Chiral magnetic textures such as Dzyaloshinskii domain walls (DDW) [1] and skyrmions [2] are attracting attention because of their possible applications as information carriers in spintronics devices. DDW are Néel walls with a fixed chirality, stabilised, in non-centrosymmetric stacks, by the Dzyaloshinskii–Moriya interaction (DMI) [3, 4] present at the interface between a magnetic layer and a heavy metal with large spin–orbit coupling. When driven by a spin Hall effect related spin–orbit torque (SHE-SOT) [5–7] DDW in systems with perpendicular magnetic anisotropy (PMA) move with large efficiency [8–10]. Also, it has been predicted that isolated skyrmions injected in nanotracks can be moved with very low current density and are moreover insensitive to defects [11]. Engineering materials with large DMI have therefore become an important issue both for domain wall and skyrmion physics.

So far ab initio calculations of interfacial DMI are rare and concern perfect interfaces difficult to compare with the mixed...
interfaces found in ‘real’ samples [12, 13]. The information presently available on the DMI strengths relies on experimental work. A large input has been given by spin-polarised scanning tunneling microscopy measurements that show the presence of chiral magnetic textures or skyrmions in systems consisting of one monolayer of Fe (or Mn) on heavy metal substrates [14–17] in ultra-high vacuum and at low temperature. In the last few years, domain wall dynamics and nucleation measurements at room temperature have revealed the presence of DMI in less ordered, non centrosymmetric ultrathin magnetic layers with PMA, made by magnetron sputtering [6, 9, 10, 18]. More recently, Brillouin light scattering experiments have also enabled quantifying DMI in similar PMA samples [19, 20].

It has been shown that when, in a nanostrip or for a bubble domain, an easy-axis field \( H_x \) drives the DW dynamics in the presence of an in-plane field \( H_z \) (aligned along \( +z \)), the DW speed is different for up/down and down/up DDWs propagating along \( \pm x \) [21–23]. This phenomenon is related to the symmetry breaking introduced by the in-plane field. The Dzyaloshinskii–Moriya interaction acts as a longitudinal chiral field\(^7\) \( H_{DMI} = D(\mu_0 M_s \Delta) \) (where \( D \) is the effective DMI constant, \( M_s \) is the saturation magnetisation and \( \Delta \) is the domain wall width parameter) localised on the domain walls, having opposite directions for up/down and down/up DWs. Beyond a critical strength, the DMI forces the DW magnetisation in the Néel configuration (see sketch in figure 1) [1]. Although the in-plane field does not drive the dynamics, it will stabilise (resp. destabilise) the DWs having their magnetisation \( m \) parallel (resp. antiparallel) to it. For a parallel (resp. antiparallel) alignment between \( H_z \) and \( m \) the DW speed increases (resp. decreases) with respect to the \( H_z = 0 \) case. In the high speed (flow) regime, the speed increase (resp. decrease) is mainly due to the widening (resp. narrowing) of the DW with \( H_z \) (see supplementary material stacks.iop.org/JPhysCM/27/326002/mmedia). In the low speed (thermally-activated) regime, the speed dependence on \( H_z \) has been related to the variation of domain wall energy [21]. The DW width (resp. DW energy) is expected to have a minimum (resp. maximum) value when the applied in-plane field is equal and opposite to the stabilising \( H_{DMI} \) field i.e. when the DW acquires a Bloch form. In the two DW propagation regimes, this is the \( H_z \) field for which the DW speed is predicted to exhibit a minimum. With these assumptions, determining the \( H_z \) field for which the speed is minimum may supply a direct measure of the DMI constant \( D \) provided that the domain wall width parameter \( \Delta = \sqrt{A/K_0} \) (\( K_0 \) being the effective uniaxial anisotropy and \( A \) the exchange constant) and \( M_s \) are known.

In the following, we will show that the DW speed versus in-plane field curves in the thermally activated regime cannot in general be used to extract the strength and the sign of the DMI, as was done for Pt/Co/Pt samples [21, 22]. Moreover, we find that the \( v(H_z) \) curves measured for the same sample in the thermally activated and in the flow regimes can have different trends. Although the mechanism determining the exact behaviour of the velocity curves in the creep regime is not clear, we show that it cannot always be described simply in terms of the variation of DW energy with \( H_z \). Our measurements on Pt/Co/GdOx films suggest that modifications of the pinning barrier landscape upon application of the in-plane field also contribute to the trend of the \( v(H_z) \) curves.

