Asymmetric domain-wall depinning induced by Dzyaloshinskii-Moriya Interaction

Asymmetric Domain-Wall Depinning Induced by Dzyaloshinskii–Moriya Interaction

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Dzyaloshinskii–Moriya interaction (DMI) is currently the focus point of many research efforts in the spintronics community. It is possible that applications and fundamental new physics motivate us to understand, measure, and manipulate this interaction. Using an elegant, alternative approach, we show that by depinning a domain wall from an anisotropy barrier in perpendicular magnetic anisotropy nanowires in the presence of a static in-plane field, the presence of DMI can be detected. This is experimentally demonstrated, and the clear effects are observed even though a sample with small DMI is used. The technique presented could be used to obtain both the sign of the DMI constant and its quantitative value.

Index Terms— **Co/Pt multilayers, interface phenomena, magnetic materials, perpendicular magnetic anisotropy, sputtering.**

I. INTRODUCTION

DZYALOSHINSKII–Moriya interaction (DMI) is relevant for spintronics in several ways. By the stabilization of a Néel-type domain wall, it enables domain-wall motion at higher velocities, which could improve the so-called racetrack memory [1], [2]. Moreover, it was recently observed that in systems with strong DMI, a novel type of spin structure can form; the magnetic skyrmion [3]–[5]. These vortex-like structures can be extremely small, stable, and movable by low current densities, and are expected to be the building block for the next generation of memory devices [6], [7].

Recently, various techniques to measure DMI have been explored: 1) the already mentioned effect of in-plane external fields on domain-wall motion; 2) influencing domain nucleation with in-plane fields [8]; 3) Brillouin light scattering [9]–[11]; and 4) scanning nanomagnetometry [12]. In all these studies, the emphasis lies on structures with strong DMI, which is understandable as this is desirable with respect to applications involving skyrmions. However, in experiments regarding the asymmetric magnetic bubble expansion under the influence of in-plane magnetic fields [13], it becomes clear that also a small DMI can have a large impact on the behavior of the system. However, these bubbles can take exotic shapes and modeling them correctly; therefore, deducing a reliable DMI value remains a challenge [14].

In this paper, we will show that the depinning of domain walls from an anisotropy barrier can be influenced by applying an in-plane magnetic field, and that, this influence differs for the top–bottom and bottom–top domain walls. This does not only prove the presence of DMI in our system with low asymmetry but also is a nice example of how even a small DMI can have a significant effect in devices. We present a plausible intuitive interpretation of the observations, and discuss how a quantitative value for the DMI can be obtained using our experimental technique.

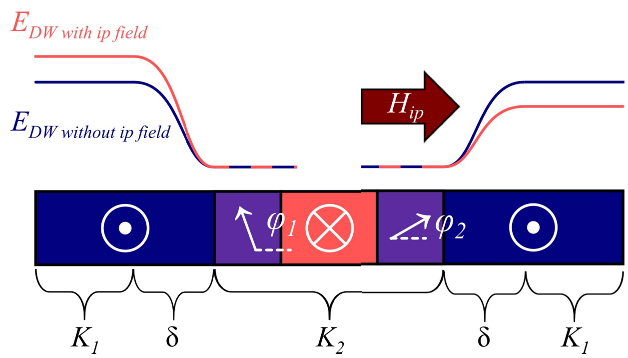

Fig. 1. Schematic of the top view of a magnetic nanostrip with PMA. The middle part with reduced anisotropy ($K_2 < K_1$), and the regions where the anisotropy transition occurs (which is assumed to occur in a linear way), indicated with δ, and the definition of the in-plane angle ϕ is shown. In the presence of DMI and an in-plane field, the energy landscape is different for the top–bottom and bottom–top domain wall.

II. DMI AND DEPINNING

We study microstrips with perpendicular magnetic anisotropy, which contain a middle region with a reduced anisotropy (for the experimental realization of such a system, see Section III). Fig. 1 shows a cartoon of the situation. Sweeping a perpendicular field can result in a situation where the region with reduced anisotropy has an opposite magnetization from the rest of the strip. The in-plane angle ϕ (see Fig. 1) is expected to be $\pm\pi/2$ (corresponding to a Bloch wall), which follows from magnetostatics [15]. The width of the domain walls is determined by a competition between anisotropy and exchange and corresponds to a domain-wall energy of $4\sqrt{AK}$. Therefore, the anisotropy boundaries pose an energy barrier and the domain walls are pinned [16]. The height of the energy barrier determines the strength of the perpendicular field that is required to depin the domain wall.

