Tunable chiral spin texture in magnetic domain-walls

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Magnetic domain-walls (DWs) with a preferred chirality exhibit very efficient current-driven motion. Since structural inversion asymmetry (SIA) is required for their stability, the observation of chiral domain walls in highly symmetric Pt/Co/Pt is intriguing. Here, we tune the layer asymmetry in this system and observe, by current-assisted DW depinning experiments, a small chiral field which sensitively changes. Moreover, we convincingly link the observed efficiency of DW motion to the DW texture, using DW microscopy image in Figure 1(e) visualizing the controlled domain structure that is essential for the DW resistance as a direct probe for the internal orientation of the DW under the influence of in-plane fields. The very delicate effect of capping layer thickness on the chiral field allows for its accurate control, which is important in designing novel materials for optimal spin-orbit-torque-driven DW motion.

Current-induced motion of magnetic DWs in materials with perpendicular magnetic anisotropy (PMA) could be used to transport data in next-generation storage devices. Recently, it has been suggested that in addition to conventional bulk STT contributions, various current-induced torques relating to the high spin-orbit coupling in these materials could play a dominant role. Most notably, the sources of these so-called spin orbit torques include the Rashba field, which enters as a current-dependent transverse $H_R$ field, and the spin Hall effect, which leads to a vertical spin current with transverse polarization $\sigma_y$. In a previous work, we demonstrated that the Spin Hall effect has the correct characteristics to describe the effect of current on domain walls in Pt/Co/Pt. It was observed that the efficiency of current-induced DW motion is practically zero, since the Bloch wall that is expected to be stable does not have the correct symmetry to be moved by a SHE-induced torque (Figure 1(a)), i.e. the cross product of the injected spin direction and magnetization direction within the DW along the current direction. However, this still contradicts the uniform motion of all DWs, at zero in-plane field, that was observed in other materials where the magnetic layer was sandwiched between two different materials. Subsequently, it was recognized by several authors that in the case of structural inversion asymmetry (SIA), the Dzyaloshinskii-Moriya interaction (DMI) gives rise to chiral spin structures, in this case chiral Néel walls, which are moved uniformly by a spin-Hall-effect-induced effective field ($H_{SHE}$ in Figure 1(b)).

In this work, we demonstrate by current-assisted depinning measurements that a measurable DMI is also present in Pt/Co/Pt, which is surprising at first since the top and bottom interfaces are in principle the same. The DMI effect is found to be highly tunable by varying the top layer thickness, and becomes very large when the top Pt layer is substituted by AlOx. In fact, the tuning is so delicate that the DW can have any in-plane angle $\phi$ in between the Bloch ($\phi = \frac{\pi}{2}$) and Néel ($\phi = 0$) states at remanence, due to the competition between the effective longitudinal DMI field $H_D$ and transverse DW anisotropy field $H_K$, as visualized in Figure 1(c). Our data can be explained by a very simple model of the internal DW angle $\phi$ under influence of $H_D$, $H_K$, and externally applied in-plane fields $H_x$ and $H_y$ (Figure 1(d)). The efficiency of DW depinning is simply proportional to $\cos \phi$, as expected from a field-like torque by the SHE. To prove that the DW angle $\phi$ is responsible for the efficiency, we measure the DW resistance as a function of in-plane fields (Figure 1(e)) and observe that the DW structure is indeed changing from Bloch to Néel, which is often just assumed based on elementary micromagnetics without any convincing experimental proof. These measurements allow us to directly correlate a high DW efficiency to the presence of Néel walls, which we show to be stabilized by the DMI in a tunable way.