A Pt(5 nm)/Co(1 nm)/Gd(t) stack with varying Gd thickness (\( t = 2–5 \) nm) was grown on a Si/SiO\(_2\) substrate by magnetron sputtering in the shape of a wedge, and oxidised by O\(_2\) plasma for 35 s. Consequently 2 nm of Al were deposited on top of the stack to protect it from further oxidation. After this process, magnetisation measurements show that the Gd

---

\(^7\) In [1], a field \( H_0 = (\pi/2)D(\mu_0 M_s \Delta) \) was first defined. This competes directly with the anisotropy field of the DW moment, due to the demagnetizing energy. In addition, for large \( D \) the Walker field was shown to obey \( H_W \approx aH_0 \). On the other hand, when comparing the effect of DMI to that of an external in-plane field, it was shown that DMI is equivalent to applying a chiral field of magnitude \( D(\mu_0 M_s \Delta) \). This field was called \( H_{DMI} \) by Emori et al [10]. One should be careful not to confuse these two definitions.
layer is totally oxidised for all Gd thicknesses. Nevertheless, the oxygen content at the Co/GdOx interface varies along the wedge, giving rise to a gradient in the interfacial anisotropy [24]. All the samples present a well defined PMA, with in-plane saturation fields varying between 1.5 T (for 2 nm Gd) and 0.7 T (for 5 nm Gd). Domain wall dynamics was studied at room temperature by wide-field magneto-optical Kerr microscopy, using a combination of easy-axis and in-plane magnetic fields. \( H_x \) pulses of amplitude between 5 and 10 mT and duration between 20 and 100 ms were applied using a conventional electromagnet. The \( H_x \) pulses, driving the displacement of the DWs, were applied in the presence of a continuous in-plane field \( H_x \), along \( \pm x \), which tunes the stability of the DDW internal structure. With such amplitudes of the \( H_x \) field, DW speeds are of the order of some 0.1 mm s\(^{-1}\), the dynamics is thermally activated and this regime is referred to as the creep regime [25].

Starting from (down or up) saturation, a bubble domain was created by applying an up or a down \( H_x \) pulse. The image of the domain was saved as a reference image. An \( H_x \) pulse was then applied to enlarge the domain by DW propagation, and the new image was acquired. The difference between the two images gives the domain wall displacement that occurred during the field pulse. A black (white) contrast in the images corresponds to the expansion of an up (down) domain. The domain wall speed in a given direction can then be extracted from the ratio of the DW displacement and the pulse duration.

For a fixed value of the \( H_x \) field, DW displacements in the \( \pm x \) directions were measured for several values of the in-plane field between –300 mT and +300 mT. In order to correct the residual \( H_x \) component that may arise from a misalignment of the in-plane electromagnet, measurements were taken for both down and up domains.

Figure 1 shows the differential images recorded in the presence of an in-plane field of +200 mT, in four positions of the wedge sample (called from now on samples (A)–(D) in the text and in the figure labels) corresponding to increasing values of the Gd thickness (from 2 to 5 nm). Without in-plane field, the propagation of the DWs is isotropic and the domains are round (not shown). As in previously reported experiments [21–23], the \( H_x \) field breaks the rotational symmetry and the propagation becomes asymmetric in the \( \pm x \) directions. Note that the sign and the amplitude of the speed asymmetry (defined as \( a = (v_{1H}^d - v_{-1H}^d)/(v_{1H}^d + v_{-1H}^d) \) where \( v_{1H}^d \) is the absolute value of the speed of the down/up DW in the presence of a positive in-plane field) depend on the sample composition. Indeed, in sample (A) the down/up DWs move faster than the up/down DWs while in sample (B) the asymmetry is practically vanishing, i.e. up/down and down/up DWs move at the same speed. In sample (C) the DW speed asymmetry reverses with respect to (A), i.e. the up/down DWs move faster. Finally, in (D) the asymmetry found in (A) is recovered.

