Out-of-plane chiral domain wall spin-structures in ultrathin in-plane magnets

Gong Chen¹, Sang Pyo Kang², Colin Ophus¹, Alpha T. N'Diaye³, Hee Young Kwon², Ryan T. Qiu¹, Changyeon Won², Kai Liu⁴, Yizheng Wu⁵ & Andreas K. Schmid¹

Chiral spin textures in ultrathin films, such as skyrmions or chiral domain walls, are believed to offer large performance advantages in the development of novel spintronics technologies. While in-plane magnetized films have been studied extensively as media for current- and field-driven domain wall dynamics with applications in memory or logic devices, the stabilization of chiral spin textures in in-plane magnetized films has remained rare. Here we report a phase of spin structures in an in-plane magnetized ultrathin film system where out-of-plane spin orientations within domain walls are stable. Moreover, while domain walls in in-plane films are generally expected to be non-chiral, we show that right-handed spin rotations are strongly favoured in this system, due to the presence of the interfacial Dzyaloshinskii–Moriya interaction. These results constitute a platform to explore unconventional spin dynamics and topological phenomena that may enable high-performance in-plane spin-orbitronics devices.
Spin textures in magnetic materials are determined by the balance of contributions to the magnetic free energy. In-plane magnetized films are a textbook case: it is generally expected that ultrathin films have Néel wall textures where the spin vector rotates within the plane, and thicker films have Bloch wall textures where spins tilt through out-of-plane alignments. Such film thickness-dependent domain wall-type transitions have been studied in various systems, for example the transition is at \( \sim 30-35 \) nm thickness in permalloy films. The domain wall transitions are a result of stray field and anisotropy energies competing along two possible hard axes.

Recently, homochiral spin textures have been observed in the presence of the interfacial Dzyaloshinskii–Moriya interaction (DMI). Such chiral spin textures have been shown to offer enormous performance advantages in electrically controlled magnetic devices, including extremely fast current-driven domain wall motion and low threshold current. However, for in-plane magnetized ultrathin films the most common wall type, Néel walls, are expected to be non-chiral. This is because effects of the DMI on in-plane Néel walls are considered to be unimportant. This assessment comes from a simple symmetry argument. The interfacial DMI term is written as \( E_{\text{DMI}} = -D_{\text{u}} \cdot \langle S_i \times S_j \rangle \), where \( S_i \) and \( S_j \) are two atomic spins on neighbouring atomic sites \( i \) and \( j \), and \( D_{\text{u}} \) is the DMI vector. For in-plane Néel walls the cross-product \( S_i \times S_j \) points out-of-plane, and \( D_{\text{u}} \) is a vector that lies within the plane; therefore the contribution of the DMI to the free energy of the wall vanishes.

In atomically thin films, the interplay between strong interfacial DMI and exchange interaction can lead to homogeneous or inhomogeneous cycloidal spin spirals. Driven by fundamental curiosity and the possibility of high-performance applications, it is interesting to explore other possibilities to stabilize chiral domain walls in in-plane magnetized thin films.

In the following, we show how the thickness-dependent Néel-to-Bloch wall transition can be reversed by deliberately adjusting magnetic anisotropies, that is, stabilizing out-of-plane domain walls in ultrathin films. Moreover, we show that out-of-plane domain walls stabilized in this way are indeed right-handed chiral walls. Modelling the domain walls in Monte-Carlo simulations, we show that their stability can be understood by taking into account a uniaxial anisotropy contribution, a perpendicular anisotropy contribution as well as the contribution of the interfacial DMI.

