UNIVERSITÀ DI PARMA
ARCHIVIO DELLA RICERCA

University of Parma Research Repository

Voltage-driven annihilation and creation of magnetic vortices in Ni discs

note finali coverpage

(Article begins on next page)

20 July 2024

Voltage-driven annihilation and creation of magnetic vortices in Ni discs

M. Ghidini[1,2,3,*], R. Mansell[4,#], R. Pellicelli[1,5], D. Pesquera[3], B. Nair[3], X. Moya[3], S. Farokhipoor[3], F. Maccherozzi[2], C. H. W. Barnes[4], R. P. Cowburn[4], S. S. Dhesi[2] and N. D. Mathur[3,†]

[1] Department of Mathematics, Physics and Computer Science, University of Parma, 43124 Parma, Italy.

[2] Diamond Light Source, Chilton, Didcot, Oxfordshire, OX11 0DE, UK.

[3] Department of Materials Science, University of Cambridge, Cambridge, CB3 0FS, UK.

[4] Cavendish Laboratory, University of Cambridge, CB3 0HE, UK.

[5] Istituto d'Istruzione Superiore A. Zanelli, 42123 Reggio Emilia, Italy.

\# Now at NanoSpin, Department of Applied Physics, Aalto University, FI-00076 Aalto, Finland

* massimo.ghidini@unipr.it

† ndm12@cam.ac.uk

Using photoemission electron microscopy (PEEM) to image ferromagnetism in~~For~~ polycrystalline ~~disks of ferromagnetic~~ Ni disks, ~~on~~ and ferroelectricity in their single-crystal ~~substrates of ferroelectric~~ BaTiO$_3$ substrates, we find that voltage-driven 90° ferroelectric domain switching ~~we use voltage-driven compressive uniaxial strain from 90° ferroelectric domain switching~~ serves to ~~to~~ reversibly annihilate each magnetic vort~~icex~~ex ~~s by overcoming growth strain. The resulting~~ via uniaxial compressive strain, and that the orientation of the resulting ~~–~~ bi-domain states ~~possess absolute domain orientation~~ reveals ~~s that follow from~~ the chirality of the annihilated vortex. ~~(The reversible annihilation was identified via high resolution vector maps of magnetization that we constructed from photoemission electron microscopy (PEEM) images, with contrast from x-ray magnetic circular dichroism (XMCD). Ferroelectric domains in the BaTiO$_3$ surrounding the discs were also imaged using PEEM, with contrast from X-ray linear dichroism (XLD).~~ Micromagnetic simulations ~~suggest~~ reveal that ~~vortex annihilation involved~~only ~60% of th~~is e uniaxial~~ strain was required for annihilation ~~that is available from the ferroelectric domain switching.)~~ ~~In addition~~

1

~~to electrically switching on and off the perpendicular stray field arising from vortex cores, we suggest that vortex chirality can be read via in-plane stray field after electrically transforming to the bi-domain state.~~ Voltage control of magnetic vortices is novel, and should be energetically favourable with respect to the use of a magnetic field or an electrical current. In future, stray field from ~~, and~~ bi-domains could be exploited to read vortex chirality. Given that core polarity can already be read via stray field, our work represents a step towards four-state low-power memory ~~contrasts the use of magnetic fields and electrical currents, thus representing a low-power alternative for data storage~~ applications.

~~. In addition to electrically switching on and off the perpendicular stray field arising from vortex cores, we suggest that vortex chirality can be read via in-plane stray field after electrically transforming to the bi-domain state.~~

Separately, magnetic vortices have been demonstrated in discs of permalloy [32,33], iron [34] and nickel [35]. Vortex geometry is~~, and~~ constrained by details of the host material, such that discs with vortices cannot be miniaturized down to the sub-10 nm dimensions associated with state-of-the-art magnetic tunnel junctions [36]. However, vortices have nevertheless attracted much interest ~~for~~ in the context of magnetic ~~recording~~ data storage because they ~~are small and~~ possess four well-defined stable states [37,38]. Specifically, a ~10 nm-wide vortex core [34] can be magnetized up or down to yield two states of polarity, while the curl of the surrounding in-plane magnetization can take either sign to yield two states of chirality. ~~Four~~The ability to independently switch ~~state memory is therefore possible [35] by using magnetic fields and electrical currents to independently switch~~ core polarity [~~37~~39,~~38~~40] and vortex chirality [~~39~~41,~~40~~42] raises hopes of four-state memory [43]. ~~However,~~ and to reduce power consumption it would be attractive to drive such changes with a voltage (non-deterministic voltage-driven switching of vortex chirality was demonstrated in ref. [~~41~~44]) ~~to reduce power consumption. Moreover, it would be attractive to reversibly modify vortices in order to create lateral stray field for reading chirality in devices.~~