To allow for DW resistance as well as DW depinning measurements, 1.5 $\mu$m wide strips with varying layer configurations were fabricated. Irradiation with Ga ions is employed to locally reduce the PMA in 1.5 $\mu$m long areas in these strips, allowing us to introduce a well-defined number of DWs into the strip. The Kerr microscopy image in Figure 1(e) visualizes the controlled domain structure that is essential for the DW resistance measurements presented later. When the perpendicular field strength is increased from this state, DWs are...
randomly depinning from the edges of the irradiated regions, as indicated in Figure 1(f). We analyze the effect of current on the depinning of two particular DWs, indicated by the red circle and blue square in Figure 1(f). The graph shows how the depinning field of these domain walls change with increasing current density in a blue square in Figure 1(f). The graph shows how the depinning field of two particular DWs, indicated by the red circle and indicated in Figure 1(f). We analyze the effect of current on the randomly depinning from the edges of the irradiated regions, as shown. (d) The internal angle can be further tuned using an external magnetic field. (e) The internal angle can be further tuned using an external magnetic field. (f) The internal angle can be further tuned using an external magnetic field. (g) The internal angle can be further tuned using an external magnetic field. (h) The internal angle can be further tuned using an external magnetic field. (i) The internal angle can be further tuned using an external magnetic field. (j) The internal angle can be further tuned using an external magnetic field. (k) The internal angle can be further tuned using an external magnetic field. (l) The internal angle can be further tuned using an external magnetic field. (m) The internal angle can be further tuned using an external magnetic field. (n) The internal angle can be further tuned using an external magnetic field. (o) The internal angle can be further tuned using an external magnetic field. (p) The internal angle can be further tuned using an external magnetic field. (q) The internal angle can be further tuned using an external magnetic field. (r) The internal angle can be further tuned using an external magnetic field. (s) The internal angle can be further tuned using an external magnetic field. (t) The internal angle can be further tuned using an external magnetic field. (u) The internal angle can be further tuned using an external magnetic field. (v) The internal angle can be further tuned using an external magnetic field. (w) The internal angle can be further tuned using an external magnetic field. (x) The internal angle can be further tuned using an external magnetic field. (y) The internal angle can be further tuned using an external magnetic field. (z) The internal angle can be further tuned using an external magnetic field.

Here,  \( J \) is the DW width (assumed constant),  \( H_K \) the shape anisotropy field of the DW, and  \( H_{DP} = \pi D/(2 \mu_0 M_s \lambda) \) the effective chiral magnetic field (with  \( D \) an energy constant characterizing the strength of the DMI). The free parameters of the fit are  \( H_{DK}, H_{DP}, \) and  \( \epsilon_{\text{SHE}} \) as indicated in Figure 2(a). This graph clearly shows that there is a contribution from DMI: the red and blue curves have been shifted to the left and right, respectively, due to the effective chiral magnetic field  \( H_D \approx 12.5 \pm 0.4 \) mT, which has opposite sign for domain walls of opposite polarity (up-down vs down-up). We should note that  \( H_D \) could be lower than in an unpattened film, since the Ga irradiation locally reduces the anisotropy and increases  \( \lambda \). Apart from the observed horizontal shift, there is a linear increase from  \( \epsilon = 0 \) to  \( \epsilon_{\text{SHE}} \) over a field range  \( \pm H_D/2 \), which is attributed to the transition from Bloch to Néel. Replacing  \( H_D \) by  \( H_{DP} \) in Figure 2(b), the efficiency simply decreases with  \( |H'_{DP}| \), because  \( H_D \) gradually pulls the wall to a Bloch state. Interestingly, the DW at zero in-plane field is neither a Bloch nor a Néel wall. From the efficiency at zero in-plane field, it can be deduced that the DW angle at remanence is  \( \phi \approx 60^\circ \), rather than the 90° that is expected in a system without SIA. The stability of such an in-between wall type, observed before on epitaxial Co/Ni multilayers, might be interesting for specific device applications of sputtered PMA films.

