Packing 360◦ domain walls of identical circulation on planar ferromagnetic nanowires with notches using circular magnetic fields

F. I. Kaya, A. Sarella, D. Wang, M. Tuominen, and K. E. Aidala

Citation: AIP Advances **6**, 056408 (2016); doi: 10.1063/1.4944702
View online: http://dx.doi.org/10.1063/1.4944702
View Table of Contents: http://scitation.aip.org/content/aip/journal/adva/6/5?ver=pdfcov
Published by the AIP Publishing

AIP ADVANCES **6**, 056408 (2016)

Packing 360° domain walls of identical circulation on planar ferromagnetic nanowires with notches using circular magnetic fields

F. I. Kaya,[1] A. Sarella,[1] D. Wang,[2] M. Tuominen,[2] and K. E. Aidala[1,a]
[1]*Department of Physics, Mount Holyoke College, South Hadley, MA, 01075, USA*
[2]*Department of Physics, University of Massachusetts, Amherst, MA, 01003, USA*

(Presented 12 January 2016; received 6 November 2015; accepted 2 February 2016; published online 18 March 2016)

360° domain walls (DWs) have generated substantial interest with the recognition that their minimal stray field creates only short range interactions, leading to a potentially higher packing density for data storage devices compared to 180° DWs. The topology of neighboring 360° DWs with identical circulation allows a higher packing density than that of 360° DWs of opposite circulation. Our simulations demonstrate the process by which we can pack 360° DWs of identical circulation on a long wire with 100 nm width (in y) and 4 nm thickness (in z), studying different size and shape notches to pin the DWs. The process to generate these walls follows a series of circular fields with non-uniform magnetic field strength that decreases as $1/r$ as if created by an infinitely long wire passing current into or out of the page and centered just above the notches. We are able to pin two 360° DWs of the same circulation on adjacent 16 nm (x) by 32 nm (y) rectangular notches 100 nm apart and on adjacent triangular notches of the same area that are 100 nm apart. The location and strength required of the series of fields is different for the different notches. Such stable high density packing of 360° DWs in simulations is unprecedented and suggests the potential for high density information storage. [http://dx.doi.org/10.1063/1.4944702]

I. INTRODUCTION

Nucleation and high-density packing of domain walls (DWs) in a thin planar ferromagnetic nanowire is essential for the realization of several proposed nanowire storage,[10] logic[5] and sensing devices.[1] Because 180° DWs interact over the scale of microns,[3,13] 360° DWs have been proposed to serve as bits in data storage devices.[9] We must understand and control the nucleation, motion, and annihilation of 360° DWs to develop these devices. A 360° DWs can be viewed as a composite magnetization structure, consisting of two 180° DWs that have the same topological edge defects, preventing them from annihilating when they come together. Previous mechanisms to generate 360° DWs in a nanowire use in-plane magnetic fields applied by an external magnet or by passing current through a planar wire.[3,4,8,10] We proposed a technique that applies a local circular magnetic field to nucleate 360° DWs at predefined pinning sites (using rectangular notches) along a ferromagnetic nanowire. We demonstrated high-density packing of 360° DWs where the adjacent DWs have opposite magnetization circulation.[6] However, the alternating circulation of the 360° DWs limits the packing density because the neighboring constituent 180° DWs have opposite topological edge charges and will therefore annihilate when the distance between the charges is within the interaction limit. In this paper, we propose a mechanism to nucleate a series of 360° DWs with the same circulation at adjacent notches, enabling closer packing density, and we investigate the role of the geometry of the notch.

[a]Electronic mail: kaidala@mtholyoke.edu.