Here we exploit strain-mediated magnetoelectric coupling from a single-crystal substrate of BaTiO$_3$ (BTO) in order to electrically annihilate/create magnetic vortices in polycrystalline Ni discs of thickness 25 nm and diameter 1 μm. By imaging both the ferromagnetic domains and

the ferroelectric domains, we found that pre-existing vortices were annihilated when a voltage drove $a \rightarrow c$ ferroelectric domain switching in the underlying substrate, and that subsequent $c \rightarrow a$ switching reversed this annihilation. Micromagnetic simulations reproduce the observed magnetoelectric effects with reasonable fidelity, and suggest that our vortices were annihilated by a change of strain that is just 60% of the uniaxial 10^{-2} strain associated with $a \rightarrow c$ switching. ~~Vortex~~ Importantly, vortex chirality was found to uniquely ~~information is stored in~~determine the orientation of the bi-domain ~~states~~ that ~~are formed by~~resulted from vortex annihilation~~,~~. This immediately suggests that one could identify the chirality of vortices in memory devices by converting them to bi-domains, and reading the lateral stray field~~and therefore vortex chirality could be read via the lateral stray field from these bi-domain states~~.

Experimental methods

A 200 nm-thick Pt electrode was sputter-deposited on the back of a 0.5-~~μ m~~mm-thick BTO substrate that adopted the pseudo-cubic (001) orientation. After ultrasonic cleaning with first acetone, then isopropyl alcohol and last deionised water, we used thermal evaporation to deposit first Ta and then Pt to form a 2 nm-thick top electrode of Ta(0.5 nm)/Pt(1.5 nm). We subsequently used electron-beam-assisted evaporation with a base pressure of 3×10^{-10} mbar to grow 25 nm of Ni, capped with 3 nm of Cu, through a lift-off mask defined by electron-beam lithography in a double layer of PMMA resist. This resulted in 10×10 arrays of 1 μm-diameter Ni discs, with nearest-neighbour centre-to-centre separations of 2 μm [Fig. 1(a)]. Ni discs of this size are known to display vortices [35], whereas thinner Ni discs form single-domain states [35,~~42~~45].

Raw PEEM images (1024×1024 pixels) were obtained in zero applied magnetic field on beamline I06 at Diamond Light Source, where we used an Elmitec SPELEEM-III microscope to map secondary-electron emission arising from circularly polarized x-rays that were incident on the sample surface at a grazing angle of 16°. The probe depth of ~7 nm was sufficient to sample the Ni discs through their 3 nm-thick Cu caps, and to sample the surrounding BTO surface through the 2 nm-thick top electrode of Pt/Ta. The lateral resolution was typically ~50 nm. A 300 V power supply was connected to the top and bottom electrodes via feedthroughs in the sample holder.

3

Raw XMCD-PEEM images were acquired during 1 s exposure times with right (R) and left (L) circularly polarized light, both on the Ni L_3 resonance at 851 eV, and off this resonance at 842 eV. The pixels in a raw XMCD-PEEM image describe the XMCD asymmetry $(I^R - I^L)/(I^R + I^L)$, which represents the projection of the local surface magnetization on the incident-beam direction. Here, $I^{R/L} = (I^{R/L}_{on} - I^{R/L}_{off})/I^{R/L}_{off}$ denotes the relative intensity for secondary electron emission due to x-ray absorption on ($I^{R/L}_{on}$) and off ($I^{R/L}_{off}$) the Ni L_3 resonance (the comparison between intensities obtained on and off resonance avoids the influence of any inhomogeneous illumination). The pixels in a raw XAS-PEEM image describe the x-ray absorption (XAS) intensity $I^R_{on} + I^L_{on}$, which represents topographical/chemical contrast.