Now, we take the effect of a DMI into account. We assume that the DMI is negligible in the area with reduced anisotropy; in the structures we use, DMI is induced at the interfaces,

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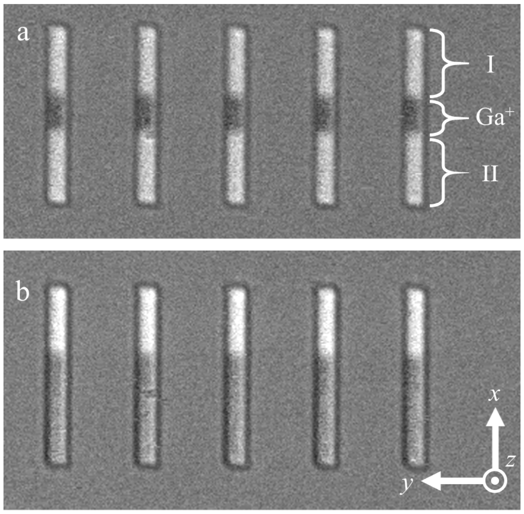

Fig. 2. Kerr microscopy image of five typical 1 μm $\times$ 10 μm Pt/Co/Pt nanowires. (a) After saturation, a magnetic field is applied in the z-direction and the magnetization in the middle region of each strip is switched because of the lower anisotropy here. In each strip, two domain walls are created and pinned at the anisotropy barrier. (b) In-plane field in the x-direction affects the two domain walls in the same strip differently. It can be seen that the lower domain walls have already depinned and propagated through the rest of the strip, while the top domain walls are still pinned. The definition of the axes is included in the lower right corner.

and the reduction of anisotropy is caused by a reduction of the interface quality (note that this not verified experimentally yet, and this assumption is further discussed in Section IV). DMI is a chiral interaction which favors Néel walls ($\phi = 0 \vee \phi = \pi$), so the domain walls will take this configuration (or an intermediate form between the Bloch and Néel configuration, depending on the strength of the DMI) when they enter the pristine regions. However, the favoured in-plane angle is opposite for the two domain walls in our system. The height of the energy barrier at the anisotropy step is still the same for both domain walls. Adding an in-plane magnetic field along the strip lifts this degeneracy, for in the one case, the field and DMI favor the same in-plane domain wall angle, while in the other case, they favor the opposite one. As a result, there will be a difference in how easily the energy barrier is overcome, i.e., there will be a difference in depinning field. This is a measurable quantity, and will be the focus point of the experimental results that will be presented.

III. Experimental Results

For this paper, we prepared magnetic strips with a lateral dimension of 1 μm patterned on a silicon wafer using a typical e-beam lithography and liftoff process. The patterned strips were deposited using dc magnetron sputtering with the following structure: Ta (5 nm)/Pt (4 nm)/Co (0.6 nm)/ Pt (4 nm), which is expected to have a certain DMI value [13]. A region with reduced perpendicular magnetic anisotropy is created in the middle of the strips by irradiation with highly energetic Ga^+ ions, similar to the samples used in [17]. In Fig. 2, an image of five typical strips is shown, with the Ga^+ irradiated area (Ga^+) and the two nonirradiated regions (I and II) indicated. In the magnetically soft region, a domain with opposite magnetization is nucleated by an external perpendicular field H_z, and two domain walls are created and pinned at the edge of the irradiation boundaries, which is the situation shown in Fig. 2(a). When the perpendicular field H_z is increased, at a critical field, i.e., depinning field H_{depin}, the domain walls are depinned from the irradiation boundaries and propagate toward the ends of strips. Measurements are performed using polar Kerr microscopy and a homebuild 3-D magnet, which can apply fields up to 40 mT. Fig. 2(b) shows the contrasting behavior of two domain walls that occurs when in-plane fields are applied along the strips (in the x-direction). For all strips, the bottom part is switched at a certain H_z, while the domain wall in the top region remains pinned. When H_z is increased further, eventually the top domain walls depin as well. Now, H_z is swept in the other direction; when negative values are reached, the Ga^+ irradiated region again switches first, but now the top parts of the strips switch first, while the bottom domain walls stay pinned.

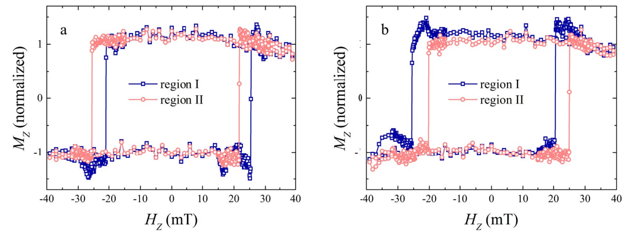

Fig. 3. Typical hysteresis loops obtained in region I and region II of a microstrip with an external in-plane field of (a) 39 mT and (b) -39 mT.