To explore the tunability of the small DMI in Pt/Co/Pt, samples with a thinner 1 nm Pt capping layer were fabricated, in order to increase the apparent SIA. Indeed, in Figure 2(c) it is observed that  \( H_D \) has increased significantly to the value  \( 37 \pm 1 \) mT. The change of efficiency  \( \delta \epsilon_{\text{SHE}} \) matches with the change in layer thickness as discussed in the Supplementary Information. The SIA can be increased much more by replacing the top Pt layer by a different material, AlOx, as shown in Figure 2(e–f). In fact,  \( H_D \) has become so large that we cannot quantify it within our setup. Regardless of the in-plane field, the domain-walls are chiral Néel walls which are pushed to the left and right, respectively, due to the effective chiral magnetic field  \( H_D \approx 12.5 \pm 0.4 \) mT, which has opposite sign for domain walls of opposite polarity (up-down vs down-up). We should note that  \( H_D \) could be lower than in an unpattened film, since the Ga irradiation locally reduces the anisotropy and increases  \( \lambda \). Apart from the observed horizontal shift, there is a linear increase from  \( \epsilon = 0 \) to  \( \epsilon_{\text{SHE}} \) over a field range  \( \pm H_D/2 \), which is attributed to the transition from Bloch to Néel. Replacing  \( H_D \) by  \( H_{DP} \) in Figure 2(b), the efficiency simply decreases with  \( |H'_{DP}| \), because  \( H_D \) gradually pulls the wall to a Bloch state. Interestingly, the DW at zero in-plane field is neither a Bloch nor a Néel wall. From the efficiency at zero in-plane field, it can be deduced that the DW angle at remanence is  \( \phi \approx 60^\circ \), rather than the 90° that is expected in a system without SIA. The stability of such an in-between wall type, observed before on epitaxial Co/Ni multilayers, might be interesting for specific device applications of sputtered PMA films.

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current-dependent $H_y$ Rashba field. Crucially, these results suggest that our Pt/Co/AlOx is not fundamentally different from Pt/Co/Pt, but only has a higher built-in chiral field due to the increased asymmetry.

Although the results presented so far here and by other authors1–3,18,19 match well with a SHE-induced torque dictated by the DW angle $\phi$, it is not at all trivial that the DW indeed has the structure that these experiments suggest. In fact, the transition from a Bloch-like to a Néel state by an in-plane field was to our knowledge not measured before. We believe that using DW resistance as a probe for the DW structure is much more direct than using the DW mobility, since the resistance does not rely on any of the spin torques. Therefore, we have performed measurements of the DW resistance as a function of in-plane field. To be able to accurately measure tiny resistance changes induced by the DWs, we use lock-in measurements on an on-sample Wheatstone bridge25,26 consisting of four nominally identical wires, one of which has a Ga-irradiation pattern.

To exclude magnetoresistive effects in the domains from polluting the measured resistance of the DWs, we measure the bias of the bridge for the monodomain state at each in-plane field, and subtract it from the bias in the presence of the multidomain state shown in Figure 1(e) (see also Methods section). When the resistance of a Bloch wall is measured (Figure 3(a)), the dominant contribution comes from the intrinsic resistance $R_{LZ} \sim 1/\lambda$ dictated by the Levy-Zhang model27 for which we recently found experimental evidence28,29. However, when the magnetization within the DW obtains a component parallel to the current flow (Figure 3(b)), an additional contribution $R_{\text{AMR}}$ from anisotropic magnetoresistance arises30, simply proportional to $\lambda \cos^2 \phi$.

