First publ. in: Applied Physics Letters 88 (2006), 232507

# Current-induced vortex nucleation and annihilation in vortex domain walls

M. Kläui,[a] M. Laufenberg, L. Heyne, D. Backes,[b] and U. Rüdiger
*Fachbereich Physik, Universität Konstanz, 78457 Konstanz, Germany*

C. A. F. Vaz and J. A. C. Bland
*Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, United Kingdom*

L. J. Heyderman
*Paul Scherrer Institut, 5232 Villigen PSI, Switzerland*

S. Cherifi,[c] A. Locatelli, T. O. Mentes, and L. Aballe
*Sincrotrone Trieste, 34012 Basovizza, Trieste, Italy*

(Received 7 March 2006; accepted 8 May 2006; published online 8 June 2006)

We report observations of the effect of electrical currents on the propagation and spin structure of vortex walls in NiFe wires. We find that magnetic vortices are nucleated and annihilated due to the spin torque effect. The velocity is found to be directly correlated with these transformations and decreases with increasing number of vortices. The transformations are observed in wide elements, while in narrower structures the propagation of single vortex walls prevails.

Current-induced domain wall motion (CIDM) has recently prompted much attention, since it can be an alternative to the conventional field-induced switching. In particular, a number of memory and sensor devices based on this effect have been suggested, a prominent example being the racetrack design envisaged by Parkin.[1] To use current-induced domain wall motion in such a device, reliable and reproducible wall propagation has to be achieved.

While CIDM has long been known theoretically[2,3] as well as experimentally,[4] only recently controlled current-induced motion of single domain walls in magnetic nanostructures has been observed.[5–12] The underlying theory of interaction between current and magnetization is still controversial. Different approaches have been suggested with adiabatic[13–15] and non-adiabatic contributions.[16,17] While these theories qualitatively reproduce CIDM, quantitative calculations of the wall velocities do not agree with the experimental observations and this has initiated a discussion about the importance of the nonadiabatic contribution.[7,8,16,17] It was recently shown[7] that vortex head-to-head domain walls are not only displaced but also the wall spin structures can be transformed to a transverse wall with consequences for the wall velocity and the reliability of the switching.[7] Theoretically it was predicted that the vortex core is not only expelled but also renucleated periodically,[17] and the latter should also have an effect on the wall velocity. The observation of such a nucleation of a vortex core is of interest for a further theoretical understanding, since it depends crucially on the nonadiabatic term;[17] it has been also predicted that for sufficiently high current densities the single domain state is not the stable ground state and nucleation occurs.[18]

In this letter we investigate current-induced domain wall propagation and wall transformations in 28 nm thick zigzag line elements to determine the wall-type transformations which occur by the nucleation and annihilation of vortex cores and their influence on the wall velocities.

28 nm thick Permalloy ($Ni_{80}Fe_{20}$) zigzag structures capped with 2 nm Au with widths $W$ between 100 nm and 2 $\mu$m and lengths of up to 100 $\mu$m have been fabricated as detailed in Ref. 19. In Fig. 1(a), a scanning electron microscopy (SEM) image of such a zigzag structure is shown ($W=1\ \mu$m). To image the magnetization configuration, x-ray magnetic circular dichroism photoemission electron microscopy (XMCDPEEM) is used.[20,21] In Fig. 1(b) we present an XMCDPEEM image of the starting magnetization configuration at zero field with vortex walls located at the kinks. From the head-to-head domain wall phase diagram[21] vortex walls are expected and indeed observed.

We inject current pulses with a length of 11 $\mu$s and varying amplitude. The magnetization configuration was imaged before and after every injection, with the result that any domain wall displacement or change in the spin structure could be determined. Since it was shown that the domain wall velocity can decay after a few injections,[7] we have deliberately mostly injected just one to two pulses before remagnetizing the sample.

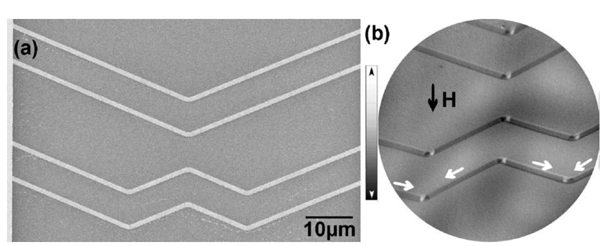


FIG. 1. (a) SEM image of the zigzag lines with kinks used in this study (width $W=1\ \mu$m, thickness $t=28$ nm). (b) XMCDPEEM image taken after initialization with a field in the direction of the black arrow with the white arrows indicating the magnetization directions in one of the lines. Vortex head-to-head domain walls are visible at the kinks, six have a counterclockwise sense of rotation and two have a clockwise sense of rotation. The gray scale bar indicates the magnetization directions.