According to previous work [21, 22], the cancellation (resp. change of sign) of the DW speed asymmetry may be attributed to a vanishing (resp. reversed) value of the DMI. This result is unexpected and counter-intuitive. As one moves across the sample, from (A) to (D), the decreasing degree of oxygen content modifies the composition of the Co/GdOx interface, as shown experimentally by the changing PMA. However the sample presents a considerable PMA even for the thinner Gd layers, which is an indication that the oxidation concerns only the top Co interface. Therefore the bottom Pt/Co interface, which is expected to provide the main contribution to the DMI [12], should not be strongly affected by the varying Gd thickness.

In order to clarify the interpretation of the DW dynamics in the creep regime and to have an independent measurement of the sign of the DMI, we carried out current-induced DW dynamics measurements. For this purpose, the samples were patterned into 1 \( \mu \)m wide strips by e-beam lithography and the DW dynamics was studied for a fixed value of the current-density \( J = 1.2 \times 10^{12} \) A m\(^{-2}\) and variable values of \( H_x \). The results show that for all samples (note that sample (C) could not be measured, due to deterioration during the patterning process) the domain walls move in the same direction, opposite to the electron flow. Since in these systems the direction of the DW displacement is determined by the sign of the Spin-Hall angle in Pt (which is the same for samples (A)–(D)) and by the chirality of the DW [1, 9, 10], this result is a strong indication that the domain walls in all the samples have the same chirality and therefore the sign of the DMI is sample independent. The results of the current-driven DW speed versus \( H_x \) field curves for samples (A) and (B) are shown in figure 2.

The speed variation as a function of in-plane field \( H_x \) is similar to that shown by other authors in strips of materials with interfacial DMI [9, 10, 26]. In all the curves, the speed of the down/up DWs increases for positive \( H_x \) fields and decreases for negative fields. The symmetric curve is found for the up/down domain walls, as expected for chiral Néel walls. If we neglect the rotation of the magnetisation within the domains, the domain wall speed driven by the current \( J \) via the SHE-SOT can be expressed as [1]:

\[
\frac{v}{\gamma_0} = \frac{\Delta}{\alpha} \frac{\pi}{2} M_s \cos \psi
\]

where \( \gamma_0 \) is the gyromagnetic ratio, \( \alpha \) is the damping parameter, \( \Delta \) is the domain wall width, \( \psi \) is the angle of the DW magnetisation with respect to the \( x \)-axis, and \( \chi = \theta_0 / (2 \epsilon \mu_0 M_s^2) \) where \( \theta_0 \) is the Spin Hall angle and \( \epsilon \) the magnetic layer thickness. It can be shown (see supplementary material stacks.iop.org/JPhysCM/27/326002/mmedia) that for our samples the variation of \( \cos \psi \) with \( H_x \) is negligible except around \( H_x = -H_{DMI} \) where it changes sign, so that the \( v(H_x) \) shape is mainly determined by the modification of the domain wall width with \( H_x \). Since the DW width increases for an \( H_x \) field parallel to the DW magnetisation, our measurement show that down/up DWs have their magnetisation parallel to the \( +x \) direction and therefore that the DWs in the Pt/Co/GdOx samples have left-handed chirality, like in Pt/Co/AIOx [18]. This is not surprising, as we expect that the DMI interaction is mainly located at the Pt/Co interface.

The velocity of the down/up DW in sample (A) changes sign under the effect of a negative in-plane field \( \mu_0 H_x \approx -280 \)
4mT; this is associated with the switching of the DW chirality when the negative $H_x$ field exceeds the local chiral $H_{DMI}$ field. This in-plane field strength is therefore a measure of $H_{DMI}$.

Note that in sample (B) the switching of the DW velocity is hindered by the larger DW pinning [9, 26].

The constant sign of the DMI for all the samples—assessed by the constant direction of current-driven DW motion at zero $H_x$ field—in contrast with the different DW velocity asymmetries observed for the different samples in figure 1, sheds doubts on the possibility to deduce the sign of the DMI from the domain expansion images in the creep regime. In order to clarify the interpretation of the field-induced measurements, we measured the DW speeds as a function of $H_x$ field for the bubble domains shown in figure 1.

