Very large domain wall velocities in Pt/Co/GdOx and Pt/Co/Gd trilayers with Dzyaloshinskii-Moriya interaction

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Abstract – We carried out measurements of domain wall (DW) velocities driven by magnetic-field pulses in symmetric Pt/Co/Pt and asymmetric Pt/Co/AlOx, Pt/Co/GdOx and Pt/Co/Gd trilayers with ultrathin Co layers and perpendicular magnetic anisotropy. The maximum observed velocity is much larger in the asymmetric samples, where the interfacial Dzyaloshinskii-Moriya interaction (DMI) stabilises chiral Néel walls. In quantitative agreement with analytical models, in all samples the maximum observed DW speed scales as $D/M_s$, where $D$ is the strength of the DMI and $M_s$ the spontaneous magnetisation. In Pt/Co/Gd, where the anti-parallel coupling between the magnetic moments of Gd and Co leads to a decrease of the total magnetisation, very large DW speeds (up to 700 m/s) are obtained.

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Introduction. – Domain wall (DW) dynamics in multilayer films with perpendicular magnetic anisotropy (PMA) is an important topic today, as these micromagnetic objects may be used as carriers of binary information in future ultrahigh density storage devices [1]. In non-centrosymmetric multilayers with ultrathin magnetic films DWs can acquire Néel internal structure with a fixed chirality stabilised by the interfacial Dzyaloshinskii-Moriya interaction (DMI) [2]. This new feature strongly modifies the DW dynamics, driven both by field and by spin-polarised current. In particular, in systems with strong DMI, DWs move at large speeds when driven by current pulses [3–6].

Field-driven DW dynamics has been studied mainly in the very low-velocity regime [7–10], while few studies have explored the effect of the DMI on the high-velocity regime [11–14]. The maximum DW velocity is limited by the breakdown occurring at the so-called Walker field $H_W$, beyond which the DW motion is no longer stationary and its internal structure undergoes continuous precession. In symmetric ultrathin films with PMA this breakdown is reached for small fields (around 10–20 mT for Pt/Co/Pt samples [15]), as the energy difference between Néel and Bloch wall configurations is small and it is thus easy to switch from one to the other. For this reason the velocities observed at high fields are relatively small [15].

This limitation is overcome in multilayer systems with strong interfacial DMI. This interaction, an antisymmetric exchange term favouring non-collinear magnetic textures [16,17], can be non-vanishing in asymmetric stacks in which an ultrathin magnetic film is deposited on a large spin-orbit metal layer [18]. The DMI acts as an effective chiral field $H_{DMI}$ normal to the DW direction and localised on the DW, which induces chiral Néel walls that become stable against precession up to larger fields [2,6]. This allows them to reach larger velocities than in symmetric stacks without DMI. A first demonstration was given by Miron et al. [3] who showed that in Pt/Co/AlOx trilayers DWs move with much larger velocities than in Pt/Co/Pt. The presence of a large DMI in Pt/Co/AlOx was confirmed experimentally using chiral nucleation experiments [19] and Brillouin light scattering (BLS) spectroscopy [20].

The aim of this work is to compare DW velocities in symmetric and asymmetric stacks with PMA and to address the effect of the DMI strength on the DW velocity.
at the Walker field and above. We show that velocities much larger than those measured for symmetric Pt/Co/Pt can be obtained in asymmetric Pt/Co/MOX (M=Al, Gd), and that these increase considerably in samples where Co and Gd interfacial moments couple antiparallelly. We also show that in the asymmetric samples the velocity saturates for large out-of-plane fields, in contrast with 1D micromagnetic simulations that predict a drop of the speed at the Walker field, but in agreement with 2D simulations.

