections that are widely used in resonant x-ray and polarized-neutron reflectometry to characterize the vertical spin profile in multilayer systems. Structures with a stable helical configuration provide a new route to store, transmit and process information in the wide range of spintronic and recording media applications.

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10. As reported in Ref. 14, \( K_1 \) is smaller compared to the experimental value \( K_1 = 2.5 \times 10^6 \text{ J/m}^3 \) because the one-dimensional model often leads to the underestimation of \( K_1 \).
11. In an experiment, one usually measures a coercive field \( B_c \) that can be found for a magnet with an uniaxial anisotropy via \( B_c = 2K/M_s \) (Ref. 17). In this study, \( B_{c1} = 800 \text{ mT} \), \( B_{c2} = 0 \text{ mT} \) and \( B_{c3} = 74 \text{ mT} \) are coercive fields for the hard FePt, soft Fe and hard Fe film, respectively. As reported in Ref. 15, \( B_{c1} \) can be obtained up to 960 mT by heating the FePt film at a temperature \( T = 800 \text{ K} \). The coercive field of the Fe film can be adjusted within a range of 1 to 100 mT via the direction of the sputtered Fe atoms relative to the orientation of the substrate surface using oblique incidence deposition (OID) at room temperature (see Ref. 15).
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