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Topology-dependent stability of vortex-antivortex structures

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1 **ABSTRACT**

2 The non-trivial topology of magnetic structures such as vortices and skyrmions is
3 considered as a key concept to explain the stability of those structures. The stability, dictated
4 by non-trivial topology, provides great potential for device applications. Although it is a very
5 critical scientific and technological issue, it is elusive to experimentally study the topology-
6 dependent stability owing to the difficulties in establishing stably formed magnetic structures
7 with different topologies. Here, we establish a platform for vortex-antivortex structures with
8 different topological charges within $\text{Ni}_{80}\text{Fe}_{20}$ rectangular elements thick enough to stabilize a
9 unique three-dimensional magnetic structure with non-uniform magnetization along the
10 thickness of the elements. The detailed magnetization configurations of the three-dimensional
11 vortex-antivortex structures and their annihilations during their field-driven motions are
12 investigated by utilizing magnetic transmission soft x-ray microscopy and micromagnetic
13 simulation. We demonstrate that the stability of vortex-antivortex structures significantly
14 depends on their topologies and the topology-dependent stability is associated with their
15 different annihilation mechanisms. We believe that this work provides in-depth insight into
16 the stability of magnetic structures and its topology dependence.

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The localized swirling magnetic structures such as skyrmions, vortices, and antivortices show scientifically and technologically intriguing physical behavior, which can be understood by the concept of topology.¹⁻⁵ The topology of magnetic structures is

characterized by topological charge $q = \frac{1}{4\pi} \int \mathbf{m} \cdot \left(\frac{\partial \mathbf{m}}{\partial x} \times \frac{\partial \mathbf{m}}{\partial y} \right) dx dy$ where $\mathbf{m}$ is the normalized magnetization vector.^{1,6} The topologically non-trivial magnetic structures with $q \neq 0$ have been thought to be more stable than those of topologically trivial magnetic structures with $q = 0$, which is closely associated with topologically protected properties of such magnetic structures.^{7,8} Indeed, it was experimentally demonstrated that skyrmions, which are characterized by $q = +1$, show a longer lifetime than the topologically trivial bubble domains with $q = 0$.⁷ The stability of magnetic structures, dictated by topology, is a critical scientific issue and also highly relevant to technological applications of magnetic structures to nanodevices.

In patterned soft magnetic materials, magnetic vortex and antivortex are representative topologically non-trivial magnetic structures,^{4,9-16} which provide a unique playground for fundamental study on non-trivial nano-spin behavior. They are composed of in-plane swirling magnetic components and out-of-plane (OOP) cores. The in-plane swirling magnetic components are defined by the winding number n . Magnetic vortex and antivortex

1 are characterized by $n = +1$ and -1 , respectively.¹⁷⁻¹⁹ The direction of OOP cores is defined by
2 the polarity p . $p = +1$ and $p = -1$ represent upward and downward vortex cores, respectively.
3 Topologically, magnetic vortex and antivortex on the top (bottom) surface of a magnetic
4 element are characterized by $q = np/2$ ($-np/2$) = $+1/2$ ($-1/2$) or $-1/2$ ($+1/2$) depending on the
5 p of vortex and antivortex cores.^{20,21} The vortex and antivortex can coexist in a patterned
6 ferromagnetic element and a vortex-antivortex (V-AV) structure can be stabilized in the
7 element.²²⁻²⁵ The V-AV structure offers great potential for the applications of logic and
8 memory devices based on its topological properties.^{24,25}

9 So far, the study on stability associated with the topology of magnetic structures has
10 been mainly focused on skyrmions.^{7,8,26-28} On the other hand, the stability of V-AV structures
11 dictated by topology has been rarely addressed experimentally since it is difficult to stably
12 form topologically different V-AV structures. Moreover, the characterization of relevant
13 physical behaviors was also restricted due to the limited availability of
14 imaging/characterization tools.

15 In this work, we establish two stably formed topologically different V-AV structures
16 within 100 nm thick-Ni₈₀Fe₂₀ rectangular-patterned elements, where compelling three-
17 dimensional magnetic structures with non-uniform magnetization along the thickness of the
18 elements are created. We find that two V-AV structures are formed within three-dimensional
19 (3D) domain walls non-uniform along the thickness direction, and study field-driven behavior

of those two structures to investigate their stability by utilizing magnetic transmission soft X-ray microscopy (MTXM) and micromagnetic simulations²⁹⁻³¹. The topologically different V-AV structures show distinct physical behavior from each other during their field-driven motions. Our results demonstrate that the stability of V-AV structures depends on the topology and the topology-dependent stability is deeply related to the annihilation mechanism of V-AV structures.

