Birth, Growth and Death of an Antivortex during the Propagation of a Transverse Domain Wall in Magnetic Nanostrips

H. Y. Yuan, X. R. Wang

Physics Department, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong and HKUST Shenzhen Research Institute, Shenzhen 518057, China

(Dated: May 11, 2014)

Antivortex birth, growth and death due to the propagation of a transverse domain wall (DW) in magnetic nanostrips are observed and analyzed. Antivortex formation is an intrinsic process of a strawberry-like transverse DW originated from magnetostatic interaction. Under an external magnetic field, DW in a wider width region tends to move faster than that of a narrower part. This speed mismatch tilts and elongates DW centre line. An antivortex is periodically born near the tail of the DW centre line. The antivortex either moves along the centre line and dies on the other side of the strip, or grows to its maximum size, detaches itself from the DW, and vanishes eventually. The former route reverses the polarity of DW while the later keeps the DW polarity unchanged. The evolution of the DW structures is analyzed using winding numbers assigned to each topological defects. The phase diagram in the field-width plane is obtained and discussed.

I. INTRODUCTION

Domain wall motion in ferromagnetic nanostrips has attracted much attention in recent years due to its potential applications in magnetic memory devices and magnetic logic gates. These applications require a detailed and deep understanding of DW motion so that one could have a better control of magnetization states. Although field driven DW motion have been extensively studied in the last few decades and lots of interesting phenomena have been found, there are still many fundamental processes poorly understood. For example, field driven DW dynamics is governed by the Landau-Lifshitz-Gilbert (LLG) equation which has a well-known Walker exact solution for a one-dimensional (1D) biaxial wire. However, simulations or experiments on the field driven DW motion are often not described by the Walker solution. For quasi-1D nanostrips with narrow width, transverse DW is a preferred low energy state as shown in Figs. 1a and 1b without (1a) and with (1b) the magnetostatic interaction. The magnetostatic field plays such an important role in the DW structure that the width of DW varies in the transverse direction, leading to a strawberry-like DW (Fig. 1b). Although similar shaped DW has already been known numerically, its consequences and connections with other DW dynamics phenomena such as antivortex generation and reduction of the Walker breakdown field have not been thoroughly investigated, and this is the main focus of this work.

In this paper we explore the consequences of the strawberry-like transverse DW on field driven DW dynamics in ferromagnetic nanostrips. When the field is larger than a certain value but substantially below the usual Walker breakdown field, a series of DW structure transformations, including periodic birth and death of antivortices, is observed and explained. Two types of antivortex evolutions and their causes are identified. A phase diagram in the field-width plane is also obtained numerically. This paper is organized as follows. Our model and method is described in the next section. An explanation of why magnetostatic interaction should give rise to a strawberry-like transverse DW is also provided in Section II. Numerical results on the antivortex generation and its afterward evolution are presented and discussed in Section III. Discussion and conclusion are given in Section IV, followed by the acknowledgments.

II. MODEL AND METHOD

Our model is a head-to-head DW in magnetic nanostrips of 5000nm long, 4nm thick, and width varying from 40nm to 120nm. The magnetization dynamics of nanostrips is governed by the LLG equation:

\[
\frac{\partial \mathbf{m}}{\partial t} = -\mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t},
\]

where \( \mathbf{m}(x, t) = \mathbf{M}(x, t)/M_s \) is the unit vector of magnetization, \( M_s \equiv |\mathbf{M}| \) is the saturation magnetization, \( \alpha \) is the phenomenological Gilbert damping constant. The time \( t \) is in the units of \( (\gamma M_s)^{-1} \) where \( \gamma \) is gyromagnetic constant. \( \mathbf{H}_{\text{eff}} = \frac{2A}{\mu_0 M_s^2} \nabla^2 \mathbf{m} + \mathbf{H}_K + \mathbf{H}_d + \mathbf{H}_0 \) is the effective field measured in the units of \( M_s \), which includes the exchange field described by the exchange constant \( A \), crystalline anisotropy field \( \mathbf{H}_K \), magnetostatic field \( \mathbf{H}_d \) and applied field \( \mathbf{H}_0 \).

The film lies in \( xy \) plane with the origin at the center of the strip. \( x \) is along the longitudinal direction with \( y \) in the width (transverse) direction and \( z \)-axis along the thickness direction. Permalloy parameters are used in the simulations with \( A = 13 \times 10^{-12} \text{J/m} \), saturation magnetization \( M_s = 800 \times 10^3 \text{A/m} \) and negligible crystalline anisotropy field. Damping constant is chosen to be \( \alpha = 0.1 \) to accelerate the simulation. The LLG equation is numerically solved by the micromagnetic package OOMMF. In our simulations, the mesh size is chosen to...
be 4nm×4nm×4nm where 4nm is about 0.7 of exchange length \(l_{ex} = \sqrt{2A/\mu_0 M_s^2}\).