Results

Observation of the inverse Néel–Bloch transition. Spin-polarized low-energy electron microscopy (SPLEEM) was used to measure maps of the orientation of the magnetization vector in ultrathin, single-crystalline Fe/Ni bilayers grown on a W(110) crystal. The characteristic spin texture of a domain wall in a bilayer composed of 15 atomic monolayers (ML) of nickel and 5.2 ML of iron is shown in Fig. 1.a. In this sample the two-fold easy magnetization axis is along [001]; low-index directions are indicated by black arrows. Rendering SPLEEM measurements as an arrow-array, Fig. 1a represents the magnetization in a \( 375 \text{ nm} \times 375 \text{ nm} \) region. Here a 180° domain wall separates a domain on the left that is magnetized in the [00–1] direction from a domain on the right that is magnetized in the [001] direction. Magnetization inside the domain wall rotates within the film plane, as expected in a conventional Néel wall. SPLEEM data of a larger area surrounding this region (dashed yellow box) are rendered as a colour plot in Fig. 1b, where the magnetization direction measured in each pixel is represented as colour according to the colour wheel in the inset (red—[00–1], cyan—[001], green/yellow—[1–10], purple—[−110]). Colour variation along the domain wall (green/yellow versus purple sections) indicates that the sense of spin rotation within the wall randomly reverses in various places. Figure 1c plots independent SPLEEM measurements of the in-plane and out-of-plane magnetization components along a trajectory crossing the domain wall, corroborating the in-plane texture of this domain wall (see Methods for details). Taken together, the data reproduced in Fig. 1a–c shows that, unsurprisingly, the domain wall has a Néel wall structure throughout and there is no chiral preference in the magnetic structure of this film.

A much more unusual result emerges when the thickness of the Fe layer is slightly less, 3.3 ML as sketched in Fig. 1d. In this case, SPLEEM data rendered as arrow-array in Fig. 1d highlights that the domain wall has a spin texture that is in stark contrast with the conventional Néel wall described above: within the 180° domain wall separating a domain on the left/back (magnetized in the [00–1] direction) from a domain on the right/front (magnetized in the [001] direction) the spins rotate through an out-of-plane alignment. Using the same colour wheel as before, Fig. 1e renders SPLEEM data of a larger area surrounding this region (355 nm \times 355 \text{ nm}, dashed yellow box) as a colour plot. In this case pixels within the domain wall appear as white or black, indicating that the magnetization direction within domain walls always rotates towards out-of-plane directions. Note that in some pixels in Fig. 1d,e the magnetization tilts slightly towards out-of-plane, which may result from additional perpendicular anisotropy induced by substrate roughness (see LEEM morphology in Supplementary Fig. 1d). This additional small anisotropy may influence spin textures when the system is close to a spin reorientation transition. Figure 1f plots independently the in-plane and out-of-plane magnetization components along a trajectory crossing the domain wall, and further supports the out-of-plane texture of this domain wall. Taking into account the fact that the width of this domain wall (full width at half maximum \( \sim 110 \) nm in Fig. 1f) is much larger than the thickness of the film (a few nm), the domain wall texture observed in Fig. 1d–f should be energetically unfavourable due to the stray field energy.

Possible origin of the observed domain wall. Now we discuss how the stability of this unusual domain wall spin texture can be understood. In the Fe/Ni/W(110) system, additional contributions to the magnetic free energy might play a role to stabilize the domain wall structure. These include perpendicular magnetic anisotropy of the Fe layer due to epitaxial strain at the Ni(111)/W(110) interface and the interfacial DMI at the Ni/W interface. Looking at Fig. 1a,b provides one hunch. The in-plane uniaxial anisotropy \( K_u \), stabilizing the magnetization direction of the two domains, is along the W[001] direction; so the spins within this conventional Néel wall point into a hard-axis direction along W[1–10]. However, in most thin film systems the energy penalty associated with rotating spins into a hard axis is smaller than the dipolar energy penalty associated with rotating spins into an out-of-plane alignment. One contribution that can counter this dipolar energy penalty is perpendicular magnetic anisotropy, which is indeed present in Fe layers grown in this orientation.