**Sample growth and characterisations.** – Measurements were carried out on a Pt(4)/Co(1)/Pt(4) symmetric stack and three asymmetric stacks, Pt(4)/Co(0.8)/AlOx(3), Pt(4)/Co(1)/GdOx(4)/Al(7) and Pt(4)/Co(1)/Gd(3)/Al(7) (thickness in nm). All samples were grown on Si/SiO₂ substrates by magnetron sputtering at room temperature and the Al and Gd layers were oxidised with an oxygen plasma. Note that the Co thicknesses are larger than the 0.6 nm value of previous works [4,14], so as to bring the Walker breakdown into the observable field region. The magnetic properties of the samples were measured with VSM-SQUID at variable temperature and X-ray magnetic circular dichroism (XMCD) at the Co L₂,₃ and Gd M₄,₅ absorption edges. The XMCD measurements were carried out at the DEIMOS beamline of the SOLEIL synchrotron (Saint Aubin, France).

The DW velocities were measured on continuous films, using magneto-optical Kerr microscopy. The film magnetisation was first saturated in the out-of-plane direction. An opposite magnetic-field pulse was then applied to nucleate one or several reverse domains. The DW velocity was deduced from the expansion of the initial bubble domain, after the application of further magnetic pulses. Using a 200 μm diameter coil and a fast current source, out-of-plane magnetic-field pulses of strength up to \( B_{z} = 300 \text{ mT} \) and duration down to 20 ns were applied. In order to visualise the various regimes of DW propagation predicted by the theoretical models, DW speeds were measured as a function of \( B_{z} \). In order to address the DMI strength in the various samples, the DW speeds driven by the \( B_{z} \) pulses were measured in the presence of a static in-plane field \( B_{x} \) normal to the DW plane [7–10].

**Domain wall dynamics in symmetric and asymmetric trilayers with PMA.** – Figure 1(a), (b) show the differential Kerr images corresponding to the expansion of a domain in Pt/Co/Pt (a) and Pt/Co/AlOx (b) after the application of a pulse, respectively without and with the simultaneous application of an in-plane field, in Pt/Co/Pt (a) and Pt/Co/AlOx (b); (c), (d): DW velocity vs. in-plane field \( B_{x} \) for Pt/Co/Pt (\( B_{x} = 88 \text{ mT} \)) and Pt/Co/AlOx (\( B_{x} = 132 \text{ mT} \)). Blue squares: down/up DWs; red dots: up/down DWs. (e), (f): DW velocity vs. \( B_{z} \) for Pt/Co/Pt (e) and Pt/Co/AlOx (\( B_{z} = 0 \)) (f). The thin lines in (e), (f) emphasise the slope of the linear regime.

In general, in symmetric magnetic layers with PMA, Bloch walls are more stable as they do not give rise to magnetostatic energy while Néel walls do. In order to decrease their Zeeman energy, the magnetisation of such walls aligns parallel to an in-plane field applied perpendicular to them, as soon as this field is larger than the DW demagnetising field. In the high-field regime, the DW velocity increases, as the DW width increases. The symmetric curves measured for Pt/Co/Pt reflect the equivalent dynamics of up/down and down/up DWs, and are in line with the presence in this sample of Bloch walls.

In Pt/Co/AlOx the DW propagation is anisotropic in the direction of \( B_{x} \). The speed-vs.-\( B_{z} \) curves show a minimum for \( \mp 220 \text{ mT} \) respectively for down/up and up/down DWs, and the trend for up/down and down/up DWs is similar for \( H_{z} \) fields applied in opposite directions. This is the fingerprint of the presence of chiral Néel walls stabilised by the Dzyaloshinskii-Moriya interaction, that acts as a local transverse field \( H_{DMI} \) having opposite directions for up/down and down/up DWs. The DW velocity presents a minimum when the applied in-plane field compensates the \( H_{DMI} \) field, i.e., for the \( B_{x} \) field for which the DW magnetisation reaches the Bloch orientation [7]. From the value of this field we can then deduce the average DMI energy density \( D \), since \( H_{DMI} = D/(\mu_{0}M_{s}\Delta) \) (where \( D \) is the DMI strength, \( M_{s} \) the spontaneous magnetisation and \( \Delta = \sqrt{A/K_{0}} \) the...
DW width parameter) [6]. The large DMI energy density
$(D = 1.63 \text{ mJ/m}^2$ for 0.8 nm Co thickness) —extracted using
$\mu_0 H_{\text{DMI}} = 220 \text{ mT}$ and the material parameters shown
in table 1—is in good agreement with the values previously
obtained for similar samples [19,20]. The sign of
$H_{\text{DMI}}$ field confirms the presence of left-handed DW
chirality [14,19,21].