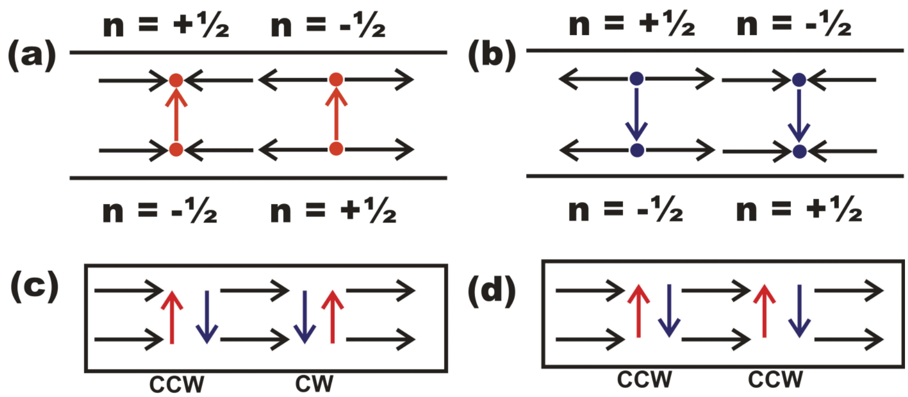

FIG. 1. Schematic representations of topological edge defects (a) Two "*up*" DWs, with opposite topological edge defects (b) Two "*down*" DWs, with opposite topological edge defects (c) 360° DWs with opposite circulation and edge defects. (d) 360° DWs with the same circulation and edge defects.

The topology of 180° DWs can be understood through their topological edge defects of $\pm\frac{1}{2}$,[7,11,12] as shown in Figure 1. When two 180° DWs with opposite topological charges (Fig. 1(a),1(b)) come together, the edge charges sum to zero and the DWs annihilate one another. When two 180° DWs with the same topological charges interact, the edge charges sum to one and the DWs form a stable 360° DW in sufficiently thin wires, as shown in Fig. 1(c), 1(d). (In thicker wires, the moments can more easily rotate out of the plane and annihilate the 360° DW.) Stable walls always have an "*up-down*" or "*down-up*" configuration (Fig. 1(c), 1(d)). This shorthand helps us quickly visualize when two 180° DWs will form a 360° DW. We determine whether the wall is clockwise (CW) or counter-clockwise (CCW) by reading the rotation of the moments from left to right. For the leftmost wall, the moments begin by pointing to the right, then up, then left (not shown), then down and finally again to the right. The moments rotate CCW through the DW.

When packing 360° DWs along a wire, neighboring DWs can have either the same circulation as shown in Fig. 1(c) (both CW or both CCW), or opposite circulation (Fig. 1(d)). Note that when neighboring walls have opposite circulation, the adjacent constituent 180° DWs are pointing in the same direction (i.e. *down-down*), with edge charges that sum to zero (Fig. 1(c)). Once the 360° DWs are close enough to interact, these 180° DWs will come together and annihilate. In contrast, when neighboring 360° DWs have the same circulation, adjacent constituent 180° DWs will not annihilate (Fig. 1(d)). For this reason, 360° DWs with the same circulation can be packed more closely.

II. SIMULATIONS

All simulations are performed using the OOMMF[2] package, which evolves the magnetization using the LLG equation. The typical nanowire dimensions used in this simulation are approximately $10{,}000 \times 100$ nm^2. The material parameters are typical for permalloy: $M_s = 8 \times 10^5$ A/m, $A = 1.3 \times 10^{-11}$ J/m with no crystalline anisotropy. The simulations presented here are performed at 0 K, employ a cell size of 4 nm along the three axes, with a damping parameter of 0.5. The magnetization state evolves until the structures reach an equilibrium state, where $\frac{d\mathbf{M}}{dt} < 0.1$ deg/ns. We apply a planar circular magnetic field that decreases in strength as $\frac{1}{r}$, as if from an infinitely long current carrying wire that is perpendicular to the plane of the ferromagnetic nanowire, where r is the distance from the center of the field to that location. The center of the field is always positioned 48 nm above the wire in the y direction, as indicated in Figure 2(a).

Figure 2 depicts the series of steps required to position 360° DWs with identical circulation on a planar nanowire that includes 16×16 nm^2 square notches spaced 120 nm apart. Initially, the nanowire is saturated along the $-x$ axis and a sequence of circular magnetic fields are applied (CCW (⊙) or CW (⊗)). The CCW field applied at notch **III** nucleates a 360° DW directly below the tip and two 180° DWs due to the spatial distribution of circular magnetic field. The *down* 180° DW to the right