The strength of this perpendicular anisotropy can be demonstrated by measuring the magnetization direction in Fe/Ni/W(110) as a function of the Fe overlayer thickness (Supplementary Fig. 2). In the absence of a Fe overlayer, 15 ML Ni/W(110) films are in-plane magnetized. The magnetization starts to cant towards the out-of-plane direction at 0.5 ML Fe coverage. This canting gradually increases and reaches fully out-of-plane magnetization around \( d_{Fe} = 2.4 \) ML. With additional Fe, the magnetization gradually cant back towards in-plane...
SPLEEM image shows larger area (dashed yellow square outlines the region shown in a); in-plane orientation of the magnetization is rendered as colour according to colour wheel in the inset, with +z/z−z out-of-plane component rendered as brightness (black/white). Scale bar, 500 nm. (c) Averaged line profile of out-of-plane (orange squares) and in-plane (blue circles) magnetization components across domain wall in b. (d) Pixel-by-pixel magnetization vector map, showing unexpected out-of-plane domain wall in a 350 × 350 nm region of 3.3 ML Fe/15 ML Ni/W(110) bilayer (sample structure sketched in inset). (e) Compound SPLEEM image shows larger area (dashed yellow square outlines the region shown in d). Scale bar, 500 nm. (f) Averaged line profile of out-of-plane (orange squares) and in-plane (blue circles) magnetization components across domain wall in e.

Chirality of the out-of-plane domain walls. Inspection of a large quantity of SPLEEM images of Fe/Ni/W(110) films similar to the sample of Fig. 1d–f reveals an additional interesting feature of the out-of-plane domain walls. Surprisingly, the handedness of these rotating spin textures is not random. This is unusual because in conventional Néel walls, such as those shown in Fig. 1a–c, the handedness of spin rotations within the walls is expected (and observed) to be energetically degenerate: for example, in Fig. 1b left-handed and right-handed sections of domain wall (purple and green/yellow) alternate at random. In contrast, handedness of the out-of-plane domain walls we observe in thinner Fe/Ni/W(110) structures follows a systematic pattern (Fig. 1e).

Simulations for the out-of-plane domain wall. To test this hypothesis, we used Monte-Carlo simulations to compute ground-state domain wall spin textures as a function of the uniaxial anisotropy $K_u$ and the total effective anisotropy $K_{\text{eff}}$. Results, summarized in Fig. 2a, show that three phases can be distinguished, where domain wall ground states have different spin textures. When $K_u$ is negligible then, as a function of increasing $K_{\text{eff}}$, there is a spin reorientation transition where the in-plane easy magnetization axis (shaded brown in Fig. 2a), with domain walls exhibiting Néel wall texture, reorients to an out-of-plane easy axis (shaded blue in Fig. 2a), also with Néel type domain walls.\(^{17,22–24}\) This is consistent with experimental observations of domain wall textures near spin reorientation transitions in Fe/Ni bilayers on Cu(100) crystals where $K_u \approx 0$ (ref. 17) (Supplementary Fig. 4). When $K_u$ is larger, a new phase appears (shaded gold in Fig. 2a) where the easy magnetization axis is in-plane, while spins within the domain walls rotate through out-of-plane alignments. Note that the strength of the DMI is considered in the simulation (Methods), and its value only slightly affects the boundary position (Supplementary Fig. 5).

Detailed domain wall spin textures predicted from Monte-Carlo simulations as a function of $K_{\text{eff}}$ (Fig. 2b–d) are in excellent agreement with detailed experimental images of domain wall spin textures where $K_{\text{eff}}$ was tuned by changing the thickness $d_{\text{Fe}}$ of the Fe layer (Fig. 2e–g).
In contrast, for the in-plane magnetized system observed here the role of the interfacial DMI cannot be neglected because, within these domain walls, the cross-product $S_i \times S_j$ has finite components within the plane, leading to a finite magnitude of $E_{\text{DMI}}$.