Let us now see what is the consequence of the differ-
ent DW structure on the mobility of the DWs driven by
a pure easy-axis field. Figures 1(e), (f) show the DW
velocity as a function of $B$, the velocity as a function of $B$
(a) shows the results for the perfect
Bloch to Néel. In this regime the asymptotic mobility
$\mu_0 M_s = \gamma_0 \Delta/(\alpha + 1/\gamma_0)$ is relatively small
and in good agreement with that obtained in [15]. From
a linear fit of the high-field curve we obtain $\alpha \approx 0.4$. On the
other hand, fitting the data under the assumption that the
linear regime is associated to the steady flow (other hand, fitting the data under the assumption that the
linear regime is associated to the steady flow ($\alpha \approx 0.4$) were tested. In addition, perfect and disordered
samples were considered (the latter realised with a spatial
fluctuation of the uniaxial anisotropy value, as was
done in [14]). Figure 2(a) shows the results for the perfect
system. The DW speed initially increases linearly with field, up to the Walker field, which is proportional to the
damping parameter. The Walker velocity is independent
of damping, as expected from the 1D collective coordinates
and 120 mT a clear linear regime appears, characterised by
a DW mobility of $3 \text{ m/s/mT}$. We correlate the large veloc-
ities with the strong DMI evidenced by the previous mea-
surements. Thiaville et al. [2] predict that in the presence
of DMI the Walker breakdown shifts to larger fields and
that, for $D > \approx 0.14 \mu_0 M_s^2$, $H_W \approx \alpha H_D = \pi \Delta H_{\text{DMI}}/2$
(see footnote 1). Using $\alpha \approx 0.35$, as extracted from the DW
mobility in the linear regime and the measured $\mu_0 H_{\text{DMI}}$
we obtain $\mu_0 H_W \approx 120 \text{ mT}$ which is, as predicted, much
larger than that of Pt/Co/Pt, and very close to the field
for which the linear regime ends and the DW velocity
practically saturates in our measurements. In agreement
with the prediction of 1D micromagnetic models [2] the
measured Walker velocity changes linearly with the in-
plane field. This is shown in the inset of fig. 3(b) for the
Pt/Co/Gd trilayer described below, where the velocity
reaches 1100 m/s for $B_x = 300 \text{ mT}$. The DMI-induced
extension of the steady flow regime therefore allows expla-
ning the large DW velocities observed for the asym-
metric samples.

Saturation of DW speeds at large fields. — In con-
trast with the predictions of micromagnetic 1D models, in
Pt/Co/AIOx, as well as in Pt/Co/Gd and Pt/Co/GdOx
shown below, the DW velocity saturates for large $B_z$
fields. We carried out large-scale 2D micromagnetic simu-
lations using the MuMax3 code [22] with the parameters
of Pt/Co/GdOx determined in this paper (see table 1).
To avoid the effects of the borders and the associated DW
tilting [11,14] we simulated a propagating DW in a mov-
ing $1 \times 1 \mu\text{m}^2 \times 1 \mu\text{m}$ box with periodic boundary condi-
tions linking the top and bottom edges. The lateral mesh
size was 2 nm. Different values of the damping $\alpha$ (0.15
to 0.35) were tested. In addition, perfect and disordered
samples were considered (the latter realised with a spatial
fluctuation of the uniaxial anisotropy value, as was
done in [14]). Figure 2(a) shows the results for the perfect
system. The DW speed initially increases linearly with field, up to the Walker field, which is proportional to the
damping parameter. The Walker velocity is independent
of damping, as expected from the 1D collective coordinates