The velocity curves are shown in figure 3 for the two domain walls propagating along the $x$-axis and having their magnetisation either parallel or antiparallel to the $H_x$ field. The up/down and the down/up DWs exhibit the same behaviour for opposite $H_x$ fields, as expected for chiral Néel walls. The curves for sample (D) (thickest Gd layer) present the main features found by other authors for DDWs in Pt/Co/Pt films [21, 22]. The speed of the down/up DW increases for a positive in-plane field, and for negative fields it decreases down to a minimum value between $-100$ mT and $-200$ mT.

In the thermally activated regime, the DW velocity is given by [25, 27]:

$$v(H_x) = v_0 \exp(-\eta H_x^\alpha)$$

Figure 2. Left: domain wall speed versus $H_x$ curves measured with constant current density $J = 1.2 \times 10^{12}$ A m$^{-2}$ for samples (A) and (B), for which a large and a vanishing field-induced domain wall speed asymmetry are found in the creep regime respectively. Right: differential Kerr image showing for sample (B) the displacement of five DWs in the direction of the current flow (pulse length 2ns, $\mu_0 H_e = 280$ mT).

Figure 3. Domain wall speed versus $H_x$ field measured in the thermally activated regime for bubble domains in Pt/Co/GdO$_x$ samples (A)–(D), for the DW propagating along the $x$-axis direction.
where $v_0$ is the characteristic speed, $\mu = 1/4$ is the creep scaling exponent and $\eta = U_c H_{\text{crit}}^H / k_B T$ where $U_c$ is an energy scaling constant and $H_{\text{crit}}$ the critical magnetic field. Following [27], $U_c$ is related to $\xi$ (the correlation length of the pinning potential) and to the Larkin length $L_c = (\sigma_{DW}^{2} \xi^{2} / \gamma)^{1/3}$ (the characteristic length of rigid microscopic DW segments) and $H_{\text{crit}} = \sigma_{DW}^{2} / \xi L_c^2$ where $\sigma_{DW}$ is the DW energy and $\gamma$ is the pinning strength of the disorder. If we assume, like it has been proposed by Ye et al [21], that neither $\xi$ nor $\gamma$ are modified by $H_c$, then the shape of $v(H_c)$ is solely due to the in-plane field dependence of the DW energy. According to [18], the energy of a DDW, taking into account the modification of the DW profile with $H_c$, reads:

$$
\sigma = \sigma_0 \left[ \sqrt{1 - h^2} + \left( h + \frac{2 D}{\pi \xi_0} \right) (\arcsin h \mp \pi / 2) \right],
$$

where $\sigma_0 = 4 \sqrt{K_0}$ is the DW energy at rest, $D_0 = 4 \sqrt{K_0 / (\pi \xi_0)} \pi$ gives the onset of magnetisation clycloids, $h = H_c / H_{K0}$ ($H_{K0}$ being the effective anisotropy field) and the $\mp$ signs refer to the DW having its magnetisation parallel/anti-parallel to the $H_c$ field. Note that for $h = 0$ one recovers the Dzyaloshinskii expression $\sigma_0 = \sigma_0 \mp \pi D$.

The energies of the DW favoured/unfavoured by the in-plane field are the same when $h = - (2/\pi)(D/D_0)$ i.e. when $H_c = - D/(4\mu_0 M_D) = - H_{\text{DM}}$. This is the in-plane field for which the DW energy is maximum. From equation (2) it then follows that the DW velocity should exhibit a minimum for $H_c = - H_{\text{DM}}$. A minimum is indeed observed for sample (D), like in the experiments reported in [21, 22]. Note that the left-handed DW chirality deduced from the measurement agrees with the results of our current-induced measurements.

The speed versus $H_c$ curves measured for samples (A)–(C) strongly deviate from the behaviour shown by sample (D). For sample (A) the speed asymmetry is the same as for sample (D) i.e. the down/up DW moves faster for positive $H_c$ fields, but the velocity of the down/up DW has a maximum for positive fields. In sample (B) the speed asymmetry practically disappears and the speeds of the up/down and down/up DWs continuously decrease with both positive and negative $H_c$ fields. In sample (C) the asymmetry is switched with respect to sample (D), i.e. the up/down DWs move faster than the down/up DWs, and moreover the speed shows a maximum, for positive $H_c$ fields. Therefore in these three samples the $v(H_c)$ curves do not follow the variation of the DW energy. Note that curves deviating from the expected behaviour have also been recently reported in the literature for Pt/Co/Pt trilayers [23].