Figure 1(a) illustrates the schematic diagram for X-ray imaging of a $\text{Ni}_{80}\text{Fe}_{20}$ rectangular element deposited on the Si_3N_4 membrane utilizing the MTXM (supplementary material: A). To form various magnetic structures at the remanence, we repeated the measurements of saturating the rectangular elements by applying the magnetic field of $H_x = 100$ mT in the x -axis and releasing them to zero field. Figures 1(b)-1(d) show MTXM images of three different OOP magnetic structures observed within various $\text{Ni}_{80}\text{Fe}_{20}$ rectangular elements with the thickness of $t = 100$ nm. The black and white contrasts represent upward and downward OOP magnetic components, respectively. The lateral dimensions of the elements in Figs. 1(b)-1(d) are $3 \times 2 \mu\text{m}^2$, $4.5 \times 3 \mu\text{m}^2$, and $4 \times 2 \mu\text{m}^2$, respectively. The MTXM image in Fig. 1(b) shows a straight domain wall shown in black contrast indicating OOP magnetic components pointing up. One noticeable thing is that in $-y$ -direction with respect to the domain wall, downward magnetic components (white contrast) along the domain wall are clearly visible. Unlike the straight domain walls in Fig. 1(b), the domain

1 walls in Figs. 1(c) and 1(d) are bent. More interestingly, the detailed magnetic configuration
2 around the kinked areas of the two domain walls is quite different from each other as shown
3 in the zoomed images. The upward polarization of the domain wall in Fig. 1(c) remains the
4 same even if it is slightly bent. However, the downward magnetic components, visible as a
5 white contrast in the image of Fig.1(b), no longer continues along the domain wall. On the
6 left side of the kinked area, the segment of downward magnetic components is positioned in
7 $-y$ -direction with respect to the domain wall while it is located in $+y$ -direction with respect to
8 the domain wall on the right side of the kinked area. The domain wall in Fig. 1(d) is more
9 complicated. The polarization of the domain wall switches from upward to downward at the
10 kink. The domain wall segments with upward and downward polarizations are paired with
11 downward and upward magnetic components, respectively, and both downward and upward
12 magnetic components are positioned in $+y$ -direction with respect to the domain wall
13 segments.

14 For better understanding those observed magnetic structures and their internal
15 magnetic configurations, we reproduced images for magnetic structures by micromagnetic
16 simulations with consideration of magnetic grains to mimic realistic conditions of real
17 systems, where intrinsic defects inevitably exist (supplementary material: A). In Figs. 1(e)-
18 1(g), simulated magnetic images, which match well with the MTXM images, are displayed.
19 The zoomed images of magnetic structures indicated by red boxes are inserted in Figs. 1(c)-

1 1(d), and 1(f)-1(g) where domain walls with upward and downward polarizations are
 2 represented by the red and blue dotted lines, respectively. Figures 1(h)-1(j) show 3D
 3 magnetic configurations of the magnetic structures indicated by the yellow dashed boxes in
 4 Figs.1(e)-1(g). The red and blue colors represent volumes with the normalized
 5 magnetizations of $m_z \geq +0.8$ and $m_z \leq -0.8$, respectively. Therefore, the colored elongated
 6 structures in Figs. 1(h)-1(j) correspond to the domain walls observed in MTXM
 7 measurements (Figs. 1(b)-1(d)). The 3D images in Figs. 1(h)-1(j) clearly show the
 8 magnetization is not uniform along the thickness direction. It presents that the domain walls
 9 in the middle part of the rectangular element connect vortex and/or antivortex core on the top
 10 and bottom surfaces of the rectangular elements. One interesting point is that the domain
 11 walls consist of not only upward OOP Bloch components (hereafter called cores) in the
 12 middle part of the rectangular element but also in-plane Néel components, called Néel caps
 13 (hereafter called caps) on the top and bottom surfaces of the element³²⁻³⁶ as indicated in the
 14 cross-section images of Figs. 1(h)-1(j). In addition, OOP Bloch components of the domain
 15 wall are paired with oppositely polarized OOP components (see small arrows in the cross-
 16 section images) and the flux-closure domains are formed on the yz -plane of the element,
 17 which likely reduces demagnetization energy. This result supports that the OOP magnetic
 18 component observed in $-y$ -direction or $+y$ -direction with respect to the domain walls in
 19 MTXM images (Figs. 1(b)-1(d)) is the other OOP component of the flux-closure domain