Raw XLD-PEEM images were acquired during 1 s exposure times with vertically (V) and horizontally (H) polarized light, both on the Ti L_3 resonance at 457 eV, and off this resonance at 446 eV. The pixels in a raw XLD-PEEM image describe the XLD asymmetry $(I^V - I^H)/(I^V + I^H)$, which represents the projection of the local surface polarization on the incident-beam direction. Here, $I^{V/H} = (I^{V/H}_{on} - I^{V/H}_{off})/I^{V/H}_{off}$ denotes the relative intensity for secondary electron emission due to x-ray absorption on ($I^{V/H}_{on}$) and off ($I^{V/H}_{off}$) the Ti L_3 resonance.

All raw PEEM images were averaged for display or the subsequent construction of magnetic vector maps. We averaged 100 raw XMCD-PEEM images to obtain XMCD-PEEM images of ferromagnetic domains. We averaged 100 raw XLD-PEEM images to obtain XLD-PEEM images of ferroelectric domains. We averaged 100 raw XAS-PEEM images to obtain XAS-PEEM images of topographical/chemical contrast. Magnetic vector maps were obtained by combining two such XMCD-PEEM images for orthogonal sample orientations, after correcting for drift and distortion via an affine transformation that was based on the averaged XAS-PEEM image for each sample orientation.

Micromagnetic simulations performed using MuMax3 [~~43~~46] involved discretizing a Ni disc of the dimensions employed experimentally into 5×5×2.5 nm³ cells, ~~and~~ assuming an exchange stiffness of 0.82×10⁻¹¹ J m⁻¹ [~~44~~47] and a saturation magnetization of 434 kA m⁻¹ [~~our NiBTO paper~~21]. The uniaxial y-axis strain ε_y from the substrate was assumed to introduce magnetic

stress anisotropy energy density $-K\cos^2\theta$, where θ is the angle between the in-plane magnetization and the uniaxial strain, $K = \frac{3}{2}E\varepsilon_y\lambda$, Young's modulus $E = 133$ GPa, and Ni magnetostriction $\lambda = -32.9 \times 10^{-6}$ [21]. Stable equilibrium configurations were i~~n~~dentified by dynamically relaxing the magnetization, and these configurations were confirmed via minimizations that exploited the conjugate gradient method [4~~3~~46]. In both of these methods, MuMax3 internally suppresses the precessional term in the Landau-Lifschitz-Gilbert equation, and the user-defined damping constant is ignored~~, such that any user-defined α would be irrelevant~~. Images and polar plots describe the average magnetization of the upper two simulation cells, whose 5 nm thickness is similar to the ~7 nm PEEM probe depth. Image quality was improved by plotting four pixels for each of the 32428 pairs of double-height cells.

Experimental results

The vortex state in the virgin disc was anisotropic, given that polar-plot lobes were oriented somewhat along x. For negative-magnetostriction Ni, this suggests the possibility of tensile strain along y. Polycrystalline films can indeed experience tensile growth strain from BTO substrates along the long c axis of a domains [17,4~~2~~45], possibly due to some degree of epitaxy. However, this indirect evidence for an a domain polarized along y is not compelling, as disc magnetization is not uniform, and the observed anisotropy could also arise from substrate-independent growth strain and any disc eccentricity. Instead, we will identify the ferroelectric domain structure via XLD-PEEM, but first we will discuss the effect of the voltage cycle on disc 1.

The anisotropic vortex in the virgin disc was annihilated when 150 V stabilized a bi-domain ~~state~~ whose absolute domain orientations follow from the chirality of the annihilated vortex. At -300 V, the two magnetic domains adopted better antiparallel alignment, and a concomitantly straighter domain wall. Given that these two large bipolar voltages resulted in similar bi-domain ~~state~~s, we may infer that they caused the disc to experience similar strains from oppositely polarized ferroelectric c domains. It is therefore natural to anticipate that vortex annihilation is driven by $a \to c$ ferroelectric domain switching, as we will show below via Fig. 3. A vortex was recovered on returning to 0 V, suggesting that $c \to a$ switching took

5

place underneath. This recovered vortex possessed the same chirality as the starting vortex, given our observation that chirality information was stored in the absolute domain orientation of the bi-domain state. The polar plots show that the recovered vortex possesses greater anisotropy than the starting vortex, evidencing irreversible strain.