In this work the ‘anomalous’ $v(H_c)$ curves are found in particular for samples (B) and (C), for which the sign of the speed asymmetry would suggest that the value of $D$ is either vanishing (for (B)) or opposite (for (C)) to the one of sample (D). This indicates that in the creep regime extreme care should be taken when extracting information on the DMI sign and amplitude simply on the basis of the asymmetry (or lack of asymmetry) of the Kerr microscopy differential images. Before assessing about $D$, the full speed versus $H_c$ curves should be examined and compared with the curves predicted by the existing theoretical models.

In order to verify the role of the DW pinning on the speed versus $H_c$ field, we have repeated the field-dependent measurements for larger values of the $H_c$ fields, bringing the domain wall velocities to a regime ($\gg 1$ m/s$^{-1}$) where the propagation is much less sensitive to the pinning generated by local variations of the anisotropy field. Pulsed $\mu_0 H_c$ fields up to 200 mT and duration down to 20 ns were obtained using a 50 $\mu$m wide microcoil coupled to a fast current pulse generator [28]. The results reported in figure 4 for samples (A)–(D) show that in these conditions the speed versus $H_c$ curves all acquire the trend expected for chiral Néel walls in the flow regime (see supplementary material stacks.iop.org/JPhysCM/27/326002/mmedia).

In the high field regime, the stationary DW velocity is given by $v = \frac{m_{\text{eff}} H_{\text{D}}}{\mu_0}$, where $\Delta H$ is the Thiele domain wall width [29] and $m_{\text{eff}}$ is the easy-axis magnetisation within the domains. The speed variation with $H_c$ is mainly related to the modification of the Thiele DW width with the in-plane field (see supplementary material stacks.iop.org/JPhysCM/27/326002/mmedia). In all the samples, the down/up DWs propagate faster than the up/down DWs for positive $H_c$ fields, confirming once again that the DW chirality is the same (left handed) in agreement with the current-induced measurements and the field-induced (creep) measurements for sample (D). For samples (A)–(C) the DW speed of the down/up DWs decrease down to the largest available negative $H_c$ field, with a saturation but not a clear minimum in the DW speed. This suggests that the DMI field in these samples is of the order or more than $+300$ mT.

These results show that the ‘anomalous’ $v(H_c)$ curves in the creep regime do not bear any information about the sign and strength of the DMI. In figure 3, the value for which the speed is maximum in samples (A) and (C) is not related to the $D$ value, and the absence of speed asymmetry for sample (B) is not a signature of a vanishing $D$. Since the anomalous behaviour of the $v(H_c)$ curves is observed only in the creep regime and only for samples (A)–(C), we conclude that this feature may be related to modifications of the domain wall pinning strength ($\gamma$ in equation (2)) with $H_c$, which is likely to depend on the details of the Co/GdOx interface. Note that a strong dependence of the trend of the $v(H_c)$ curves on the Pt/Co interface structure has been recently shown for domain walls in Pt/Co/Pt stacks grown with different Ar pressures [23].

Some information on the nature of the top interface, like the presence or not of CoO, can be obtained from the temperature dependence of magnetic hysteresis loops. We have carried out magnetisation measurements with variable temperature between 10 K and 300 K in a VSM-SQUID of Quantum Design (figure 5). Magnetisation measurements show that for all the samples the magnetic moment varies very little (less than 10%) between 10 and 300 K, indicating that the amount of magnetic, non-oxidized Gd is negligible. For samples (A)–(C) the measurements reveal the presence of a partially oxidised Co layer. The data measured for sample (C) are presented in figure 5. A change of the hysteresis loops, which are square with 100% remanence at 300 K, is observed around 225 K, where they become partly tilted and the remanence decreases to about 60%. This indicates a decrease of the
PMA. Upon decreasing the temperature further, the coercivity increases strongly and below 70 K a shift of the hysteresis loop to negative fields develops. Both observations can be attributed to the presence of a thin layer of CoO at the Co/GdOx interface, which becomes antiferromagnetic around 225 K with a blocking temperature around 70 K. This exchange bias cannot be due to the Gd oxide, since (i) the Néel temperature of GdO is 18 K and (ii) the exchange bias is already present at 70 K, iii) there is no exchange bias in sample (D), which also has Gd oxide at the top interface. For sample (D), the only one presenting ‘expected’ $v(H_x)$ curves in the creep regime, the cycles do not exhibit any exchange bias indicating that no CoO is formed at the top Co interface.