To obtain more quantitative data about this phenomenon, we perform measurements of two hysteresis loops (the magnetic field is swept along the out-of-plane direction) per nanostrip; one for region I, and one for region II. The switch in the hysteresis loops corresponds to the depinning of the domain wall from the anisotropy barrier. This routine is repeated for various strengths of a static in-plane magnetic field, H_x applied along the length of the strips. Typical results are shown in Fig. 3(a), where it can be seen that the loop obtained in region I is shifted with respect to the loop obtained in region II. This means that when the z-field is swept from negative to positive, the domain wall at region II is the first to depin, while when the z-field is swept from positive to negative, the domain wall at region I is the first to depin. In Fig. 3(b), the results obtained with the in-plane field in the opposite direction are shown, and it can be clearly seen that the loops for region I and region II are now shifted in the opposite direction.

We further plotted the difference in depinning field, ΔH_{depin}, between region I and region II domain walls versus H_x. The ΔH_{depin} shows an almost linear dependence on H_x (see Fig. 4). This behavior is consistent with the interpretation in Section II. The larger the in-plane field, the larger the degeneracy so a larger difference in depinning field is expected. The results were reproducible for different samples.

IV. Discussion

The experimental findings correspond well to the interpretation given in Section II. The energy landscape

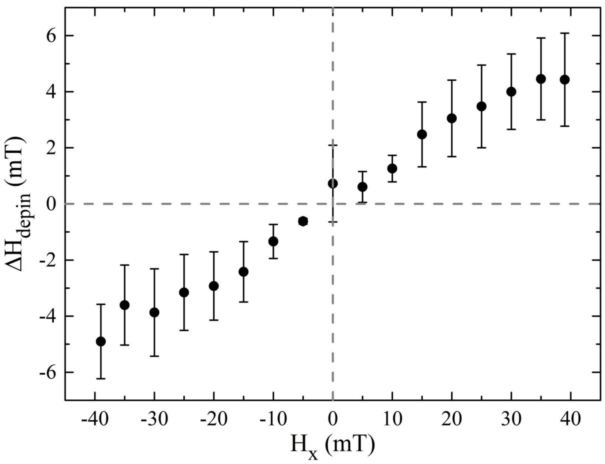

Fig. 4. ΔH_{depin} (the difference between the depinning fields for region I and region II) as a function of the static magnetic field in the x-direction for a typical sample. Each point represents an average over ten microstrips.

should be symmetrical in the absence of an in-plane field, and we indeed see that there is no shift at zero-field. From the model, we would expect that the asymmetry in depinning field is proportional to the in-plane field, up to the field strength that is equal to the DMI field [18]. At this field, the shift versus in-plane field curves are expected to saturate. This is not observed, indicating that the DMI field is larger than 40 mT. Measurements with a modified setup that can reach fields up to 300 mT are in progress. This saturation field gives a quantitative value for the difference in DMI between the irradiated and nonirradiated regions. If the DMI in the irradiated region vanishes completely, this means that both the sign and the strength of the DMI in the structure as deposited can be determined. However, the vanishing of DMI by ion irradiation that is assumed here is not trivial; it is possible that the two interfaces of the magnetic layer are influenced in a different way, resulting in an asymmetry [19]. Further experiments to determine whether this assumption is justified are ongoing.

An electromagnet is used to apply the external in-plane field during the measurements. We note that a possible out-of-plane leakage field from the in-plane magnet cannot explain our observations. Such a leakage field would indeed shift the hysteresis loops, but the shift would be the same for region I and region II of the wires. Because we look at the difference in depinning field between the top and the bottom domain wall, we are not susceptible to this experimental error. Another consideration is that the depinning fields do not have to be identical for all domain walls for they depend on random local irregularities that can cause additional pinning. The fact that all bottom domain walls have a lower depinning field than the top domain walls in Fig. 2 could be explained by asymmetry of the ion irradiation process. However, this cannot explain the in-plane field dependence; when the in-plane field is reversed, the bottom domain walls have a higher depinning field than the top ones. This makes us confident that the observed effect should indeed be explained by a combination of the in-plane field and the presence of DMI.

V. Conclusion

We observe that in-plane magnetic fields affect the depinning field of a top–bottom and bottom–top domain wall in our sample stacks in the opposite way. An explanation is that the DMI field for the one domain wall is parallel to the applied field, and in the other case antiparallel, resulting in a different energy barrier at the anisotropy transition. The in-plane field at which the difference between the top–bottom and bottom-top domain wall sizes to increase is equal to the DMI field, providing an easy method to determine the DMI constant, even in the case of small DMI.

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