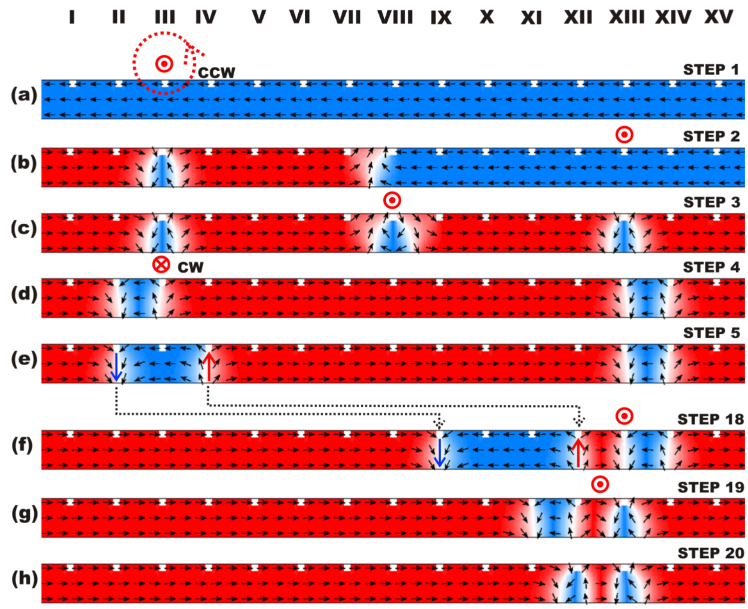

FIG. 2. The sequence of steps for packing 360° DWs of identical circulation at two adjacent notches spaced 120 *nm* apart. Blue indicates moments pointing in the -x direction; red in the +x direction. (a) Initialization. (b) Resulting state after applying a CCW field that results from a 21 mA current above notch **III**. (c) Resulting state after applying 21 mA above notch **XIII**, nucleating a second 360° DW directly below, and two 180° DWs, one of which joins the 180° DW at notch **VIII** to form a 360° DW. (d) Resulting state after applying 80 mA above notch **VIII**. The strong field annihilates the 360° DW directly below and unwinds the remaining 360° DWs into 180° DWs. (e) Resulting state after applying −15 mA above notch **III**. We continue to apply the −15 mA at subsequent notches to move the *up* 180° DW to notch **XII**, and then a CCW is used to move the *down* 180° DW at notch **II** sequentially to notch **IX**. These fifteen steps are not shown and the results state is depicted in (f). (g) Resulting state after applying 30 mA at notch **XIII**, forming the 360° DW directly below, and pinning the *down* 180° DW at notch **XI**. (h) Resulting state after applying 30 mA between notches **XII** and **XIII**, forming the second 360° DW pinned at notch **XII**.

is pinned five notches away at notch **VIII** while the other is annihilated at the left edge of the wire. Note that the 180° DW would not move five notches away if the notches were spaced farther apart. Because the notches are so close, the strength of the field at the nearby notches is larger.

We next apply a CCW field five notches away from the pinned 180° DW, nucleating a 360° DW at notch **XIII** and a *down* 180° DW that moves to the left and combines with the *up* 180° DW at notch VIII. The 360° DWs at notches **III** and **XIII** have the same (CW, or *down* – *up*) circulation, while the 360° DW at notch **VIII** has the opposite. We annihilate the DW at notch **VIII** by applying a stronger CCW field, which also splits the other two 360° DWs into their constituent 180° DWs. The two remaining 360° DWs would not unwind if the spacing between notches were larger.

We then continue the process of unwinding one of the 360° DWs by moving the individual 180° DWs along the wire towards the other 360° DW. This is accomplished by a series of fields that sequentially extends the *up* wall initially at notch **III** towards the DW at notch **XIII** and then brings the *down* 180° DW initially at notch **II** also towards notch **XIII**. In Fig. 2(d) (Step 4), we apply a CW field to move the 180° DW that is pinned at notch **III** over to notch **IV**. From step 4 to step 18, we apply a series of CW fields at each notch (from **IV** to **XII**, not shown) to move the *up* 180° DW to notch **XII**, and a series of CCW fields to move the *down* DW to notch **IX**. The final two steps require a larger field to reform the 360° DWs, and we end with two 360° DWs with the same circulation at notches **XII** and **XIII**.