Fig. 3(a) is a composite image that describes the virgin state of the sample in our 15 μm-diameter field of view. The vector map of disc 1 is accompanied by a vector map of disc 2, revealing another anisotropic vortex with opposite chirality. The XMCD-PEEM image representing the other discs reveals anisotropic vortices with different chiralities. The XLD-PEEM image representing the BTO between discs does not contain any domain walls, implying that the field of view shows a single ferroelectric domain. Below we will identify this ferroelectric domain to be *a* type.

Fig. 3(b) corresponds to Fig. 3(a) after applying the 150 V. The vector map of disc 1 is accompanied by a vector map of disc 2, revealing another bi-domain state with the same easy axis. However, the two domain magnetizations were each reversed due to the opposite chirality of the virgin state. The XMCD-PEEM image representing the other discs reveals bi-domain states with the same easy axis as discs 1 and 2, while the absolute directions of magnetization likewise depend on virgin chirality. The XLD-PEEM image representing the BTO between discs reveals the presence of two outer ferroelectric domains that were associated with all of the observed discs, and a middle domain that was continuously annihilated over the course of several minutes (not shown). We attribute this lack of stability to an elastic energy cost associated with the unexpected [4548] meeting of long *c* axes and short *a* axes at the two observed walls. We may consequently deduce that the as-marked *c-a-c* configuration [Fig. 3(b)] arose from $a \rightarrow c$ switching under the discs, which thus experienced compressive strain along *y* to yield the observed easy axis along *y*. The complementary *a-c-a* configuration can be ruled out because it would imply that the discs experienced $c \rightarrow a$ switching with *a* domains polarized along *y*, i.e. tensile strain along *y* and thus an easy axis along *x*.

After completing the cycle shown in Fig. 2, vector maps of disc 2 (not shown) confirm that the virgin vortex chirality had also been restored in this disc, consistent with the reversed bi-domain state that we observed at finite voltage [Fig. 3(b)]. The corresponding XLD-PEEM

images at -300 V and 0 V were not measured. However, XMCD-PEEM images (not shown) confirmed that the bi-domain state was stable at 0 V.

Modelling

For an unstrained Ni disc of the dimensions employed here, the lowest energy state would be an isotropic vortex [Fig. 4(a-c)], as expected [35], and the core would be 30 nm wide [Fig. 4(b)]. Introducing the inferred tensile growth strain along y resulted in an anisotropic vortex [Fig. 5(a,e,i)], where we have set $\varepsilon_y = 2\times10^{-3}$ to best match the anisotropic vortex state of discs 1 and 2 in the virgin sample [Fig. 3(a)]. The resulting value of $K = \frac{3}{2}E\varepsilon_y\lambda = -10$ kJ m^{-3} has the expected order of magnitude for Ni on BTO [21].

Replacing the y-axis tensile strain arising from growth with a y-axis compressive strain due to the $a \rightarrow c$ switching observed at 150 V [Fig. 3(b)] resulted in a bi-domain state [Fig. 5(b,f,j)], where we have set $\varepsilon_y = -4\times10^{-3}$ ($K = 20$ kJ m^{-3}) to best match the bi-domain state in disc 1 at 150 V [Fig. 2(j,n)]. The simulated bi-domain state at 150 V is 3% more energetically expensive than a vortex state that we modelled at the same strain (not shown). However, an unexplored energy barrier will determine the related issues of stability and interconversion, and experimentally the ~~vortex~~ vortices and bi-domain states were found to persist over many hours at a given voltage while collecting XMCD-PEEM images. The domain wall in the simulated bi-domain state at 150 V is seen to bend and widen at the top, explaining the slightly imperfect lobe alignment in the corresponding polar plot. This finding is reminiscent of our observation that disc 1 displays a wavy domain wall at 150 V, and misaligned polar-plot lobes.