[a] Author to whom correspondence should be addressd; electronic mail: mathias@klaeui.de
[b] Also at Paul Scherrer Institut, CH-5232 Villigen PSI.
[c] Permanent address: CNRS Laboratoire Louis Néel, BP 166, 38042 Grenoble, France.

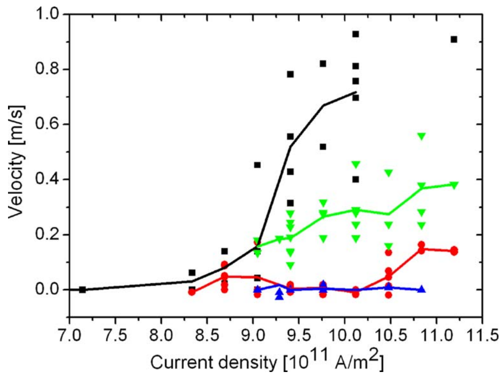


FIG. 2. (Color online) Black squares: velocities of vortex wall that did not transform (apart from the value for $11.2\times10^{11}$ A/m$^2$, which is a lower boundary). Green down triangles: walls which are extended vortex walls before and after the injection, or transform from or to a single vortex wall. Red disks: walls which are single vortex walls and then transform to a double vortex. Blue up triangles: walls which are multivortex walls (double, triple, etc.) before and after the injection. Continuous lines are the averaged wall velocities as a function of current density.

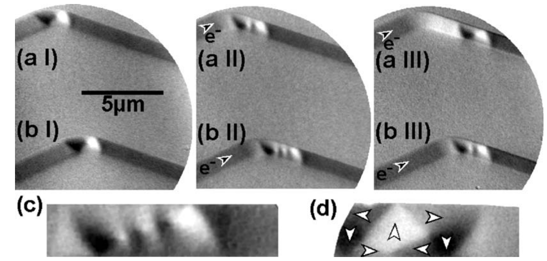


FIG. 4. XMCDPEEM images of two domain walls in adjacent lines after consecutive pulse injections with $j=8.7\times10^{11}$ A/m$^2$. Top wall: (a I) vortex wall after remagnetization which transforms to a double vortex (a II) and back (a III) during consecutive injections. Bottom wall: (b I) a vortex wall that transforms to a triple vortex (b II) and back to a double vortex spin structure (b III). (c) High resolution image of the spin structure of a triple vortex wall. (d) High resolution spin structure of the double vortex wall with two vortices that have opposite sense of rotation.

We first consider the propagation of walls exhibiting the same vortex wall spin structure before and after the displacement (top black solid line and black squares in Fig. 2). The movement starts at around $8.3\times10^{11}$ A/m$^2$ and the average wall velocity increases with increasing current density, in line with previously reported experiments.[8]

In addition to the movement of these unperturbed walls, we also observe transformations of the domain wall spin structure. In Fig. 3(a) we present images of a head-to-head wall after remagnetization (top) and after an injection (bottom). Here a vortex wall is transformed to a more complicated spin structure, which contains two vortices. A high resolution image of this double vortex wall is shown in Fig. 3(b) and a simulation of such a double vortex wall in Fig. 3(c). At the center between the vortices, a cross-tie structure is formed.[22] The transformation from a vortex to a double vortex occurs by the nucleation of a second vortex with the same sense of rotation as the original one. This transformation from a vortex to a double vortex is most common but other transformations do also occur. In Fig. 3(d) an extended vortex wall structure is shown with a cross-tie structure at the center.[22] This structure is observed less often than the double vortex.

In addition to the nucleation of vortices, the annihilation of vortices may be expected as well, since a transformation from vortex to transverse walls was already observed in Ref. 7. However, from the wall-type phase diagram[21] we immediately see that in contrast to the 10 nm thick and 500 nm

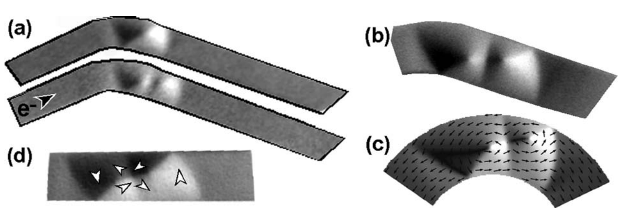


FIG. 3. (a) XMCDPEEM image of a vortex wall after remagnetization (top) and after injection of a pulse with $j=8.3\times10^{11}$ A/m$^2$ (bottom). An extra vortex has been nucleated downstream. (b) A high resolution image of the double vortex wall and a simulation with arrows (c) visualizing the spin structure. (d) Image of an extended vortex wall with a cross-tie structure at the center and arrows indicating the magnetization direction.

narrow wires in Ref. 7, the 28 nm thick and 1 $\mu$m wide structures studied here are far away from the phase boundary. Thus vortex walls are energetically much more favorable than transverse walls, which are therefore not attained. But since both the single vortex walls and multivortex walls are stable, we can expect that double vortices are transformed back to single vortex walls by annihilating vortex cores during subsequent injections. An example of this is shown in Fig. 4. A vortex wall (a I) is first transformed to a double vortex wall (a II) and then in the next injection back to a single vortex wall (a III). In the lower line (b) we see that the nucleation of domain walls can occur twice during one injection leading to the transformation from a single vortex (b I) to a triple vortex wall (b II). Annihilating one vortex then switches the wall back to a double vortex as seen in (b III). A high resolution image of the spin structure of this triple vortex wall with two cross-tie structures in between the vortices is shown in Fig. 4(c).

