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Spontaneous domain nucleation under in-plane fields in ultrathin films with Dzyaloshinskii-Moriya interaction

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In this paper, we show that applying a hard axis field reduces the energy barrier for the spontaneous formation of a multi-domain state in magnetic ultrathin films sandwiched between a heavy metal and an oxide. This provides a simple technique to generate a metastable multi-domain state in magnetic films where the ground state is uniform. This approach could be particularly interesting in materials with strong Dzyaloshinskii-Moriya interaction as a means to realize metastable chiral textures. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4917057]

Out of plane magnetized thin films which are sandwiched between an appropriate heavy metal and an oxide can exhibit chiral spin textures such as Néel domain walls and skyrmions. This is because of the Dzyaloshinskii-Moriya Interaction (DMI) that comes from broken inversion symmetry and a strong spin orbit coupling in these systems.[1–5] In these sandwich structures, the heavy metal underlayer contributes to the strong spin orbit coupling.[6–9] The inversion symmetry is broken because the magnetic layer has different under-layer and over-layer. If DMI is strong enough, the system will spontaneously exhibit stable chiral spin structures.[2] However, in this paper, we show that in the ultrathin sandwich structures of Pt/CoFe/MgO, where the stable state is a uniform magnetic domain, we can induce a metastable multi-domain state by the application of in-plane magnetic field parallel to the film plane, which is higher than a critical threshold but less than the uniaxial anisotropy field.

Recently, it has been shown that micromagnetic simulations predict, and spin Hall switching experiments confirm, the creation of chiral intermediate states in Pt/CoFe bilayer strips with a combination of field application and pulsed current injection parallel to each other and the film plane.[10] However, this could only be achieved with a limited combination of current and field values along the switching phase boundary. Moreover, this process of creation of intermediate states involved additional complexity due to the need for simultaneous application of current pulses and in-plane field. Here, we describe a process where only in-plane fields are applied to create the metastable multi-domain state.

Thin films with Ta(3 nm)/Pt(3 nm)/$Co_{80}Fe_{20}$(0.6 nm)/MgO(1.8 nm)/Ta(2 nm) were prepared by DC magnetron sputtering under 3 mTorr Ar with a background pressure of $\sim 1 \times 10^{-7}$ Torr, on thermally oxidized Si(100) substrates at room temperature. MgO was RF sputtered at 3 mTorr Ar. Vibrating sample magnetometry measurements of these samples confirmed the presence of perpendicular anisotropy in these films with an in-plane anisotropy field $H_K \sim 5000$ Oe.[1] The magnetization was probed by using Polar Magneto-Optic Kerr Effect (MOKE) with a 532 nm diode laser focused on a 3 μm spot and attenuated to 1 mW. These films have a strong DMI with a DMI-effective field H_D $\sim$2200 Oe.[11] Thus, the ratio of the DMI-effective field to the in-plane anisotropy field in these films is 0.44, which is about 70% of the critical ratio required for spontaneous formation of chiral spin textures.

Fig. 1 shows a series of hysteresis loops measured by using the MOKE in the presence of different in-plane (parallel to the film plane) fields H_x. In the absence of any in-plane field, the hysteresis loop is square with a coercivity (H_c) of 40 Oe, which is characteristic of the single domain magnetic state pointing out of the film-plane expected in these thin films. H_c in this case corresponds to the nucleation field of reverse domains, since the domain wall propagation field in these samples is <20 Oe.[1] As the magnitude of in-plane field is increased, we find that the coercivity decreases with in-plane field, showing that it becomes easier to nucleate reverse domains when an external in-plane field is present. The hysteresis loops start becoming more and more sheared and the remnant magnetization M_R at zero out-of-plane field H_z also starts decreasing after a critical threshold of in-plane field is crossed (see Figs. 1(d)–1(f)). Note that these in-plane fields are lower than the anisotropy field for these films which is around 5000 Oe.[11] An M_R/M_S ratio of <1 in the presence of in-plane fields lower than the anisotropy field is indicative of a multi-domain state with stripe domain pattern.[10,12] This stripe domain pattern is expected whenever the demagnetization field exceeds the threshold for nucleation of reverse domains.