1 paired with the OOP Bloch component of the domain wall. Interestingly, the domain wall
 2 composed of cap and core (hereafter called asymmetric Bloch wall, ABW) can be
 3 transformed through the switching of cap and core within the ABW.^{34,37} Images in Figs. 1(c)
 4 and 1(d) show ABWs with a cap switch and with both cap and core switches, respectively.
 5 Within the ABW in Fig. 1(i), at the point where cap switching occurs as indicated in cross-
 6 section images, the vortex and antivortex with $p = +1$ are generated on the top and bottom
 7 surfaces of the element, respectively. In the ABW in Fig. 1(j), the antivortex and vortex are
 8 generated at the kink as seen in the ABW in Fig. 1(i). However, the vortex cores connected
 9 by the ABW segment on the right side of the kink have $p = -1$ due to the core switch. The
 10 cap and core switches along with the switching of rotational sense of flux-closure domains
 11 are identified in MTXM images in Figs. 1(b)-1(d). The results in Figs. 1(i) and 1(j) show that
 12 V-AV structures can be established through cap and core switches in the rectangular elements
 13 where the magnetization is not uniform along the thickness direction. More interestingly, we
 14 found that topological charges of V-AV structures (q_{V-AV}) indicated by green boxes in Figs.
 15 1(i) and 1(j) are different. The q_{V-AV} of V-AV structure (hereafter, called V-AV _{$q=0$} structure) in
 16 Fig. 1(i) is zero ($q_V = -1/2$ and $q_{AV} = +1/2$), which is topologically trivial, while the V-AV
 17 structure (hereafter, called V-AV _{$q=-1$} structure) in Fig. 1(j) is not topologically trivial as it is
 18 characterized by $q_{V-AV} = -1$ ($q_V = -1/2$ and $q_{AV} = +1/2$) (supplementary material: B). That is,
 19 those two V-AV structures stably established in Ni₈₀Fe₂₀ rectangular elements are

topologically different. The 3D magnetic elements, 100 nm-thick $\text{Ni}_{80}\text{Fe}_{20}$ rectangular elements, can stabilize two topologically different V-AV structures.

We investigated the physical behavior of those topologically different V-AV structures by applying external magnetic fields (Fig. 2). MTXM images in Fig. 2(a) show that the vortex and the antivortex get close to each other with increasing the field from $H_y = 0$ mT to $H_y = 10$ mT. At $H_y = 12$ mT, the antivortex generated by the cap switch disappears together with the vortex, which is identified by the straight ABW that remains without the kink. The simulation result in Fig. 2(b) also shows the annihilation of the $\text{V-AV}_{q=0}$ structure as observed in MTXM images. The detailed annihilation process of the $\text{V-AV}_{q=0}$ structure is illustrated in Fig. 2(c). On the bottom surface of the rectangular element, the vortex with $q_V = -1/2$ moves toward the antivortex with $q_{AV} = +1/2$ as the magnetic field increases. Once the antivortex with $q_{AV} = +1/2$ and the vortex with $q_V = -1/2$ on the bottom surface of the rectangular element get close enough, the two merge and disappear. The annihilation of $\text{V-AV}_{q=0}$ structure is topologically trivial process. The annihilation can be considered as continuous transformation of $\text{V-AV}_{q=0}$ structure into another topologically trivial magnetic structure with $q = 0$ in the same homotopy class. There is no energy barrier associated with the topology to overcome for the $\text{V-AV}_{q=0}$ structure to be annihilated. It explains why the $\text{V-AV}_{q=0}$ structure can be easily annihilated.

To investigate the stability of topologically non-trivial V-AV structure, we

1 performed the same type of measurement for the V-AV _{$q=-1$} structure as shown in Fig. 1(d).
 2 The antivortex and the vortex get closer to each other with increasing the magnetic field as
 3 observed in the V-AV _{$q=0$} structure. However, unlike the V-AV _{$q=0$} structure, the antivortex
 4 generated through both cap and core switches remains stable along with the vortex without
 5 their annihilations even they get very close. This behavior was also confirmed by
 6 micromagnetic simulations (Figs. 3(b) and 3(c)). Figure 3(c) illustrates the detailed 3D
 7 magnetic configurations of the V-AV _{$q=-1$} structures at $H_x = 2$ mT and $H_x = 7$ mT marked by
 8 the yellow dashed boxes in Fig. 3(b). The antivortex with $q_{AV} = -1/2$ moves toward the
 9 vortex with $q_V = -1/2$ on the top surface of the rectangular element with increasing the field
 10 to $H_x = 7$ mT. The antivortex structure and vortex structure are not annihilated even if they
 11 get very close, and the V-AV _{$q=-1$} structure on the top surface of the rectangular element
 12 remains stable (green box in Fig.3(c)). By further micromagnetic simulations for the field-
 13 driven behavior of the two structures performed in an identical rectangular element under the
 14 magnetic field applied to the same direction, it was confirmed that the V-AV _{$q=0$} structure is
 15 indeed annihilated at $H_x = 4.3$ mT and $H_y = 10$ mT while the V-AV _{$q=-1$} structure stays strong
 16 without its annihilation even at high magnetic fields of $H_x = 8$ mT and $H_y = 14$ mT, which
 17 quantitatively supports the higher stability of topologically non-trivial V-AV structure
 18 (supplementary material: C). From the simulations, we also found that the overall field-driven
 19 motions of the V-AV structures are the same regardless of the field direction. The magnetic