The spin structure in the domain wall surrounding a circular bubble domain is a convenient shorthand to describe the chiral magnetic properties of this system. Figure 3a sketches the spin texture of a circle-shaped domain, essentially modelling the domain at the top, right of centre, in Fig. 1e. Trajectories across such a bubble domain along two orthogonal in-plane directions can be visualized as two types of spin spirals, that is, cycloidal (Neél-type) spin spirals along $W[001]$ (Fig. 3c) and helical (Bloch-type) spin spirals along $W[1–10]$ (Fig. 3d). Within this
Stability of chiral out-of-plane walls in nanowires. The Slonczewski-like torque that drives fast chiral domain wall motion in perpendicularly magnetized spin-orbitronics systems 23,25–27 vanishes for conventional in-plane Néel wall textures (such as transverse walls in nanowire geometries) 25. But out-of-plane domain wall spin textures with DMI-stabilized chirality, as seen here in the Fe/Ni/W(110) system, may offer important benefits for current-driven domain wall dynamics. Furthermore, one key ingredient in stabilizing these out-of-plane domain wall textures—a uniaxial anisotropy 28—is present in nanowires even in absence of the uniaxial anisotropy provided by the W(110) substrate: considering that the shape-induced uniaxial anisotropy provides a hard axis in the direction across the nanowire 28, it is interesting to consider whether a tailored addition of perpendicular anisotropy to in-plane magnetized nanowires could result in domain wall textures similar to those we observed in the Fe/Ni/W(110) films. To provide an estimate of this possibility, we modelled such a nanowire in a Monte-Carlo simulation. A simulated spin structure in a nanowire with 200 × 10 spin blocks is shown in Fig. 5. This result shows that, with dimensionless values (expressed as fractions of the exchange interaction J) for the effective anisotropy 29, nanowire shape-induced uniaxial anisotropy 29, and strength of the DMI 29 is 0.1, we find that right-handed chiral out-of-plane domain walls have the lowest energy in this nanowire. In the presence of the giant spin Hall effect of tungsten 29 and strength of the DMI similar as in a number of systems (the strength of the DMI found here, ~0.53 mV per atom (Methods), is of the same order as in other reported systems 17,18,22,24,26,27, the Slonczewski-like torque exerts a significant effect on the domain wall motion.)
significant force that may enable fast current-driven domain wall propagation, extending the possibility of efficient electrical control of magnetic structures to in-plane magnetized systems.

Conclusions

In summary, using micromagnetic imaging experiments we found an unusual type of chiral out-of-plane domain wall spin textures in an in-plane magnetized ultrathin film system. Supported by Monte-Carlo simulation, the interplay between magnetic anistropies is understood to be the driving force stabilizing the out-of-plane wall textures. The magnetic chirality of these domain walls is stabilized along in-plane orientations and is understood to result from the interfacial DMI. Current-31–38 Supported by Monte-Carlo simulation, the interplay between systems. Physical vapour deposition from electron beam evaporators, and the Fe film ultrahigh vacuum. Fe and Ni layers were deposited at room temperature by each Cartesian direction, after application of a drift correction routine based on 7.5 eV to maximize the magnetic contrast. Supplementary Fig. 1a–c shows typical dynamics and topological phenomena 45–48 that may enable the out-of-plane domain wall structures described in this paper may provide a platform to explore unconventional spin dynamics and topological phenomena that may enable high-performance in-plane magnetized memory and logic devices.

Methods

Sample preparation. The W(110) substrate was cleaned by flash heating to 1950°C in 3 × 10⁻¹ Torr O₂, and final annealing at the same temperature under ultrahigh vacuum. Fe and Ni layers were deposited at room temperature by physical vapour deposition from electron beam evaporators, and the Fe film thickness d₀Fe and Ni film thickness d₀Ni was controlled by monitoring the image intensity oscillations associated with atomic layer-by-layer growth. The sample was annealed to 630°C for several minutes after growth of the first 1 ML to develop the well-ordered c-(1×7) structure as a template for subsequent growth of Ni film and Fe film in fcc(111) epoxy.