Table 1: Co thickness $t_{Co}$, spontaneous magnetisation $M_s$, effective anisotropy energy $K_0$, exchange stiffness $A$ (two values taken from the literature), DW parameter $\Delta$, damping constant $\alpha$, DMI field $\mu_0 H_{\text{DMI}}$, DMI energy density $D$ extracted from the DMI field, DMI energy density $D^*$ obtained from other measurements: (a) nucleation [19], (b) BLS, on a similar sample [10], (c) BLS on the same sample. Note that the best agreement between $D$ and $D^*$ is obtained using $A = 16 \mu_\text{J/m}$.

| Sample          | $t_{Co}$ | $M_s$ | $K_0$ | $A$ | $\Delta$ | $\alpha$ | $\mu_0 H_{\text{DMI}}$ | $D$ | $D^*$ | $\mu_0 H_{W}^{\text{th}}$ | $\mu_0 H_{W}^{\text{exp}}$ |
|-----------------|---------|-------|-------|-----|---------|---------|-----------------------|-----|-------|------------------------|------------------------|
| Pt/Co/AIOx      | 0.8     | 1.18  | 0.41  | 22  | 7.2     | 0.45    | 0.22                  | 1.9 | 1.63  | 1.65(a)                | 140                    |
|                 |         |       |       |     |         |         |                       |     | 1.63  | 120                    |                        |
| Pt/Co/GdOx      | 1       | 1.26  | 0.41  | 22  | 7.2     | 0.33    | 0.20                  | 1.7 | 1.48  | 1.5(b)                 | 79                     |
|                 |         |       |       |     |         |         |                       |     | 1.48  | 83                     |                        |
| Pt/Co/Gd        | 1       | 0.64  | 0.26  | 22  | 9.2     | 0.34    | 0.30                  | 1.7 | 1.78  | 1.5(c)                 | 156                    |
|                 |         |       |       |     |         |         |                       |     | 1.78  | 133                    | 116                    |
Fig. 2: (Colour online) Simulated DW dynamics in a 1 μm × 1 μm moving window, with the parameters of Pt/Co/GdOx: $A = 16 \text{ pJ/m}$, $M_s = 1.26 \text{ MA/m}$, $D = 1.5 \text{ mJ/m}^2$, $K_u = 1.44 \text{ MJ/m}^3$. A perfect sample (a), (c) and a disordered sample (b) are considered. In the magnetisation snapshot (c), white/black corresponds to the perpendicular magnetisation component and the colours to the in-plane component (see colour wheel in the inset). Large arrows indicate the Bloch lines.

$(q, \Phi)$ model [2]. Above the Walker field, the speed reaches a plateau with $\approx 300 \text{ m/s}$, in quantitative agreement with the experimental results (fig. 3(a)). This plateau is a characteristic of the dissipation mechanisms in 2D Dzyaloshinskii DWs above the Walker field [11,12]. A representative snapshot of the DW structure above the Walker field is shown in fig. 2(c). The DW presents a complex meander shape and its magnetisation rotates several times along the wall. As discussed by Yoshimura et al. [11], pairs of Bloch lines (marked with large arrows in the magnified view) are continuously nucleated in the DW. These lines, with their Néel-like orientation, can have two very different widths, depending on whether they rotate in the sense favoured by DMI or not. The DW sections containing such lines are slower, hence the meandering DW shape. The lines disappear either by collapse of winding pairs with emission of spin waves (like in [11]), or by the creation of bubble domains (visible in the figure) that detach by pinching off the wall meanders, and eventually collapse. When the bubbles contain Bloch lines, these annihilate and transform the bubbles into skyrmions with structure stabilised by DMI, before the skyrmions themselves collapse. The creation of bubbles is a second dissipation mechanism that was not seen in the calculations by Yoshimura et al., as the DMI considered in that work was relatively small (typically 16% of the critical value $D_c$ for destabilisation of the uniform magnetisation), whereas here $D/D_c = 0.45$. The reduced DW energy in the case considered here favours the meandering of the DW and the subsequent creation of bubbles. Altogether, as explained by [11] who called it a solitonic behaviour, the DW structure is on the average that of a chiral Bloch wall. Indeed, with dominant DMI, this is the DW structure just before the Walker breakdown [2]. In the case with disorder, the effects are qualitatively the same, as seen in fig. 2(b). As expected, the disorder induces a non-zero propagation field, but does not change the Walker field nor the maximum velocity. The shape of the DW and the energy dissipation mechanism (collapse of Bloch line pairs and creation of detached bubbles) are also not significantly affected. At fields beyond the experiment range (about 200 mT), the simulations reveal that the plateau ends and the DW velocity decreases. This indicates that the dissipation mechanisms can no longer sustain a constant velocity. In fact, the data show that the dissipated power reduces.