Increasing the y-axis compressive strain to model the subsequent application of a larger voltage with opposite sign resulted in an asymmetric bi-domain state [Fig. 5(c,g,k)], where setting $\varepsilon_y = -5\times10^{-3}$ ($K = 25$ kJ m^{-3}) achieved good agreement with the asymmetric bi-domain state in disc 1 at -300 V [Fig. 2(k,o)]. The agreement is better at -300 V than 150 V, implying the possibility that switching reduced some uncontrolled long-range strain from unobserved ferroelectric domains. On reaching 300 V, the growth of one domain at the expense of the other can be understood as a step towards the single-domain state expected at sufficiently high strain. Switching the y-axis strain to tensile in order to model the final $c \rightarrow a$ switching step resulted in an anisotropic vortex [Fig. 5(d,h,l)], where we have exceeded the growth strain of $\varepsilon_y = 2\times10^{-}$

7

[3] by setting $\varepsilon_y = 5 \times 10^{-3}$ ($K = -25$ kJ m^{-3}) to best match the more anisotropic vortex that arose in disc 1 after returning to 0 V [Fig. 2(l)].

Discussion

Let us now consider the magnitudes of the strains that we have used to model vortex annihilation in disc 1. By overcoming the tensile growth strain of 2×10^{-3} with a compressive strain of -4×10^{-3}, we may infer that $a \rightarrow c$ switching resulted in a compressive strain of 6×10^{-3}. This represents 60% of the uniaxial 10^{-2} strain that one would expect from a 90° rotation of the BTO unit cell, implying the likelihood of imperfect strain transmission. The increase of strain that we identified with the magnetic changes observed from 150 V to -300 V is likely to be associated with the concomitant ferroelectric domain reversal, as the increase of strain associated with the continuous piezoelectric effect [21] is two orders of magnitude too small to explain our calculated strain increase.

In summary, we have used XMCD-PEEM imaging and XLD-PEEM imaging to demonstrate that voltage-driven 90° ferroelectric domain switching in a BTO substrate can reversibly annihilate magnetic vortices in 1 μm-diameter Ni discs, and that the chirality of the annihilated vortex determines the orientation of the resulting bi-domain state. We subsequently used micromagnetic modelling to suggest that vortex annihilation was achieved with 60% of the strain that one might expect for the ferroelectric domain switching, which demonstrates scope for optimization. The reversible magnetoelectric annihilation that we have demonstrated ~~would~~ should in future permit vortex chirality to be read via lateral stray field, just as the polarity of a vortex can be read via perpendicular stray field.

Ultimately, it would be interesting to read all four stable vortex states [~~35~~43], via stray field, using the smallest discs of a given material to show vortices [35]. To exploit ~~this idea~~four-state vortex memory in low-power electric-write magnetic-read memory devices would require ~~the following~~two key improvements. First, it would be important to overcome the key challenge of electrically switching chirality and polarity, possibly via inhomgenous/dynamic electrically driven strain. Second, it would be important to define individually addressable ferroelectric elements that overcome clamping from a fixed substrate, possibly via pillars with a high aspect ratio. ~~Third, it would be important to use~~ These improvements could also be relevant for

8

magnetoelectric control of magnetic skyrmions. ~~much smaller Ni discs that nevertheless show~~

Figure captions

Fig. 1. Sample schematic and area of interest. (a) Cross-sectional schematic showing three of many Cu-capped Ni discs on an electroded BTO substrate in the pseudo-cubic (001) orientation. (b) XAS-PEEM image, obtained in the as-shown 15 μm-diameter field of view. Disc diameter 1 μm, Ni thickness 25 nm. Labels identify discs 1 and 2.

Fig. 2. Magnetic images of disc 1 under voltage control. (a-h) XMCD-PEEM images obtained while applying the specified voltages across the BTO substrate, with the in-plane projection of the grazing-incidence X-ray beam parallel to (a-d) the red arrow and (e-h) the green arrow. Pairwise image combination yields near-surface magnetization direction α, which we present on (i-l) magnetic vector maps and (m-p) polar histograms. Histograms show the fraction of pixels n with in-plane magnetization direction α after binning at 1°. Data obtained in a 10 μm-diameter field of view. Disc diameter 1 μm. Vector maps in (j,k) also appear in Fig. 3(a,b).