Looking at the measured DW resistance in Pt(4)/Co(0.4)/Pt(2) as a function of $H_x$ (open orange diamonds in Figure 3(c)), we indeed see an increase when the in-plane field increases, owing to the transformation to a Néel wall. However, beyond $H_x = 30$ mT, the measured DW resistance starts to decrease again. This decrease is seen over the entire $H_y$-field range (purple triangles), which can be regarded as a kind of background measurement. We attribute this to a change of $R_{LZ}$ related to the domain structure. Since the anisotropy in one of the domains is reduced strongly by the Ga irradiation treatment29, this region tends to be pulled in plane, modifying the domain-wall profile as sketched in (Figure 3(d)). This has a strong effect on $R_{LZ}$, and also a small effect on $R_{\text{AMR}}$ (see Supplementary Information for details of the model). From the DW-depinning data (top pane of Figure 3(c)), we can deduce $\phi(H_y, H_x)$, and use this as input in our resistance model. The best-fit to this model is presented as the dashed orange and solid purple lines in Figure 3(c), where the free parameters are the anisotropy in the irradiated domain, the AMR resistivity, and the strength of the intrinsic DWR. The model reproduces the measurements, apart from two kinks at each field polarity (when the angles of either the ‘red’ or the ‘blue’ domain walls saturate, compare to top panel). It is not surprising that these sharp features from the 1D model become smooth in reality, especially since we measure the sum of 20 DWs, each with slightly different local properties.

Looking at the DW resistance measurements in Pt/Co/AlOx in Figure 3(e), only minor changes as a function of in-plane field are observed, and there is no clear difference between the $H_x$ and $H_y$ data. Similar to the DW-depinning results, this suggests that the Néel character of the DWs is stabilized by a strong built-in chiral field and is not significantly influenced by the range of applied in-plane fields. The background due to magnetization canting is largely absent here, because the anisotropy in the irradiated domain is much higher. Although any change as a function of in-plane field is relatively small.

Figure 2 | Depinning efficiency $\epsilon$ under in-plane fields in systems with varying SIA. (a) in almost symmetric Pt(4)/Co(0.4)/Pt(2), $\epsilon(H_x)$ shows a small opening between the two domain walls (red discs and blue squares) of opposite polarity, indicative of a DMI field $H_{y5}$. The slope of the transition from $\epsilon=0$ to its saturation level $\epsilon_{\text{sat}}$ is characterized by the DW anisotropy $H_{LZ}$. To determine these parameters, a global fit (dashed lines) is performed together with the $H_x$-data in (b). (c,d) Increasing the stack asymmetry by reducing the top Pt layer to 1 nm gives a higher DMI opening. (e,f) Replacing the top Pt layer by AlOx, the DMI opening becomes too large to measure in our setup. The DMI is so strong that the DW angle $\phi$ is hardly influenced by $H_x$ and $H_y$. The fit corresponds to the average level.

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Figure 3 | Bloch–Néel transition revealed by DW resistance measurements. (a) A Bloch wall yields only an intrinsic contribution $R_{LZ}$ to the DW resistance. (b) As $\phi$ approaches 0 (Néel wall), an additional contribution from the AMR effect arises. (c) (top) Depinning efficiency as a function of $H_x$ and (bottom) Resistance change induced by 20 DWs of alternating polarity, as a function of $H_x$ (open diamonds) and $H_y$ (filled triangles), measured on the same Pt(4)/Co(0.5)/Pt(2) sample. The dashed orange and solid purple line are a fit including the two resistance contributions, in which $H_x$ and $H_y$ have been taken from the fit of the depinning data. The DW resistance peaks around $H_y = 20$ mT due to the transition from Bloch to Néel. A decreasing background signal is present in both the $H_x$ and the $H_y$ data due to canting of the magnetization in the irradiated domain (d), leading to a lower intrinsic contribution $R_{LZ}$. (e) DW resistance in Pt/Co/AlOx does not show the Bloch–Néel transition since Néel walls are highly stable.