To probe the formation of the stripe domain state, in detail, we measure the out-of-plane component of magnetization M_z as a function of applied in-plane field H_x. M_z was measured by using polar MOKE system described above. Fig. 2(a) shows a schematic for this measurement. An in-plane field H_x serves to cant the magnetization $\vec{M}$ of the film such that the out-of-plane component of the magnetic moment vector $M_z = M_S \sin(\varphi)$, where φ is the canting angle. According to the Stoner-Wohlfarth model, $\cos(\varphi) = H_x/H_K$ for $H_x < H_K$. So

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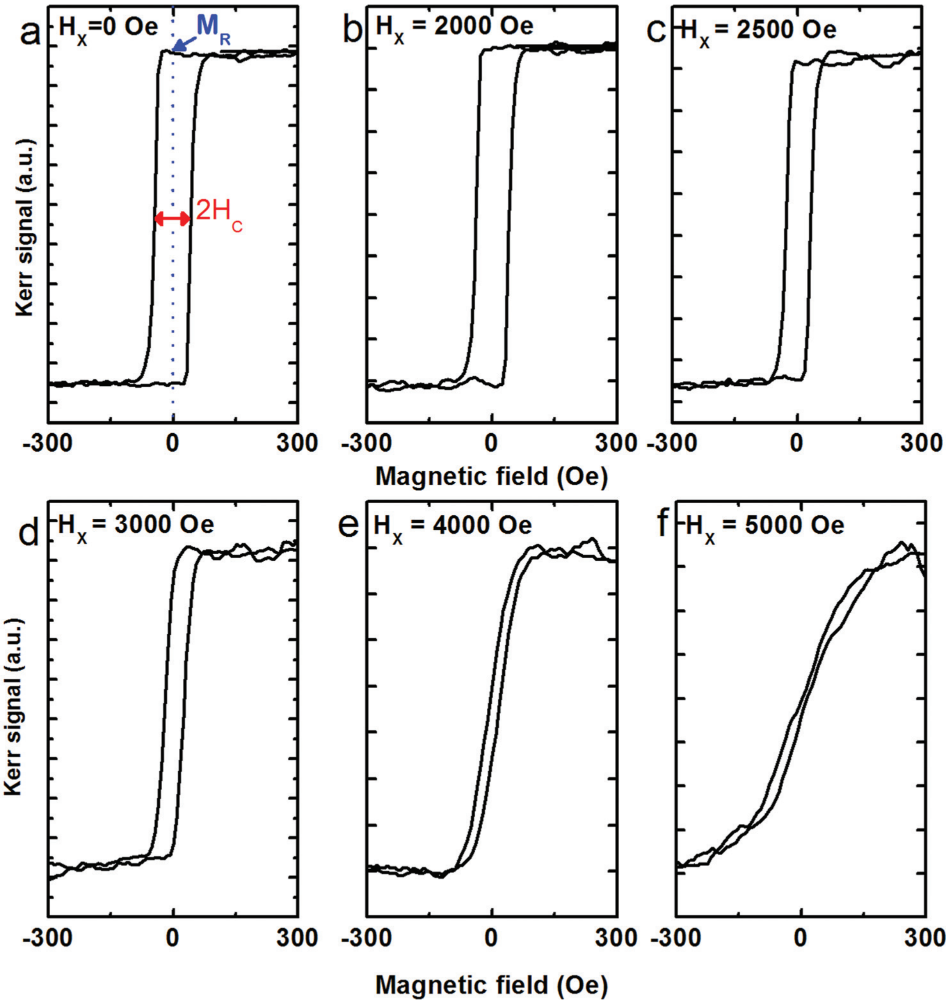

FIG. 1. Easy axis hysteresis loops of Pt/CoFe/MgO measured by using Polar MOKE system at in-plane field H_x of (a) 0 Oe; (b) 2000 Oe; (c) 2500 Oe; (d) 3000 Oe; (e) 4000 Oe, and (f) 5000 Oe. M_r and H_c decrease progressively as in-plane field increases.

$$M_z/M_S = \sin\left(\arccos\left(H_x/H_K\right)\right). \tag{1}$$

We measured M_z vs H_x using a lock-in technique to improve the signal-to-noise ratio. In this measurement scheme, we apply pulses of out-of-plane field H_z, as shown in Fig. 2(b), to toggle the magnetic moment M_S above and below the film plane. A lock-in amplifier which is phase locked to the H_z field pulses is then used to extract M_z, as shown in Fig. 2(b). For a uniaxial system, M_z vs H_x should take the form of Eq. (1). Fig. 2(c) shows a plot (blue dots) of the measured magnetization M_z as a function of in-plane field H_x. The red curve is the expected M_z vs H_x plot simulated by using Eq. (1) and using anisotropy field value H_K as 5000 Oe from Ref. 11. The measured M_z is significantly lower than the expected curve for in-plane field above 1500 Oe. This suggests spontaneous demagnetization and the formation of multi-domain state above the threshold in-plane field. The hysteresis loops in Figs. 1(a)–1(f) were measured at the corresponding in-plane field values as marked in Fig. 2(c) showing a steady decrease in remanence.