Fig. 3. Voltage-driven switching of ferroelectric domains and disc magnetization. Composite images at (a) 0 V and (b) 150 V, which each show magnetic vector maps of the near-surface magnetization direction α for discs 1 and 2, an XMCD-PEEM image of other Ni discs, and an XLD-PEEM image of the surrounding ferroelectric domains. BTO unit cell schematics overlie a and c domains. Blue bars in (b) help identify the surviving a domain. The XMCD-PEEM and XLD-PEEM images were obtained in the as-shown 15 μm-diameter field of view that we used for Fig. 1(b), with the in-plane projection of the grazing-incidence X-ray beam parallel to the purple arrow. The vector maps were constructed from XMCD-PEEM images that were obtained in a 10 μm-diameter field of view, with the in-plane projections of the grazing-incidence X-ray beam parallel to the red and green arrows. Disc diameter 1 μm. The two vector maps for disc 1 also appear in Fig. 2(j,k).

Fig. 4. Micromagnetic modelling of a Ni disc with no growth strain. We present the near-surface magnetization via (a) a map of in-plane magnetization direction α, (b) a map of out-of-plane magnetization M_z, and (c) a polar histogram of α. Histogram shows the fraction of pixels n with in-plane magnetization direction α after binning at 1°. The magnitude of the local magnetization is denoted M. Disc diameter 1 μm.

10

Fig. 5. Micromagnetic modelling of Ni discs under voltage control. For the uniaxial strains ε_y that we identify for our experimentally applied voltages, we present the near-surface magnetization via (a-d) maps of in-plane magnetization direction α, (e-h) maps of out-of-plane magnetization M_z, and (i-l) polar histograms of α. Histograms show the fraction of pixels n with in-plane magnetization direction α after binning at 1°. The magnitude of the local magnetization is denoted M. <mark>Disc diameter 1 μm.</mark>

References

[1] M. Fiebig, *J. Phys. D*, **38** (2005) R123.

[2] W. Eerenstein, N. D. Mathur and J. F. Scott, *Nature* **442** (2006) 759.

[3] R. Ramesh and N. A. Spaldin, *Nature Materials* **6** (2007) 21.

[4] S.-W. Cheong and M. Mostvoy, *Nature Materials* **6** (2007) 13.

[5] C.-W. Nan, M. I. Bichurin, S. Dong, D. Viehland and G. Srinivasan, *J. Appl. Phys.* **103** (2008) 031101.

[6] D. Lebeugle, D. Colson, A. Forget, M. Viret, A. M. Bataille and A. Gukasov, *Phys. Rev. Lett.* **100** (2008) 227602.

[7] Y. J. Choi, C. L. Zhang, N. Lee and S.-W. Cheong, *Phys. Rev. Lett.* **105** (2010) 097201.

[8] Y. Tokunaga, Y. Taguchi, T. H. Arima and Y. Tokura, *Nature Physics* **8** (2012) 838.

[9] S. H. Chun, Y. S. Chai, B.-G. Jeon, H. J. Kim, Y. S. Oh, I. Kim, H. Kim, B. J. Jeon, S. Y. Haam, J.-Y. Park, S. H. Lee, J.-H. Chung, J.-H. Park and K. H. Kim, *Phys. Rev. Lett.* **108** (2012) 177201.

[10] Y.-S. Chai, S. Kwon, S.-H. Chun, I. Kim, B.-G. Jeon, K.-H. Kim and S. Lee, *Nature Communications* **5** (2014) 4208.

[11] W. Eerenstein, M. Wiora, J. L. Prieto, J. F. Scott and N. D. Mathur, *Nature Materials* **6** (2007) 348.

[12] C. Thiele, K. Dörr, O. Bilani, J. Rödel and L. Schultz, *Phys. Rev. B* **75** (2007) 054408.

[13] S. Sahoo, S. Polisetty, C. G. Duan, S. S. Jaswal, E. Y. Tsymbal and C. Binek, *Phys. Rev. B* **76** (2007) 092108.

[14] S. Geprägs, A. Brandlmaier, M. Opel, R. Gross and S. T. B. Goennenwein, *Appl. Phys. Lett.* **96** (2010) 142509.