Methods

**A. Sample fabrication.** All samples consisted of 1.5 μm wide strips fabricated on Si/ SiO$_2$ substrates by Electron-Beam lithography, DC sputtering, and lift-off. The Pt(4)/ Co(0.8)/Al(1.5) samples were oxidized in a 15 W, 0.1 mbar O$_2$ plasma for 10 minutes to obtain Pt/Co/AlOx. These samples were annealed for 20 minutes at 573 K. The Pt/ Co/Pt samples did not undergo an annealing treatment. The samples were designed to form an on-sample Wheatstone bridge configuration to be able to measure resistance changes accurately (for details see3). The samples were locally irradiated with a 30 keV Ga FIB to make it possible to create a stable domain pattern with a well-defined number of domain walls. At the same time, the edges of the irradiation boundaries acted as pinning sites, to enable the well-controlled depinning measurements. The Ga doses were chosen to ensure that all DWs are stable during DWR measurements and amounted to $1.13 \times 10^{13}$ ions/cm$^2$ on Pt/Co/AlOx, $0.50 \times 10^{13}$ ions/cm$^2$ on Pt(4)/Co(0.5)/Pt(2) and Pt(4)/Co(0.4)/Pt(2), and $0.81 \times 10^{13}$ ions/cm$^2$ on Pt(4)/Co(0.4)/Pt(1). Table S1 (Supplementary Information) provides the material parameters (PMA constant and M$_S$) obtained by VSM-SQUID magnetometry on unpatterned films.

**B. DW depinning measurements.** Very low DC current densities in the range $\pm 2 \times 10^4$ A/m$^2$ were used to exclude significant effects from Joule heating and Oersted fields. The current and in-plane field are kept constant, while the $z$-field is being ramped up until both DWs have depinned which is automatically detected by an image analysis routine. This is repeated at least 10 times for each current point to obtain sufficient signal to noise. Table S1 presents the fit parameters of the 1D model ($H_{Kx}, H_{Kz}$ and $E_{SHE}$) for each used material composition, and compares the latter to the expected efficiency $E_{calc}$ based on the layer thicknesses.
C. DW resistance measurements. Our measurement routine is very similar to what we described in 25. We use a combination of an on-sample Wheatstone bridge and a lock-in technique to measure the resistance change due to the presence of domain walls. The in-plane field is applied constantly, and first the wire is saturated (zero DWs) by a negative $H_x$, and the lock-in voltage at $H_x = -1 \text{ mT}$ is recorded. Then, the domain walls are created by a positive $H_x$, the field is reduced to $H_x = 1 \text{ mT}$ and the lock-in voltage is recorded again. The difference is presented in Figure 3 as $\Delta R$, and represents the resistance change due to all the DWs (20 or 18 for Pt/Co/Pt and Pt/Co/AlOx, respectively). Since the background voltage is recorded at the same in-plane field as the voltage in the presence of DWs, magnetoresistive effects within the bulk of the domains, such as AMR due to canting or the magnon contribution 25, are automatically filtered out, leaving only resistance changes in the DW region. We always check the number and positions of the DWs present by real-time comparison to a Kerr-microscopy image. Furthermore, we always ensure that the magnetization underneath the 20 nm thick Pt contacts and the three reference strips in the bridge does not switch, as this can give rise to additional magnetoresistive signals. The small $H_x$ during measurements serves to ensure the DW pattern remains stable during measurements. An AC probe current of 1 mA (0.75 mA) at 500 Hz was sent through two parallel series of Pt(4)/Co(0.5)/Pt(2) (Pt(4)/Co(0.8)/AlOx) wires and it was verified that a lower amplitude does not significantly alter the results. Because the bridge is not perfectly balanced, a bias of typically 10 mV occurs, even when all strips are magnetized in the same direction. When we introduce domain walls into one of the strips, the signal typically changes by 10 $\mu$V. Note that a sample with slightly thicker $t_{Co} = 0.5 \text{ nm}$ had to be used, because the samples with $t_{Co} = 0.4 \text{ nm}$ turned out to be very easily switched by the spin Hall effect from the probe current. Therefore, much lower probe currents have to be used, and the thinner magnetic Co layer further deteriorates the signal/noise. Details on the modeling of in-plane field effects on the measured DW resistance are presented in the Supplementary Information, and the individual contributions to the modeled resistance are plotted in Figure S2.

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Author contributions
J.H.F. designed the experiments and prepared the manuscript. M.H. and J.H.F. performed the experiments and the data analysis. H.J.M.S. and B.K. assisted in the analysis and commented on the final manuscript.

Additional information
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