This observation of the nucleation as well as the annihilation of vortices is in line with theoretical considerations and micromagnetic calculations. Recent calculations have shown that due to the spin torque effect a force acts on the vortex core, pushing it towards the element edge to annihilate it.[23] For very high current densities, calculations have shown that the single domain state is not the energetically favorable state and nucleation occurs.[18] Thiaville *et al.* have even predicted a periodic nucleation and annihilation of vortices due to spin torque.[17] Most interestingly, we always observe that a vortex is nucleated that has the same sense of rotation as the one already present, regardless of whether the second vortex nucleates upstream or downstream from the vortex already present. We have only twice observed a double vortex structure with two vortices with opposite sense of orientation as shown in Fig. 4(d) and neither of these spin structures resulted from a transformation from a single vortex but from a double or triple vortex state, which could happen if one of the cross-tie structures collapses into a vortex. This asymmetry of the vortex circulation direction in nucleated walls rules out thermally activated nucleation, where both vortex circulation directions should then occur in equal numbers. To check for thermal effects, we have directly determined the temperature rise during pulse injections by monitoring the resistance as suggested by Yamaguchi *et al.*[12] The maximum heating for the highest current densities used was found to be 60 K, in line with earlier estimates,[9] but significantly less than observed in Ref. 12. A further indication that the nucleation of vortices is not primarily due to temperature effects is the fact that all the vortices were nucleated in the vicinity of an existing vortex, whereas a thermally activated nucleation occurs anywhere in the wire as observed by Yamaguchi *et al.*[12] What is more, the energies of the multivortex spin structures are higher than that of the single vortex, which means that we do not observe the thermally activated transition to an energetically more favorable spin structure. Thus the likely explanation for the nucleation and annihilation of vortices is the spin torque effect due to the current.

Now that we have discussed the observed domain wall transformations, we turn to the consequences for the wall displacement. In Fig. 2 the velocity is plotted as a function of current density not only for the case of the movement of single vortex walls without transformation (black solid line and black squares as discussed above) but also for injections which involve transformations. The up triangles show that multivortex domain walls do not move significantly for the current densities used here. During injections when the wall transforms from a single vortex to a double vortex or back (disks in Fig. 2), the walls move with a very low average velocity. These transformations set in at the same current density as the wall motion, which points to the same origin for transformation and wall motion. Since the red disks include the transformation from a single vortex wall to a double vortex and since we know the average velocity of a single vortex wall (black line) we can infer from the low velocity that the transformation takes place close to the beginning of the pulse. If this transformation occurred only towards the end of the pulse, we would expect that the average velocity would be similar to that of single vortex walls. Finally, we see that the extended vortex walls show a very different behavior from the double vortex wall. The down triangles show the velocity as a function of current density for injections where the wall is transformed from a single vortex wall to an extended vortex or remains an extended vortex. We see that the velocities lie in a distinct region between those of single vortex walls and those of double vortex walls. Since there is no significant difference in the velocities of extended vortex walls that do not change their spin structure and of single vortex walls that transform to extended vortex walls, we can again deduce that the transformation takes place towards the beginning of the pulse injection. The drastic difference in velocities between the single, extended, double, and multivortex wall structures indicates the importance of the number of vortices for the velocity. As theoretically predicted,[17] walls undergoing a transformation exhibit a much smaller velocity than vortex walls which stay single vortex walls. This is analogous to field-induced propagation, where wall spin structure transformations reduce the average velocity as well.[24]

In order to use these elements in applications, the switching speed has to be high and the wall velocity reproducible to allow for fast and reliable switching. From our results we can infer that this requires structures where no domain wall transformation takes place. To prevent transformations to transverse walls,[7] we have to be far away from the phase boundary,[21] which can be achieved by increasing the thickness from the 10 nm used in Ref. 7 to the 28 nm used here. To prevent the nucleation of vortices we can reduce the width, since the increasing shape anisotropy of narrower wires increases the energy barrier for vortex nucleation. We have measured the domain wall propagation in 28 nm thick and 500 nm narrow wires and in these elements domain wall propagation with no transformations and thus reproducible displacement prevails.