The ‘anomalous’ behaviour of the $v(H_x)$ curves in the creep regime seems therefore to be related to the presence of Co oxide at the top Co interface, and the details of the curves to the different degree of oxidation. Although the CoO is paramagnetic at room temperature, it exhibits a magnetic susceptibility

---

**Figure 4.** Domain wall speed versus $H_x$ field measured for bubble domains in Pt/Co/GdOx for samples (A)-(D). The $\mu_0H$ field pulses are 20 ns-long and their amplitudes vary between 70 mT and 200 mT. For samples (B)-(D) the curves were measured for two $H_z$ field values (empty symbols correspond to the scale to the right). The trends of the normalised speed curves are the same for each field value. For sample (D) the speeds are much larger, as the depinning of the DWs occurs for lower $H_z$ fields.

**Figure 5.** VSM-SQUID measurements carried out from 10 K to 300 K for an out-of-plane field up to 1 T. Left: in sample (C), the shift of the cycle at low temperature is an indication of the presence of CoO at the top Co/GdOx interface. Right: in sample (D), the cycle does not exhibit a shift, sign of the absence of relevant oxidation. Note the factor 10 difference in the field scale.
in the $x$-direction [30]. We speculate that the CoO magnetic moments induced in the $x$ direction by the in-plane field may act as an extra pinning potential acting on the DWs. Since the magnetic susceptibility may depend on the CoO thickness, this could explain why different samples exhibit maximum velocity for different $H_x$ fields. The description of the creep law simply in terms of the variation of the DW energy may not be general, as the pinning potential landscape may also be strongly affected by the in-plane field.

Finally we would like to discuss the values of the DMI strength that may be extracted from the values of the $H_{DMI}$ fields in the flow regime, and compare them with the values obtained using the Brillouin light scattering (BLS) technique. The details on how the non-reciprocal spin wave propagation in our samples has been related to the DMI strengths can be found in [20] and in the supplementary material stacks.iop.org/JPhysCM/27/326002/mmedia. For sample (D), $\mu_A H_{DMI} \approx -180$ mT (figure 4). By taking $M_r = 1.2 \times 10^6$ A m$^{-1}$ (measured by VSM-SQUID), $\mu_A H_{KO} = 0.7$ T (measured by extraordinary Hall effect), $A = 1.6 \times 10^{-11}$ J m$^{-1}$ [31] which gives $\Delta = 6.2$ nm, the expression $H_{DMI} = D(\mu_A \Delta M_r)$ gives $D = 1.48 \pm 0.2$ mJ m$^{-2}$ for the effective DMI constant, which corresponds to $D_s = D : t = 1.48 \pm 0.2$ pJ m$^{-1}$ for the interfacial DMI constant ($t_{Co} = 1$ nm). Note that the interfacial DMI constant $D_s$ is more adapted for comparing data appearing in the literature, as it does not depend on the layer thickness [20]. The $D_s$ value is, within the error bars (due mainly to the estimation of the exchange constant $A$) consistent with the value that we measured with BLS (see supplementary material stacks.iop.org/JPhysCM/27/326002/mmedia) for the same sample ($D_s = 1.6 \pm 0.2$ pJ m$^{-1}$). Note also that $D_s \sim 1.7$ pJ m$^{-1}$ was found by BLS for Pt/Co(0.6–1.2 nm)/AlOx in [20] and that chiral nucleation measurements allowed us to extract a value of $D_s = 1.32$ pJ m$^{-1}$ ($D = 2.2 \pm 0.2$ mJ m$^{-2}$) for Pt/Co(0.6 nm)/AlOx [18]. The cited measurements concern Pt/Co/MOx ($M = Al, Gd$) stacks prepared by magnetron sputtering in different conditions. The small dispersion of the $D_s$ values obtained for the various samples give us confidence on the value found for sample (D) in this work, but do not allow us to conclude on the relative contribution of the Pt/Co and Co/GdOx interfaces to DMI.