We found that this multi-domain state persisted even after the in-plane field was removed. This was confirmed by performing another series of experiments where we applied an in-plane field to induce the formation of the multi-domain state, then turned it off and probed the out-of-plane magnetic moment M_z using the polar MOKE. We then applied an out-of-plane field H_z to find the field required to drive the multi-domain state to complete saturation. Fig. 3(a) shows a schematic of this measurement. We see that the Kerr signal (which is proportional to M_z) drops significantly on the application of in-plane field H_x and the demagnetized state is retained until H_z is swept. Fig. 3(b) shows a plot of M_z as a function of H_z measured in the region where H_x is turned off. As seen from the plot, the initial magnetization (M_i in the figure) is close to zero immediately after the application of a high H_x, and gradually increases as out of plane field increases until it reaches saturation magnetization M_S. Note that the initial magnetization is not zero because of misalignment of the in-plane field. The small out-of-plane component of the in-plane field biases the magnetic moment either up or down leading to some fractional remanence. Branch 1 of the loop corresponds to the initial magnetization curve of the sample which occurs through domain expansion. The saturation field starting from the demagnetized state is denoted by H^* in the figure, and is a measure of the range of out-of-plane field required to drive domain walls. In repeated measurements, we found H^* to be systematically somewhat lower than H_c, which is the field required to nucleate a reverse domain (branch 3). We also noticed that branch 1 is typically more spread out than branches 2 and 3.

Fig. 3(c) plots the absolute value of the initial magnetization M_i described above as a function of in-plane field H_x.

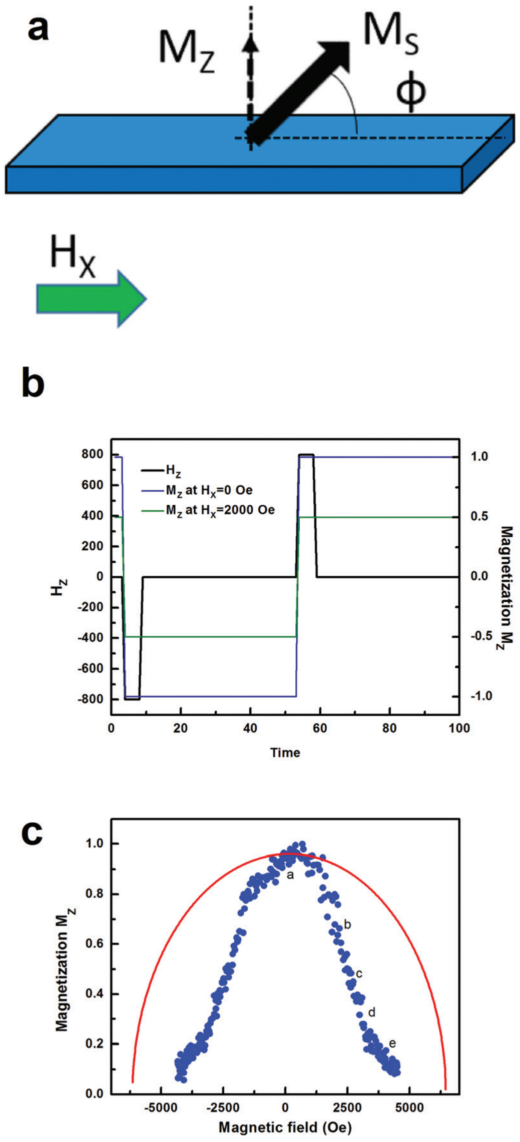

FIG. 2. Measurement of remnant magnetization as a function of in-plane field: (a) Schematic representation of canting of total magnetic moment M_S of the film by the application of in-plane field H_x. M_z represents the out-of-plane component of the magnetic moment vector. (b) Out-of-plane field H_z waveform used to toggle the net magnetic moment between up and down states. The blue and green curves show the toggling of M_z with H_z at in-plane fields of 0 Oe (blue) and 2000 Oe (green). (c) Plot of out-of-plane magnetization M_z as a function of in-plane field, measured by lock-in amplifier (blue curve) and theoretically predicted (red curve) by Stoner-Wohlfarth model.

This mimics the data shown in Fig. 2(c) (which were measured by the lock-in technique), showing a sharp drop in M_i beyond an in-plane field of ~1500 Oe and hence indicating the spontaneous formation of the multi-domain state beyond this threshold field.