[15] T. Wu, A. Bur, P. Zhao, K. P. Mohanchandra, K. Wong, K. L. Wang, C. S. Lynch and G. P. Carman, *Appl. Phys. Lett.* **98** (2011) 012504.

[16] T. Wu, A. Bur, K. Wong, P. Zhao, C. S. Lynch, P. Khalili Amiri, K. L. Wang and G. P. Carman, *Appl. Phys. Lett.* **98** (2011) 262504.

[17] T. H. E. Lahtinen, K. J. A. Franke and S. van Dijken, *Sci. Rep.* **2** (2012) 258.

[18] S. Zhang, Y. G. Zhao, P. S. Li, J. J. Yang, S. Rizwan, J. X. Zhang, J. Seidel, T. L.Qu, Y. J. Yang, Z. L. Luo, Q. He, T. Zou, Q. P. Chen, J.W. Wang, L. F. Yang, Y. Sun, Y. Z. Wu, X. Xiao, X. F. Jin, J. Huang, C. Gao, X. F. Han and R. Ramesh, *Phys. Rev. Lett.* **108** (2012) 137203.

[19] M. Buzzi, R.V. Chopdekar, J. L. Hockel, A. Bur, T. Wu, N. Pilet, P. Warnicke, G. P. Carman, L. J. Heyderman and F. Nolting, *Phys. Rev. Lett.* **111** (2013) 027204.

[20] R. O. Cherifi, V. Ivanovskaya, L. C. Phillips, A. Zobelli, I. C. Infante, E. Jacquet, V. Garcia, S. Fusil, P. R. Briddon, N. Guiblin, A. Mougin, A. A. Ünal, F. Kronast, S. Valencia, B. Dkhil, A. Barthélémy and M. Bibes, *Nature Materials* **13** (2014) 345.

[21] M. Ghidini, F. Maccherozzi, X. Moya, L .C. Phillips, W. Yan, J. Soussi, N. Métallier, M. E. Vickers, N. -J. Steinke, R. Mansell, C. H. W. Barnes, S. S. Dhesi and N. D. Mathur, *Adv. Mater.* **27** (2015) 1460.

[22] R. V. Chopdekar, M. Buzzi, C. Jenkins, E. Arenholz, F. Nolting and Y. Takamura, *Sci. Rep.* **6** (2016) 27501.

[23] Ya Gao, J.-M. Hu, C. T. Nelson, T. N. Yang, Y. Shen, L. Q. Chen, R. Ramesh and C. W. Nan, *Sci. Rep.* **6** (2016) 23696.

[24] P. Li, Y. Zhao, S. Zhang, A. Chen, D. Li, J. Ma, Y. Liu, D. T. Pierce, J. Unguris, H.-G. Piao, H. Zhang, M. Zhu, X. Zhang, X. Han, M. Pan and C.-W. Nan, *ACS Appl. Mater. Interfaces* **9** (2017) 2642.

[25] R. Lo Conte, Z. Xiao, C. Chen, C. V. Stan, J. Gorchon, A. El-Ghazaly, M. E. Nowakowski, H. Sohn, A. Pattabi, A. Scholl, N. Tamura, A. Sepulveda, G. P. Carman, R. N. Candler and J. Bokor, *Nano Lett.* **18** (2018) 1952.

[26] H. J. A. Molegraaf, J. Hoffman, C. A. F. Vaz, S. Gariglio, D. van der Marel, C. H. Ahn and J.M. Triscone, *Adv. Mater.* **21** (2009) 1.

[27] V. Skumryev, V. Laukhin, I. Fina, X. Martí, F. Sánchez, M. Gospodinov and J. Fontcuberta, *Phys. Rev. Lett.* **106** (2011) 057206.

[28] J. T. Heron, J. L. Bosse,Q. He,Y. Gao, M. Trassin, L. Ye, J. D. Clarkson, C. Wang, Jian Liu, S. Salahuddin, D. C. Ralph, D. G. Schlom, J. Íñiguez, B. D. Huey and R. Ramesh, *Nature* **516** (2014) 370.