Influence of the saturation magnetisation on the maximum DW speed. – In order to address the role of the top interface on the strength of the DMI and on the maximum attainable DW velocity, we have studied samples in which the top AlOx layer was replaced by GdOx or Gd. Figures 3(a), (b) show the DW speed vs. $B_z$ curves measured for two samples: Pt/Co/GdOx with a completely oxidised Gd layer and a Pt/Co/Gd sample where the Gd layer was not deliberately oxidised. The most striking result is that while the saturation DW speed in the Pt/Co/GdOx is of the same order of magnitude as that measured for Pt/Co/AlOx (around 300 m/s) the velocity in Pt/Co/Gd is a factor 2 larger.

In order to clarify this behaviour, we examined the magnetic properties of the two samples. Both samples have out-of-plane magnetic anisotropy with very similar anisotropy fields. VSM-SQUID measurements (figs. 3(c), (d)) show that the magnetisation of Pt/Co/GdOx changes weakly when going from 300 K to 10 K; since the moment of Co is expected to change little...
in this temperature range \((T_C \gg 300\, \text{K})\), we attribute the slight decrease of the magnetisation to the presence in the sample of a small amount (less than 0.1 atomic layer) of non-oxidised Gd, which may be intermixed with the Co and acquire a moment antiparallel to that of Co. On the other hand in Pt/Co/Gd the magnetisation is strongly temperature dependent, with an increase of the magnetisation at low temperature and a minimum at around 100 K. This is the behaviour found for ferrimagnetic rare-earth/transition metal (RE-TM) compounds, where the RE moment strongly increases at low temperature while the TM moment changes little. This results in the presence of a compensation temperature, where the two sublattice magnetisations are equal. From this behaviour we can be confident that a large part of the Gd layer is non-oxidised in this sample, the Co and Gd layers are coupled at the interface and their moments align antiparallel to each other. Note also that while the magnetisation measured for Pt/Co/GdOx is \(12.6 \times 10^5\, \text{A/m}\), that of Pt/Co/Gd is \(6.4 \times 10^5\, \text{A/m}\) at room temperature (RT). This is a clear indication that the Gd contributes to the total magnetisation even at RT.

In order to quantify the contribution of Gd to the total magnetisation in the Pt/Co/GdOx sample and at RT, we carried out XMCD measurements at the Gd \(M_{4,5}\), and Co \(L_{2,3}\) edges. The X-ray absorption and XMCD spectra measured at 300 K in a magnetic field of 1 T are shown in fig. 4. The integrated XMCD signals can be related to the magnetic moment per absorbing atom [23,24]. A nonvanishing XMCD signal with sign opposite to that of Co is found at the Gd edge at 300 K. This emphasises: i) that part of the Gd is magnetic at RT and ii) that the Gd 4\(f\) and Co 3\(d\) moments are antiparallel. At 4 K, the Co and Gd XMCD signs are reversed and the Gd signal is much larger (not shown). This is coherent with the fact that at low temperature the Gd magnetisation increases, the total Gd moment becomes larger than that of Co and aligns with the external magnetic field.

If we suppose that the Gd intermixed with the Co at the interface has a magnetic moment similar to the one measured by López-Flores et al. [25] at 290 K (4.5 \(\mu_B\) in Gd\(_{20}\)Co\(_{80}\), we can deduce that 10% (0.3 nm) of the Gd layer is magnetic at RT. This is the proportion of Gd atoms that is coupled to Co. In that case, we obtain that the contribution of Gd to the moment per unit surface found by VSM-SQUID (6.4 \(\times 10^{-4}\) A) is \(-4.1 \times 10^{-4}\) A, while the contribution of Co is \(10.5 \times 10^{-4}\) A. For a Co thickness of 1 nm, this corresponds to \(M_{s,\text{Co}} = 10.5 \times 10^5\, \text{A/m}\), in reasonable agreement with the one obtained from XMCD (\(M_s = 14 \times 10^5\, \text{A/m}\)) and that of Co found, e.g., in the Pt/Co/GdOx sample.