We see that application of an in-plane field reduces the energy barrier for the creation of a domain wall. This can be mathematically seen by considering the domain wall energy as a function of in-plane field as given by[13]

$$\sigma_{DW}(H_x) = \sigma_o + 2K_D\Delta - \pi\Delta M_S|H_x + H_{DMI}|, \qquad (2)$$

where σ_o is the Bloch-type domain wall energy density, K_D is domain wall anisotropy energy density, and Δ is the domain wall width. At high in-plane fields, the third term on the right becomes larger and so the domain wall energy becomes negative. Thus, the demagnetizing field dominates the system dynamics and a multi-domain state is preferred.

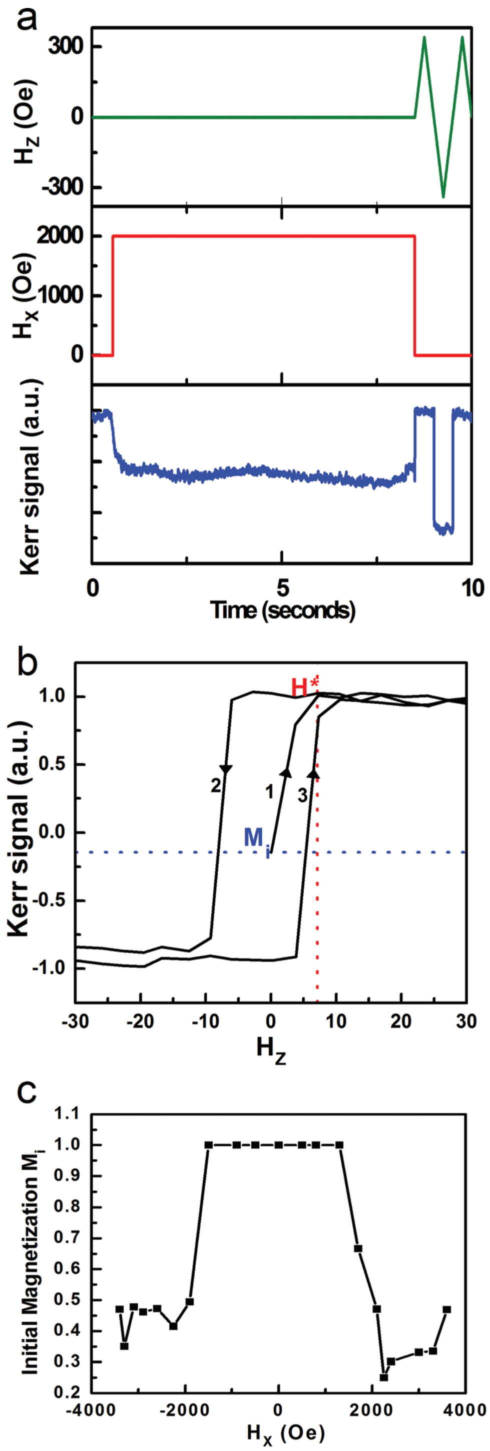

FIG. 3. Measurement of initial magnetization after application of in-plane field: (a) Applied out-of-plane field H_z, in-plane field H_x and the measured Kerr signal as a function of time. Kerr signal drops down significantly after the application of in-plane field denoting the formation of multi-domain state. (b) Plot of Kerr signal against out-of-plane field H_z measured after the in-plane field has been turned off to zero. Arrows denote the order of measurement starting from initial magnetization M_i. (c) Initial magnetization as a function of in-plane field H_x.

In summary, we have shown a simple approach for the creation of metastable multi-domain state in Pt/CoFe/MgO thin films, which could be extended to other films with similar layer structure and DMI parameter. Chiral magnetic textures in thin films are of great interest from the point-of view of low-power data storage in magnetic memory devices.[14,15] Magnetic thin films with perpendicular magnetic anisotropy, strong spin-orbit coupling, and strong Dzyaloshinskii Moriya Interaction promise to be excellent candidates for the creation and stabilization of these chiral textures. If the DMI effective field is strong enough, these chiral textures are spontaneously stabilized. However, even in systems with weaker DMI, perturbations can be introduced to create metastable non-uniform states and manipulate them.[2] We have shown that destabilization of the ferromagnetic state and formation of stripe domain textures can be achieved simply by applying an in-plane field. This approach could be used, for example, to generate skyrmions in confined structures, such as magnetic dots, rather than through current pulses as previously proposed.[2,10,16]

This work was supported by the National Science Foundation under NSF-CCS-1408172.

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