If the spacing between notches were larger, the 180° DWs would be pinned closer to the nucleated 360° DW, and fewer steps are required to generate the adjacent 360° DWs with the same circulation. For notches that are positioned 300 *nm* apart, the procedure requires only seven steps. If the spacing between notches were smaller, the magnetization would not evolve from Step 19 (Figure 2(g)) to the final state in Step 20 (Figure 2(h)). Essentially, one of the two 360° DWs would unwind into its constituent 180° DWs once the circular field were removed.

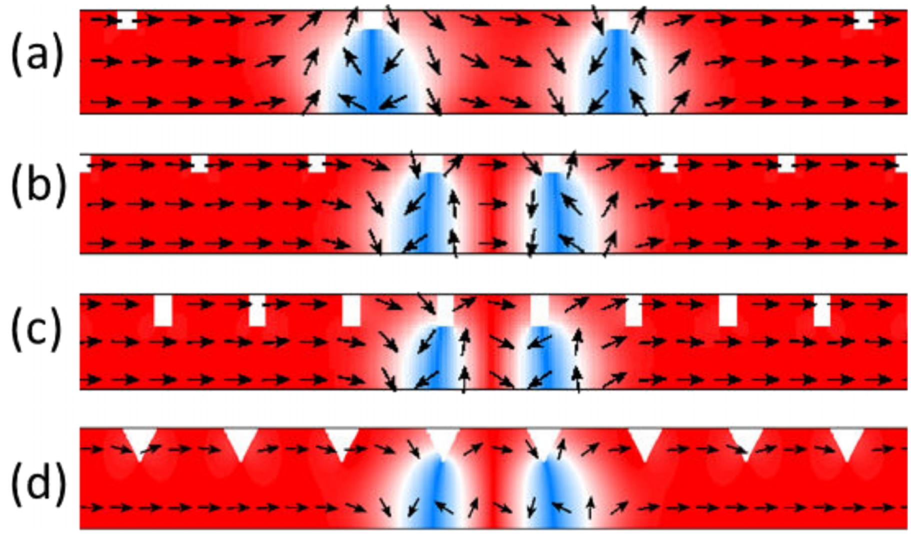

FIG. 3. Packing of 360° DWs at two adjacent notches. (a) Two 360° DWs of opposite circulation are packed on a wire with 16×16 nm^2 notches at the inter-notch distance of 240 nm. (b) Two 360° DWs of identical circulation are packed on a wire with 16×16 nm^2 notches at the inter-notch distance of 120 nm. (c) Two 360° DWs of identical circulation are packed on a wire with 16×32 nm^2 notches at the inter-notch distance of 100 nm. (d) Two 360° DWs of identical circulation are packed on a wire with triangular notches of 32 nm width ($\hat{x}$) and 32 nm depth ($\hat{y}$) at the inter-notch distance of 100 nm.

To investigate the pinning and interactions of 360° DWs on a planar nanowire, we studied the effects of notch size, shape, inter-notch distance and magnetization circulation of adjacent DWs. Our previous work[6] was focused on understanding the packing of 360° DWs with opposite circulation using 16×16 nm^2 square notches, which limited the minimum spacing between DWs to 240 nm but could be performed in only three steps (Fig. 3(a)). By understanding the failure mechanism that caused the adjacent constituent 180° DWs to interact and annihilate, we see that 360° DWs with the same circulation can be packed more closely, given the same notch geometry. Fig. 3(b) shows the minimal inter-notch distance (120 nm) for the 16×16 nm^2 notch configuration for 360° DWs with the same magnetization circulation, as described in Fig. 2. Fig. 3(c) shows the closest packing we have achieved for a rectangular 16×32 nm^2 notch configuration for 360° DWs with the same magnetization circulation, spaced by 100 nm, and Fig. 3(d) shows this for triangular notches of 32 nm width ($\hat{x}$) and 32 nm depth ($\hat{y}$). By packing 360° DWs with the same circulation, we can reduce the spacing between the notches by a factor of two, for the geometry studied. We were able to pin 360° DWs for all the geometries that we tried (including wider and trapezoidal notches, not shown), though the exact procedure, magnitudes of current, and minimal spacing varied. To further test the sensitivity of our procedure to imperfections in fabrication and positioning of the tip, we centered our field up to $1/6th$ the distance between the notches, and were still able to pin the 360° DW at the intended notch.