Let us now see what is the effect of the different spontaneous magnetisation of Pt/Co/GdOx and Pt/Co/Gd on the DW dynamics. Following Thiaville et al. [2] for samples with strong DMI the DW speed at the Walker field is given by

\[
v_W = \gamma_0 \frac{\Delta}{\alpha} H_W \approx \frac{\pi}{2} \gamma_0 H_{\text{DMI}} \Delta = \frac{\pi}{2} \gamma_0 \frac{D}{M_s} \tag{1}\]

Therefore, \(v_W\) is related to the \(H_{\text{DMI}}\Delta\) product, and does not depend on \(\alpha\). This is intuitive, as the DMI field increases the Walker field, and the widening of the DW increases the mobility. Indeed for the Pt/Co/Gd sample, where the speed is enhanced, a larger DMI field and a larger DW width are found (table 1). By inserting in eq. (1) the experimental \(H_{\text{DMI}}\) and the calculated DW width parameter, we obtain that within this model the ratio between the Walker velocities in Pt/Co/Gd and Pt/Co/GdOx is \(\approx 1.90\). This is very close to the ratio 1.8 between the experimental values of the DW velocities at the end of the linear regime (570 m/s for Pt/Co/Gd and 320 m/s for Pt/Co/GdOx), and even closer to the ratio of the terminal velocities (1.9).

The second part of eq. (1) shows that, very interestingly, \(v_W\) is simply proportional to \(D/M_s\). One of the sources of the large difference in the saturation DW velocities found for Pt/Co/GdOx and Pt/Co/Gd is therefore the very different spontaneous magnetisation. In order to check whether the difference in the DW velocities may also be affected by the DMI strength, we have extracted the \(D\) values from the experimental \(H_{\text{DMI}}\) fields (table 1). Very similar \(D\) values varying between 1.5 and 1.7 mJ/m\(^2\) are obtained for the two samples\(^2\). Since the Pt/Co interfaces are very similar in the two samples (they were grown in the same run) and hence contribute equally to the global DMI strength, our measurements suggest that the top Co interfaces give similar contributions to the global DMI.

We thus conclude that the large difference in the saturation DW velocities found for the asymmetric samples treated in this work is related mainly to the very different magnetisation. However, we anticipate that the maximum attainable DW velocity may be optimised by tuning the magnetisation of the magnetic layer as well as the DMI strength. Moreover, the measurement of \(v_W\) should provide a parameter-free estimation of the DMI strength. The suppression of the Walker breakdown in samples with DMI creates a speed plateau that may ease the estimation of \(v_W\) in cases in which the propagation field may be relatively

\(^2\)The extracted values of \(D\) depend on the exchange stiffness \(A\), the only material parameter that we could not measure. The best agreement with the \(D\) values measured with BLS spectroscopy is obtained using \(A = 16\, \text{pJ/m}\).

Fig. 4: (Colour online) XAS (blue line) and XMCD measurements (red line) of the Pt/Co/Gd sample at the Co \(L_{2,3}\) and Gd \(M_{4,5}\) edges, at 300 K and in an applied magnetic field of 1 T.
large, hiding the linear regime. We alert that, although the plateau velocity seems to be close to \(v_W\) with the parameters used in this work, this may not always be the case. The relation between \(v_W\) and the plateau velocity is not straightforward and deserves further study.

**Conclusion.** – We have shown that the DMI stabilises chiral Néel walls and no breakdown is observed, as already found in Co/Ni/Co ultrathin films [1]. We demonstrate experimentally that, in agreement with the 1D model [2], the Walker velocity is proportional to the ratio \(D/M_s\), so that its measurement may provide a direct method to obtain the DMI strength.

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