Magnetic imaging and vector field analysis. Magnetic images were measured using the SPELEEM instrument at the National Center for Electron Microscopy at Lawrence Berkeley National Laboratory. The contrast in SPELEEM images represents the asymmetry of the spin-dependent reflection between spin-polarized electron beam evaporation and the Fe film thickness. The triangle vector R₀ = R – R₀ between sites i and j and, as a result of the bcc(110) interface, the DMI is anisotropic such that the DMI vector has a finite magnitude along W(110) directions and vanishes along W(001) directions. The strength of D₀M can be estimated as D₀M = k₀Fe/k₀Ni, where k₀Fe = 4π × 10⁻¹⁰ H m⁻¹, μ₀ = 4π × 10⁻⁷ A m⁻¹, μ₀ = 2.67μ₀, d₀Ni = 3.3 ML, a₀ = 2.49 Å. We find D₀N ≈ 0.53 mV/atom. These simulations best match the observed dependence of domain wall handedness on domain wall orientation (Fig. 4b) when D = D₀M, which provides an experimental estimate of the strength of the DMI in this system of ~0.53 mV/atom.

Data availability. The data that support the findings of this study are available from the corresponding author upon request.

References

1. Hubert, A. & Schafer, R. Magnetic Domains: The Analysis of Magnetic Microstructures (Springer, 1998).
2. Néel, L. Énergie des parois de Bloch dans les couches minces. C.R. Acad. Sci. (Paris) 241, 533 (1955).
3. Bloch, F. Zur Theorie des Austauschproblems und der Remanenzerscheinung der Ferromagnetika. Z. Phys. 74, 295–335 (1932).
4. Landau, L. & Lifshitz, E. On the theory of the dispersion of magnetic permeability in ferromagnetic bodies. Phys. Z. Sowjetunion 8, 153–169 (1935).
5. Middelhoek, S. Domain walls in thin Ni–Fe films. J. Appl. Phys. 34, 1054–1059 (1963).
6. Torok, E. J., Olson, A. L. & Oredson, H. N. Transition between Bloch and Néel walls. J. Appl. Phys. 36, 1394–1399 (1965).
7. Hubert, A. Domain wall structures in thin magnetic films. IEEE Trans. Magn. 11, 1285–1290 (1975).
8. Trunk, T., Redjal, M., Káky, A., Ruane, M. F. & Humphrey, F. B. Domain wall structure in Permalloy films with decreasing thickness at the Bloch to Néel transition. J. Appl. Phys. 89, 7606–7608 (2001).
9. Ramstöck, K., Hartung, W. & Hubert, A. The phase diagram of domain walls in narrow magnetic strips. Phys. Status Solidi A 135, 505–518 (1996).
10. Dzyaloshinskii, I. E. Thermodynamic theory of ‘weak’ ferromagnetism in antiferromagnetic substances. Sov. Phys. JETP 5, 1259–1272 (1957).
11. Moriya, T. Anisotropic superexchange interaction and weak ferromagnetism. Phys. Rev. 120, 91–98 (1960).
12. Fert, A. Magnetic and transport properties of metallic multilayers. Metallic Multilayers 59–60, 439–480 (1990).
13. Crespin, S., Croix, C. & Dzyaloshinskii-Moriya interactions induced by symmetry breaking at a surface. J. Magn. Magn. Mater. 182, 341–348 (1998).
14. Bode, M. et al. Chiral magnetic order at surfaces driven by inversion asymmetry. Nature 447, 190–193 (2007).
15. Ferriani, P. et al. Atomic-scale spin spiral with a unique rotational sense: Multistability on W(001). Science 320, 1027–1030 (2008).
16. Meckler, S. et al. Real-space observation of a right-rotating inhomogeneous cycloidal spin spiral by spin-polarized scanning tunneling microscopy in a triple axes vector magnet. Phys. Rev. Lett. 103, 157201 (2009).
17. Chen, G. et al. Novel chiral magnetic domain wall structure in Fe/Ni/Cu(001) films. Phys. Rev. Lett. 110, 177204 (2013).
18. Soumyanarayanan, A., Reyren, N., Fert, A. & Panagopoulos, C. Nature 539, 509–517 (2016).
19. Altman, M. S., Pinkvos, H., Hurst, J., Marx, G. & Bauer, E. Spin polarized low energy electron microscopy of surface magnetic structure. MRS Symp. Proc. 232, 125–132 (1991).
20. Rougemolle, N. & Schmid, A. K. Magnetic imaging with spin-polarized low-energy electron microscopy. Appl. Surf. Sci. 1, Appl. Phys. 50, 29101 (2010).
21. Meyerheim, H. I. et al. Spin reorientation and structural relaxation of atomic layers: pushing the limits of accuracy. Phys. Rev. Lett. 93, 156105 (2004).
22. Chen, G. et al. Unlocking Bloch-type chirality in ultrathin magnets through uniaxial strain. Nat. Commun. 6, 6958 (2015).
23. Thiaville, A. et al. Dynamics of Dzyaloshinskii domain walls in ultrathin magnetic films. Europhys. Lett. 100, 57002 (2012).
24. Chen, G. et al. Tailoring the chirality of magnetic domain walls by interface engineering. Nat. Commun. 4, 2671 (2013).
25. Khvalkovskiy, A. V. et al. Matching domain-wall configuration and spin–orbit torques for efficient domain-wall motion. Phys. Rev. B 87, 020402(R) (2013).