[29] W. Saenrang, B. A. Davidson, F. Maccherozzi, J. P. Podkaminer, J. Irwin, R. D. Johnson, J. W. Freeland, J. Íñiguez, J. L. Schad, K. Reierson, J. C. Frederick, C. A. F.

Vaz, L. Howald, T. H. Kim, S. Ryu, M. v. Veenendaal, P. G. Radaelli, S. S. Dhesi, M. S. Rzchowski and C. B. Eom, *Nature Communications* **8** (2017) 1583.

[30] V. Skumryev, V. Laukhin, I. Fina, X. Martí, F. Sánchez, M. Gospodinov and J. Fontcuberta, *Phys. Rev. Lett.* **106** (2011) 057206.

[31] N. Lei, T. Devolder, G. Agnus, P. Aubert, L. Daniel, J.-V. Kim, W. Zhao, T. Trypiniotis, R. P. Cowburn, C. Chappert, D. Ravelosona and Philippe Lecoeur, *Nature Communications* **4** (2013) 1378.

[32] R. P. Cowburn, D. K. Koltsov, A. O. Adeyeye, M. E. Welland and D. M. Tricker, *Phys. Rev. Lett.* **83** (1999) 1042.

[33] T. Shinjo, T. Okuno, R. Hassdorf, K. Shigeto and T. Ono, *Science* **289** (2000) 930.

[34] A. Wachowiak, J. Wiebe, M. Bode, O. Pietzsch, M. Morgenstern and R. Wiesendanger, *Science* **298** (2002) 577.

[35] T. Wren, B. Gribkov, V. Petrashov and O. Kazakova1, *J. Appl. Phys.* **118** (2015) 023906.

[36] K. Watanabe, B. Jinnai, S. Fukami, H. Sato and H. Ohno, *Nature Communications* **9** (2018) 663.

[37] S. Bohlens, B. Krüger, A. Drews, M. Bolte, G. Meier and D. Pfannkuche, *Appl. Phys. Lett.* **93** (2008) 142508.

[38] K. Nakano, D. Chiba, N. Ohshima, S. Kasai, T. Sato, Y. Nakatani, K. Sekiguchi, K. Kobayashi and T. Ono, *Appl. Phys. Lett.* **99** (2011) 262505.

V. Uhlíř, M. Urbánek, L. Hladík, J. Spousta, M-Y. Im, P. Fischer, N. Eibagi, J. J. Kan, E. E. Fullerton and T. Šikola, *Nature Nanotechnology* **8** (2013) 341.

[3840] K. Yamada, S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, A. Thiaville and T. Ono, *Nature Materials* **6** (2007) 270.

[3941] S. Y. H. Lua , S. S. Kushvaha, Y. H. Wu, K. L. Teo and T. C. Chong, *Appl. Phys. Lett.* **93** (2008) 122504.

[4042] M. Schneider, H. Hoffmann and J. Zweck, *Appl. Phys. Lett.* **79** (2001) 3113.

[43] V. Uhlíř, M. Urbánek, L. Hladík, J. Spousta, M-Y. Im, P. Fischer, N. Eibagi, J. J. Kan, E. E. Fullerton and T. Šikola, *Nature Nanotechnology* **8** (2013) 341.

[4144] Q. Li, A. Tan, A. Scholl, A. T. Young, M. Yang, C. Hwang, A. T. N'Diaye, E. Arenholz, J. Li and Z. Q. Qiu, *Appl. Phys. Lett.* **110** (2017) 262405.

[4245] M. Ghidini, B. Zhu, R. Mansell, R. Pellicelli, A. Lesaine, X. Moya, S. Crossley, B. Nair, F. Maccherozzi, C. H. W. Barnes, R. P. Cowburn, S. S. Dhesi and N. D. Mathur, *J. Phys. D: Appl. Phys.* **51** (2018) 224007.

[4346] A. Vansteenkiste, J. Leliaert, M. Dvornik, M. Helsen, F. Garcia-Sanchez and B. Van Waeyenberge, *AIP Advances* **4** (2014) 107133.

[4447] A. Michels, J. Weissmüller, A. Wiedenmann and J. G. Barker *J. Appl. Phys.* **87** (2000) 5953.

[4548] H. F. Kay and P. Vousden, *Philos. Mag.* **7** (1949) 1019.

14