The static DW is transverse for the types of strips in the current investigations, as illustrated in Fig. 1 which is numerically obtained from an initial configuration of \(m_x = -\tanh(x/\Delta), \ m_y = 1/\cosh(x/\Delta)\) and \(m_z = 0\) for a head-to-head DW, and parameter \(\Delta\) is close to the static DW width. When the magnetostatic interaction includes only the shape anisotropy, but neglects all contributions from the non-uniform magnetization distribution, the final DW is homogeneous in which DW width is \(y\)-independent and the net magnetic moments point up (polarity +1) as shown in Fig. 1. When all the magnetic dipole-dipole interaction is included in the magnetostatic interaction, the magnetostatic field generated by the magnetic charges along the edges (Fig. 1c) shall modify the effective magnetic anisotropy such that a typical DW shape is strawberry-like as shown in Fig. 1b. Specifically, the \(y\)-component of edge charges field tends to reduce the anisotropy field in the direction while its \(x\)-component lowers the anisotropy field near upper edge and enhances the \(x\)-component of the field near the lower edge. Because the decrease of anisotropy leads to the increase of DW width, this anisotropy modification gives rise to the strawberry-like DW that closely follow the increase of DW width, this anisotropy modification of the Walker breakdown field is therefore needed. The detail simulation could happen such as antivortex generation and reduction near the tail of the centre line. Complicated changes change interaction, creating a large magnetization gradient and stretch due to the speed mismatch and the existence of the Walker breakdown field. The detail simulation results on the field-driven strawberry-like transverse DW are presented below with a qualitative understanding.

### III. RESULTS

We use a magnetic strip of width 80nm as an example to illustrate possible types of field-driven transverse wall motion. Since the only anisotropy comes from sample shape in the model, the Walker breakdown field is \(H_W = \frac{1}{2}a(N_x - N_y)M_s = 4170Oe\), where \(N_x, N_y\) are demagnetization factors along \(z\)- and \(y\)-directions. For fields below 237Oe, the transverse wall propagates eventually like a rigid-body after a short transient process. When the field is greater than 237Oe, antivortex is generated and no rigid-body DW propagation is observed. The possible types of the antivortex evolution depends on field strength. For fields 237Oe ≤ \(H < 255\)Oe, antivortices generated at one edge defect move along its DW centre line to the other edge and die there. At the same time the polarity of the transverse wall is reversed.

![FIG. 1: (Color online) DW structures and magnetic charge distribution near the DW. For clarity, each spin represents average magnetization of 4 cells of 8nm×8nm×4nm. a) Homogeneous transverse DW when the magnetostatic interaction due to the edge magnetic charges of DW is neglected. b) The strawberry-like transverse DW when all magnetostatic interactions are included. The color codes the values of \(m_x\), varying from orange for \(m_x = 1\) to green for \(m_x = -1\) with white for \(m_x = 0\) (DW center). Both strips have dimensions 3000nm ×100nm ×4nm. c) The magnetic charge distribution for DW structure shown in a). The black curved lines with arrows indicate the magnetic field generated by the edge charges.](image-url)
on the bottom edge, the tail of DW centre line. Since the defects are topological objects with well-defined winding numbers, edge defect of $-1/2$ winding number can only give a birth to an antivortex of winding number $-1$ and change its own winding number to a $+1/2$ edge defect. This is illustrated in the right plot of Fig. 2b with the blue big dot representing the antivortex and two filled circles for the edge defects of $+1/2$ winding number. Then, this antivortex moves toward the other side of the strip (Fig. 2c at 1.17ns and Fig. 2d at 1.66ns) along the DW centre line. At 1.98ns, the antivortex reaches the top edge defect and die there as shown in Fig. 2e. At the same time, top edge defect changes its winding number from $+1/2$ to $-1/2$, and transverse wall reverses its polarity (from $+1$ to $-1$). After a transient period, the above mentioned process will repeat again, starting from the top edge of the strip this time. This birth-death process of antivortices repeats periodically while the transverse DW propagates along the while with an averaged speed of about 440m/s. This result is also consistent with previous studies.