26. Emori, K. et al. Spin transfer torque devices utilizing the giant spin Hall effect of tungsten. Appl. Phys. Lett. 101, 122404 (2012).
27. Miron, I. M. et al. Fast current-induced domain-wall motion controlled by the Rashba effect. Nat. Mater. 10, 419–423 (2011).
28. Grollier, J. et al. Switching a spin valve back and forth by current-induced domain wall motion. Appl. Phys. Lett. 83, 509–511 (2003).
29. Vermolen, S. J., Allwood, D. A., Atkinson, D., Cooke, M. D. & Cowburn, R. P. Domain wall propagation in magnetic nanowires by spin-polarized current injection. Europhys. Lett. 65, 526–532 (2004).
30. Yamaguchi, A. et al. Real-space observation of current-driven domain wall motion in submicron magnetic wires. Phys. Rev. Lett. 92, 077205 (2004).
31. Klaus, M. et al. Direct observation of domain-wall configurations transformed by spin currents. Phys. Rev. Lett. 95, 026601 (2005).
32. Thomas, L. et al. Oscillatory dependence of current-driven magnetic domain wall motion on current pulse length. Nature 443, 197–200 (2006).
33. Beach, G. S. D., Knutson, C., Nistor, C., Tsoi, M. & Erskine, J. L. Nonlinear domain-wall velocity enhancement by spin-polarized electric current. Phys. Rev. Lett. 97, 057203 (2006).
34. Klaui, M. et al. Spin transfer torque devices utilizing the giant spin Hall effect of tungsten. Appl. Phys. Lett. 101, 122404 (2012).
35. Thomas, L. et al. Oscillatory dependence of current-driven magnetic domain wall motion on current pulse length. Nature 443, 197–200 (2006).
36. Beach, G. S. D., Knutson, C., Nistor, C., Tsoi, M. & Erskine, J. L. Nonlinear domain-wall velocity enhancement by spin-polarized electric current. Phys. Rev. Lett. 97, 057203 (2006).
37. Hayashi, M. et al. Dependence of current and field driven depinning of domain walls on their structure and chirality in permalloy nanowires. Phys. Rev. Lett. 97, 207205 (2006).
38. Thomas, L., Moriya, R., Rettner, C. & Parkin, S. Dynamics of magnetic domain walls under their own inertia. Science 330, 1810–1813 (2010).
39. Ono, T. et al. Propagation of a domain wall in a submicrometer magnetic wire. Science 284, 468–470 (1999).
40. Atkinsson, D. et al. Magnetic domain-wall dynamics in a submicrometre ferromagnetic structure. Nat. Mater. 2, 83–87 (2003).
41. Saitoh, E., Miyajima, H., Yamaoka, T. & Tatara, G. Current-induced resonance and mass determination of a single magnetic domain wall. Nature 432, 203–206 (2004).
42. Thiaville, A., Garcia, J. M. & Miltat, J. Domain wall dynamics in nanowires. J. Magn. Magn. Mater. 242–245, 1061–1063 (2002).
43. Nakatani, Y., Thiaville, A. & Miltat, J. Faster magnetic waves in rough wires. Nat. Mater. 2, 521–523 (2003).
44. Beach, G. S. D., Nistor, C., Knutson, C., Tsoi, M. & Erskine, J. L. Dynamics of field-driven domain-wall propagation in ferromagnetic nanowires. Nat. Mater. 4, 741–744 (2005).
45. Thomas, L., Hayashi, M., Moriya, R., Rettner, C. & Parkin, S. S. P. Topological repulsion between domain walls in magnetic nanowires leading to the formation of bound states. Nat. Commun. 3, 810 (2012).
46. Pushp, A. et al. Domain wall trajectory determined by its fractional topological edge defects. Nat. Phys. 9, 505–511 (2013).
47. Li, J. et al. Tailoring the topology of an artificial magnetic skyrmion. Nat. Commun. 5, 4704 (2014).
48. Gilbert, D. A. et al. Realisation of ground-state artificial skyrmion lattices at room temperature. Nat. Commun. 6, 8462 (2015).
49. Parkin, S. S. P., Hayashi, M. & Thomas, L. Magnetic domain-wall racetrack memory. Science 320, 190–194 (2008).
50. Allwood, D. A. et al. Magnetic domain-wall logic. Science 309, 1688–1692 (2005).
51. Hayashi, M., Thomas, L., Moriya, R., Rettner, C. & Parkin, S. S. P. Current-controlled magnetic domain-wall nanowire shift register. Science 320, 209–211 (2008).
52. Sander, D. et al. Structure and perpendicular magnetization of Fe/Ni(111) bilayers on W(110). J. Appl. Phys. 81, 4702–4704 (1997).
53. Ding, H. F., Schmid, A. K., Li, D., Guslienko, K. Y. & Bader, S. D. Magnetic domain-wall duality of Co nanowires. Phys. Rev. B 87, 125401 (2013).
54. Kwon, H. Y. et al. A study of the stripe domain phase at the spin reorientation transition of two-dimensional magnetic system. J. Magn. Magn. Mater. 332, 2742–2748 (2010).
55. Kwon, H. Y. & Won, C. Effects of Dzyaloshinskii–Moriya interaction on magnetic stripe domains. J. Magn. Magn. Mater. 351, 8–15 (2014).