Generally, notches that create stronger pinning sites (deeper notches, and narrower notches), allow for closer packing of the 360° DWs. Each geometry requires a slightly different procedure and strength of applied circular fields. For a device that requires the use of spin polarized current to move DWs, stronger pinning at the notches would require a larger current to move the DWs, though it would enable closer packing of the DWs. We do not anticipate experimental agreement with the predicted field strength from the simulations, because the simulations do not include temperature or edge roughness. Nucleating the 360° DWs under these conditions would become a statistical process that merits further investigation. Experimentally, we can use the metal tip of an atomic force microscope to apply the local fields, as we have previously demonstrated.[14] We did determine that short current pulses (≈ 4 ns) were sufficient to form the DWs in the geometry that we tested. This would be challenging to implement with the tip of an AFM, but practical from a device standpoint.

III. SUMMARY

In summary, we propose a mechanism for nucleating and manipulating 360° DWs with identical magnetization circulation at adjacent notches on planar nanowires, such that neighboring topological edge defects will always be the same. A series of circular magnetic fields (CW or CCW) applied along the nanowire above the notches can nucleate, unwind, or annihilate the 360° DWs. While the exact strength and location of applied fields varies for different geometry notches, our general technique allows us to investigate the closest packing of 360° DWs, which will occur when the DWs have the same circulation. For the geometries that we studied, the closest we could form two 360° DWs is 100 nm. Whether this technique could become a practical device depends on actual current values and duration and the ease and reproducibility of fabrication, all of which pose substantial challenges. Regardless, this technique offers the ability to nucleate and manipulate 360° DWs in a controllable fashion in order to study the behavior or individual DWs and their interactions.

ACKNOWLEDGEMENTS

The authors acknowledge the support by NSF grants No. DMR 1208042 and 1207924, the STC Center for Integrated Quantum Materials, NSF Grant No. DMR-1231319. The computations in this paper were run on the Odyssey cluster supported by the FAS Division of Science, Research Computing Group at Harvard University.

[1] M. Diegel, E. Mattheis, and R. Halder, IEEE Trans. Magn. **40**(4), 2655–2657 (2004).
[2] Michael. J Donahue and D. G Porter, *OOMMF user's Guide, Version 1.0, Interagency Report NISTIR 6376* (National Institute of Standards and Technology, 1999).
[3] M. Haysahi, L. Thomas, R. Moriya, C. Rettner, and S.S.P. Parkin, Science 320 (2008).
[4] M. Haysahi, L. Thomas, C. Rettner, Rai. Moriya, Xin. Jiang, and S.S.P. Parkin, Phys. Rev. Lett. 97 (2006).
[5] G. Hrkac, J. Dean, and D. A. Allwood, Philos. Trans. R. Soc. A **369**(1948), 3214–3228 (2011).
[6] F. I. Kaya, A. Sarella, K. E. Aidala, D. Wang, and M. Tuominen, arXiv:1511.00167 [cond-mat.mtrl-sci] (2015).
[7] Andrew. Kunz, Appl. Phys. Lett. **94**(13), 132502 (2009).
[8] A. L. Gonzalez Oyarce, Y. Nakatani, and C. H. W. Barnes, Phys. Rev. B **87**(21), 214403 (2013).
[9] A. L. Gonzalez Oyarce, Y. Nakatani, P. E. Roy, and C. H. W. Barnes, Phys. Rev. B **87**(21), 214403 (2013).
[10] S. S. Papworth Parkin, M Haysahi, and L. Thomas, Science **320**, 190 (2008).
[11] Aakash Pushp, Timothy Phung, Charles Rettner, Brian P. Hughes, See-Hun Yang, Luc Thomas, and Stuart S. P. Parkin, Nature Phys. **9**, 505 (2013).
[12] Oleg Tchernyshyov and Gia-Wei. Chern, Phys. Rev. Lett. **95**, 197204 (2005).
[13] L. Thomas, M. Hayashi, R. Moriya, C Rettner, and S.S.P. Parkin, Nat. Commun. **3(May)**, 810 (2012).
[14] T. Yang, Nihar R. Pradhan, Abby Goldman, Abigail S. Licht, Yihan Li, M. Kemei, Mark T. Tuominen, and Katherine E. Aidala, Appl. Phys. Lett. **98**, 242505 (2011).