For a field greater than 255Oe, an antivortex will not be able to reach the other edge of the strip because distortion of the DW centre line is too large so that the corner space is not large enough to accommodate the antivortex. Fig. 3 is DW transformations under a 260Oe field. The left plot of Fig. 3 shows the initial spin configuration of Fig. 3a. The internal DW structure at 0.54ns, right before the generation of an antivortex at the edge defect on the bottom edge, is shown in the left plot of Fig. 3a. The right plot of Fig. 3b are the corresponding DW centre line and antivortex (blue dot) and two edge defects of winding number 1/2. Different from the previous case, this newly born antivortex cannot reach the other edge. The left plot of Fig. 3c is the DW configuration at 0.76ns. The corresponding location of the antivortex, edge defects, as well as the DW centre line are indicated in the right plot of Fig. 3c. The antivortex makes a U-turn back to bottom edge. Together with two edge defects of winding number 1/2 at the bottom edge, the antivortex detaches itself from the DW by creating an isolated defect region, leaving the DW to be transverse with polarity 1 as shown in Fig. 3d at 1.02ns. The isolated defect region is topologically trivial, and vanishes through dissipating its extra energy. As shown in Fig. 3e at 1.27ns, the DW keeps its polarity unchanged at the end of this process, and this birth-death process of an antivortex repeats itself periodically. Furthermore, to numerically demonstrate the above antivortex generation originates from the magnetostatic field of DW structure, we also carried out the OOMMF simulation without this local magnetic charge interaction. No antivortex generation is obtained below the Walker breakdown field, and the transverse wall always ends up with a rigid-body propagation as what was predicted by the Walker solution.

In order to obtain the phase diagram of these two types of antivortex evolution in the parameter space of field and strip width, we repeat the same OOMMF simulations for various strip width. Fig. 4 is the numerical results. Below the width 15.44 (in units of $l_{ex}$), the Walker rigid-body DW propagation (phase I) exists at low fields. At the intermediate fields, a propagation of a strawberry-like transverse wall gives birth to an antivortex that moves to the other edge and disappears there. At the same time, the transverse wall changes its polarity to the opposite sign. This is denoted as the phase II in Fig. 4. In the phase III, the generated antivortex cannot move to the other edge. It grows to its maximal size and detaches itself from the DW by creating an isolated defect region that disappears eventually through energy dissipation. Above the width 15.44, we don’t observe phase II within the field step of 1Oe and only phase I and phase III are observed.
FIG. 3: (Color online) Similar to Fig. 2 but with an applied field of 260Oe. Again \( x_t \) is x-coordinate of DW centre at the top edge. The averaged DW speed is about 587m/s. a) The initial strawberry-like transverse wall at \( t = 0 \)ns with \( x_t = 0 \)nm. b) DW structure with \( x_t = 365 \)nm at \( t = 0.54 \)ns. c) DW structure with \( x_t = 486 \)nm at \( t = 0.76 \)ns. d) DW structure with \( x_t = 599 \)nm at \( t = 1.02 \)ns. e) DW structure with \( x_t = 769 \)nm at \( t = 1.27 \)ns.

IV. DISCUSSION AND CONCLUSION

Our study shows that the birth of antivortices arises from the motion of a strawberry-like DW caused by the anisotropy modification due to the magnetic charges of the DW. The uneven energy dissipation in the transverse direction due to the DW width variation leads to an uneven propagation speed along the direction. As a result, the DW centre line is elongated and tilted. A large magnetization gradient near the tail of the DW centre line is then produced and this gradient tends to generate antivortices near the tail of the line. It is clear that the Walker rigid-body propagation mode applies only to a transverse DW (Bloch or Neel type), not for a vortex or antivortex DW. This is because a vortex tends to move in the transverse direction under a gyrotropic force. A transversally moving vortex wall in a nanostrip must modify its own DW structure due to the edge charge effects. Thus, DW propagating speed shall vary with time according to the connection between DW structure and instantaneous DW speed. Thus, the antivortex birth invalidates the Walker rigid-body propagating mode. This is why the Walker breakdown field is substantially reduced in a strip. The actual amount of breakdown field reduction depends on the geometry and other material parameters. In general, the larger the strip width is, the greater reduction of the Walker breakdown field will be.

In conclusion, we investigate field-driven DW propagation along magnetic strips below the predicted Walker breakdown field. A strawberry-like DW causes reduction of Walker breakdown field because of the antivortices generation. The Walker rigid-body DW propagation mode is only possible at weak fields when a propagating DW does not create antivortices. If external fields are larger than a critical value, this strawberry-like DW generates antivortices at the tail of the DW centre line, and the antivortices move to the other side of strip and reverse the DW polarity. This process prefers to appear in narrower strips according to our simulation. If the field is further increased above another critical value, still below the Walker breakdown field, the generated antivortex will not be able to reach the other edge of the strip, but detaches itself from the DW and vanishes eventually in a domain through energy dissipation. The original transverse DW does not change its polarity in this field range. It is noticed that motion of an inhomogeneous DW generates antivortices even in zero damping case whose details need further investigations.

FIG. 4: Phase diagram of three possible phases in the plane of field and strip width. The field is in units of \( H_W \) and width in units of \( l_{ex} \). Phase I is the rigid-body propagation mode. Phases II and III denote antivortex formation modes. Phase II corresponds to case that an antivortex can move from one side of strip to the opposite side, and at the same time the DW polarity is reversed. Phase III is the case that an antivortex is born, grows to its maximal size and detaches itself from the transverse wall, then eventually dies inside the strip. In phase III, DW polarity does not change.