For samples (A)-(C) the minimum speed in the $v(H_x)$ obtained with large $H_x$ fields (figure 4) is not well defined, so that the DMI strength is difficult to obtain. The value of $D_s$ for sample (A) may be derived from current driven experiments, where the DMI field field corresponds to the in-plane field for which the DW chirality switches ($\mu_A H_{DMI} \approx -280$ mT) (figure 2). VSM-SQUID measurements show a strong reduction of the total magnetic moment for this sample. If we assume that the unoxidised Co layer has the same magnetisation as in sample (D), we deduce that the ferromagnetic Co layer is now 0.6 nm thick, the rest of the initial Co layer being oxidised. Using $A = 1.6 \times 10^{-11}$ J m$^{-1}$, and the measured in plane saturation field $\mu_A H_K = 1.5$ T, we obtain a value of $D_s = 1$ pJ m$^{-1}$. Under the assumption that the magnetic parameters ($M_r$ and $A$) do not change in sample (A) with respect to sample (D), this results may indicate that the overall DMI strength is reduced in this sample. Since the Pt/Co interface is unaffected by the Co oxidation, this may call for a contribution of the top Co interface to DMI, which may change depending on its oxidation state. However the very poor knowledge of the magnetic parameters of the Co layer makes us cautious, and we believe that no conclusion should be drawn about the DMI strength in this sample. Moreover, BLS measurements carried out on sample (A) and on all samples in which Co is partially oxidised were not conclusive, due to a reduced signal and a large broadening of the spin waves peaks. These results suggest the presence of a very inhomogeneous Co layer and a rough top interface.

In conclusion, we have shown that in Pt/Co/GdOx samples with different oxidation degrees of the top interface the dependence of the DW velocity as a function of the in-plane field cannot be interpreted within the creep law relating the DW speed changes exclusively to the DW energy variations. Therefore in these samples, the $v(H_x)$ curves fail to give information about the sign and the strength of the DM interaction. We have correlated the failure of the proposed creep law with the modification of the pinning potential landscape induced by the in-plane field, in the samples having a partially oxidised Co layer. When by applying strong and ultrashort out-of-plane field pulses, the dynamic regime of the DW propagation is changed and is no longer depending on pinning, the $v(H_x)$ curves recover the expected behaviour and indicate that the chirality of the DDW is left-handed. The interfacial DMI constant $D_s$ found for the sample having an unoxidised Co layer, is of the order of 1.5 pJ m$^{-1}$, in good agreement with the values found in the literature for similar samples. Note that since the measurements were taken with ns-long pulses in the creep regime and with ns-long pulses in the flow regime, the effect of the pulse length on the DW pinning may also play a role.

**Acknowledgments**

This work was supported by the Agence Nationale de la Recherche, projects ANR-11-BST0008 (ESPERADO) and ANR-14-CE26-0012 (ULTRASKY). We acknowledge the support of E Wagner, Ph David, D Dufeu and E Mossang and of the staff of the Nanofab facility at the Institut Néel. This work was partially financially supported by the Government of the Russian Federation (Grant 074-U01).

**References**

[1] Thiaville A, Rohart S, Jué E, Cros V and Fert A 2012 Europhys. Lett. 100 57002
[2] Skyrme T 1962 Nucl. Phys. 31 558
[3] Dzyaloshinskii I E 1957 Sov. Phys.—JETP 5 1259
[4] Moriya T 1960 Phys. Rev. 120 91
[5] Liu L, Lee O, Gudmundsen T, Ralph D and Buhrman R 2012 Phys. Rev. Lett. 109 096602
[6] Haazen P P J, Mure E, Franken J H, Larriese R, Swagten H J M and Koopmans B 2013 Nat. Mater. 12 299
[7] Garello K, Miron I, Avci C, Freimuth F, Mokrousov Y, Blügel S, Auffret S, Boullé O, Gaudin G and Gambardella P 2013 Nat. Nanotechnol. 8 587
[8] Miron I et al 2011 Nat. Mater. 10 419
[9] Ryu K-S, Thomas L, Yang S H and Parkin S 2013 Nat. Nanotechnol. 8 527