Acknowledgements
The authors would like to thank Prof. André Thiaville and Dr Satoru Emori for fruitful discussions. Work at the Molecular Foundry was supported by the Office of Science, Office of Basic Energy Sciences, of the US Department of Energy under Contract No. DE-AC02-05CH11231. Y.W. was supported by the National Key Basic Research Program of China (Grant No. 2015CB921401), the National Key Research and Development Program of China (Grant No. 2016YFA0308703), and the National Science Foundation of China (Grant Nos. 11434003 and 11474066). Work at Kyung Hee University was supported by the National Research Foundation of Korea Grant funded by the Korean Government (2015R1D1A1A01056971). Work at UCD was supported by the US National Science Foundation (DMR-1610060).

Author contributions
G.C. conceived the experiment and carried out the measurements. A.K.S. supervised the SPLEEM facility. C.O. and A.T.N. developed and implemented algorithms for the quantitative analysis of SPLEEM data. G.C., S.P.K., A.T.N., R.T.Q., C.W., K.L., Y.W. and A.K.S. analysed and interpreted the results. S.P.K., H.Y.K. and C.W. performed Monte-Carlo simulations. G.C. and A.K.S. prepared the manuscript. All authors commented on the manuscript.

Additional information
Supplementary Information accompanies this paper at http://www.nature.com/naturecommunications

Competing interests: The authors declare no competing financial interests.

Reprints and permission information is available online at http://npg.nature.com/reprintsandpermissions/

How to cite this article: Chen, G. et al. Out-of-plane chiral domain wall spin-structures in ultrathin in-plane magnets. Nat. Commun. 8, 15302 doi: 10.1038/ncomms15302 (2017).

Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.