In conclusion, we investigate field-driven DW propagation along magnetic strips below the predicted Walker breakdown field. A strawberry-like DW causes reduction of Walker breakdown field because of the antivortices generation. The Walker rigid-body DW propagation mode is only possible at weak fields when a propagating DW does not create antivortices. If external fields are larger than a critical value, this strawberry-like DW generates antivortices at the tail of the DW centre line, and the antivortices move to the other side of strip and reverse the DW polarity. This process prefers to appear in narrower strips according to our simulation. If the field is further increased above another critical value, still below the Walker breakdown field, the generated antivortex will not be able to reach the other edge of the strip, but detaches itself from the DW and vanishes eventually in a domain through energy dissipation. The original transverse DW does not change its polarity in this field range. It is noticed that motion of an inhomogeneous DW generates antivortices even in zero damping case whose details need further investigations.

Acknowledgments

HYY acknowledges the support of Hong Kong PhD Fellowship. He would also like to thank Xiansi Wang, Bin Hu, Yin Zhang and Chen Wang for helpful discussions. This work was supported by Hong Kong RGC Grants (604109 and 605413), and the grant from NSF of China.
1. S. S. P. Parkin, M. Hayashi, and L. Thomas, Science 320, 190 (2008).
2. D. A. Allwood, G. Xiong, C. C. Faulkner, D. Atkinson, D. Petit, and R. P. Cowburn, Science 309, 1688 (2005).
3. N. L. Schryn and L. R. Walker, J. Appl. Phys. 45, 5406 (1974).
4. X. R. Wang, P. Yan, J. Lu and C. He, Ann. Phys. (N.Y.) 324, 1815 (2009); X. R. Wang, P. Yan, and J. Lu, EPL 86, 67001 (2009).
5. R. Wieser, U. Nowak, and K. D. Usadel, Phys. Rev. B 69, 064401 (2004).
6. P. Yan, X. S. Wang, and X. R. Wang, Phys. Rev. Lett. 107, 177207 (2011); X. S. Wang, P. Yan, Y. H. Shen, G. E. W. Bauer, and X. R. Wang, ibid. 109, 167209 (2012); B. Hu and X. R. Wang, ibid. (in press).
7. D. G. Porter and M. J. Donahue, J. Appl. Phys. 95, 6729 (2004).
8. G. S. D. Beach, C. Knutson, C. Nistor, M. Tsoi, and J. L. Erskine, Phys. Rev. Lett. 97, 057203 (2006).
9. G. S. D. Beach, C. Knutson, C. Nistor, M. Tsoi and J. L. Erskine, Nat. Mater. 4, 741 (2005).
10. J. Linder, Phys. Rev. B 87, 054434 (2013).
11. M. Hayashi, L. Thomas, C. Rettner, R. Moriya, X. Jiang, and S. S. P. Parkin, Phys. Rev. Lett. 97, 207205 (2006).
12. R. D. McMichael and M. J. Donahue, IEEE Trans. Magn. 33, 4167 (1997).
13. Y. Nakatani, A. Thiaville and J. Militat, J. Magn. Magn. Mater. 290, 750 (2005).
14. L. Laurson, A. Mughal, G. Durin, and S. Zapperi, IEEE Trans. Magn. 46, 262 (2010).
15. http://math.nist.gov/oommf
16. A. Vanhaverbeke, A. Bischof, and R. Allenspach, Phys. Rev. Lett. 101, 107202(2008).
17. M. T. Bryan, T. Schrefl, and D. A. Allwood, IEEE Trans. Magn. 46, 1135 (2010).
18. O. Tchernyshyov and G. -W. Chern, Phys. Rev. Lett. 95, 197204 (2005).
19. P. M. Chaikin and T. C. Lubensky, Principles of Condensed Matter Physics (Cambridge University Press, 2000).
20. Y. Nakatani, A. Thiaville, and J. Militat, Nat. Mater. 2, 521 (2003).
21. R. Cowburn and D. Petit, Nat. Mater. 4, 721 (2005).
22. J. -Y. Lee, K. -S. Lee, S. Choi, K. Y. Guslienko, and S.-K. Kim, Phys. Rev. B 76, 184408 (2007).
23. A. Kunz, E. C. Breitbach, and A. J. Smith, J. Appl. Phys. 105, 07D502 (2009).
24. C. Zinoni, A. Vanhaverbeke, P. Eib, G. Salis, and R. Allenspach, Phys. Rev. Lett. 107, 207204 (2011).
25. A. A. Thiele, Phys. Rev. Lett. 30, 230 (1973).
26. S. Glathe, M. Zeisberger, U. Hubner, and R. Mattheis, D. V. Berkov Phys. Rev. B 81, 020412(R) (2010).