In conclusion, we have observed in addition to propagation of unperturbed vortex walls a number of different wall transformations in 1 $\mu$m wide and 28 nm thick NiFe wires. In particular, we find that in line with theoretical predictions, vortices are nucleated and annihilated due to the spin torque effect. This leads to transformations to and from extended, double, and triple vortex walls. The velocity is found to be directly correlated with these transformations and decreases with increasing number of vortices. More reliable switching is obtained in narrower structures, where the nucleation of vortices is more difficult and thus propagation of single vortices prevails.

The authors acknowledge support by the Deutsche Forschungsgemeinschaft through SFB 513, by the Landesstiftung Baden-Württemberg, by the EPSRC (UK), by the EC and the EU through the Sixth Framework Program. Part of this work was carried out at Elettra, Trieste/Italy.

[1]S. S. P. Parkin, U.S. Patent No. 6834005 (2004).
[2]J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
[3]L. Berger, J. Appl. Phys. **55**, 1954 (1984).
[4]P. P. Freitas and L. Berger, J. Appl. Phys. **57**, 1266 (1985).
[5]J. Grollier, P. Boulenc, V. Cros, A. Hamzic, A. Vaurs, A. Fert, and G. Faini, Appl. Phys. Lett. **83**, 509 (2003).
[6]M. Kläui, C. A. F. Vaz, J. A. C. Bland, W. Wernsdorfer, G. Faini, E. Cambril, and L. J. Heyderman, Appl. Phys. Lett. **83**, 105 (2003).
[7]M. Kläui, P.-O. Jubert, R. Allenspach, A. Bischof, J. A. C. Bland, G. Faini, U. Rüdiger, C. A. F. Vaz, L. Vila, and C. Vouille, Phys. Rev. Lett. **95**, 026601 (2005).
[8]A. Yamaguchi, T. Ono, S. Nasu, K. Miyake, K. Mibu, and T. Shinjo, Phys. Rev. Lett. **92**, 077205 (2004).
[9]N. Vernier, D. A. Allwood, D. Atkinson, M. D. Cooke, and R. P. Cowburn, Europhys. Lett. **65**, 526 (2004).
[10]M. Kläui, C. A. F. Vaz, J. A. C. Bland, W. Wernsdorfer, G. Faini, E. Cambril, L. J. Heyderman, F. Nolting, and U. Rüdiger, Phys. Rev. Lett. **94**, 106601 (2005).
[11]D. Ravelosona, D. Lacour, J. A. Katine, B. D. Terris, and C. Chappert, Phys. Rev. Lett. **95**, 117203 (2005).
[12]A. Yamaguchi, S. Nasu, H. Tanigawa, T. Ono, K. Miyake, K. Mibu, and T. Shinjo, Appl. Phys. Lett. **86**, 12511 (2005).
[13]G. Tatara and H. Kohno, Phys. Rev. Lett. **92**, 086601 (2004).
[14]A. Thiaville, Y. Nakatani, J. Miltat, and N. Vernier, J. Appl. Phys. **95**, 7049 (2004).
[15]Z. Li and S. Zhang, Phys. Rev. Lett. **92**, 207203 (2004).
[16]S. Zhang and Z. Li, Phys. Rev. Lett. **93**, 127204 (2004).
[17]A. Thiaville, Y. Nakatani, J. Miltat, and Y. Suzuki, Europhys. Lett. **69**, 990 (2005).
[18]J. Shibata, G. Tatara, and H. Kohno, Phys. Rev. Lett. **94**, 076601 (2005).
[19]L. J. Heyderman, M. Kläui, B. Nöhammer, C. A. F. Vaz, J. A. C. Bland, and C. David, Microelectron. Eng. **73–74**, 780 (2004).
[20]J. Stöhr, Y. Wu, B. D. Hermsmeier, M. G. Samant, G. R. Harp, S. Koranda, D. Dunham, and B. P. Tonner, Science **259**, 658 (1993).
[21]M. Laufenberg, D. Backes, W. Bührer, D. Bedau, M. Kläui, U. Rüdiger, C. A. F. Vaz, J. A. C. Bland, L. J. Heyderman, and F. Nolting, Appl. Phys. Lett. **88**, 52507 (2006).
[22]A. Hubert and R. Schäfer, *Magnetic Domains* (Springer, Berlin, 1998); A. Neudert, J. McCord, R. Schäfer, R. Kaltofen, I. Mönch, H. Vinzelberg, and L. Schultz, J. Appl. Phys. **99**, 08F302 (2006).
[23]J. Shibata, Y. Nakatani, G. Tatara, H. Kohno, and Y. Otani, Phys. Rev. B **73**, 020403 (2006).
[24]G. S. D. Beach, C. Nistor, C. Knutson, M. Tsoi, and J. L. Erskine, Nat. Mater. **4**, 741 (2005).