1 fields push the antivortex and the vortex structure toward each other, resulting in the
 2 antivortex and the vortex becoming closer until they annihilate. However, when the magnetic
 3 field is applied to the x -axis, the $V\text{-}AV_{q=0}$ structure is annihilated at a much lower field ($H_x =$
 4 4.3 mT) than when the magnetic field is applied to the y -axis ($H_y = 10$ mT). The shape
 5 anisotropy might make the $V\text{-}AV$ structure more perturbed when the magnetic field is applied
 6 in the x -axis. It is expected that the $V\text{-}AV_{q=0}$ structure is annihilated under the magnetic field
 7 applied in the x -axis lower than $H_x = 7$ mT in experiments. The results in Fig. 3 support that
 8 the annihilation of the topologically non-trivial $V\text{-}AV$ structure does not occur easily, and
 9 that the $V\text{-}AV_{q=-1}$ structure is more stable than the $V\text{-}AV_{q=0}$ structure. The higher stability of
 10 the topologically non-trivial $V\text{-}AV$ structure could be understood from topologically
 11 perspective. The transformation of the $V\text{-}AV_{q=-1}$ structure into a topologically trivial structure
 12 with $q = 0$ is difficult to happen because the topologically non-trivial $V\text{-}AV$ structure must
 13 overcome a high energy barrier dictated by topology to be converted into a topologically
 14 trivial magnetic structure.

15 For a clearer interpretation of the higher stability of $V\text{-}AV_{q=-1}$ structure compared to
 16 the $V\text{-}AV_{q=0}$ structure, we investigated the annihilation process of the $V\text{-}AV_{q=-1}$ structure by
 17 applying higher magnetic field (Fig. 4). We observed that the annihilation of the $V\text{-}AV_{q=-1}$
 18 structure happens at $H_y = 19$ mT (Figs. 4(a) and 4(b)). Interestingly, the annihilation of the $V\text{-}$
 19 $AV_{q=-1}$ structure is achieved through the injection of a magnetic singularity called Bloch

point, the vanishing point of local magnetization ($m_x = m_y = m_z = 0$) (Fig. 4(a)).³⁷⁻⁴² The Bloch point injection is revealed in the change of magnetic contrasts around the kinked area (Fig. 4(b)). The vertical boundary between upward and downward ABWs at $H_y = 18.9$ mT changes to the diagonal boundary at $H_y = 19$ mT. A Bloch point is injected from the top surface of the rectangular element where the V-AV _{$q=-1$} structure is present (Fig. 4(c)). Simultaneously, V-AV _{$q=-1$} structure is annihilated. Then, the Bloch point is stabilized in the middle part of the rectangular element. The results in Fig. 4 show that the annihilation of V-AV _{$q=-1$} structure can occur when a strong external perturbation such as a magnetic field enough to trigger the injection of the Bloch point, is applied (supplementary material: D). The annihilation mechanism of the topologically non-trivial V-AV structure involving Bloch point is clearly distinguished from that of the topologically trivial V-AV structure.

In summary, we directly observe V-AV structures with different topologies stably formed in Ni₈₀Fe₂₀ rectangular elements, where intriguing 3D magnetic structures with non-uniform magnetization along the thickness direction are created, utilizing MTXM measurements, and comprehensively understand their 3D magnetic configurations using micromagnetic simulations. We find that the topologically trivial V-AV structure is easily annihilated during its field-driven motion while the topologically non-trivial V-AV structure stays stable without its annihilation. Our results show that the topologically non-trivial V-AV structure has higher stability than the topologically trivial V-AV structure. We demonstrate

1 that the annihilation of the topologically non-trivial V-AV structure can be achieved only
2 through the injection of the Bloch point and this is responsible for the higher stability of
3 topologically non-trivial V-AV structure. This work provides fundamental scientific insight
4 into the stability of V-AV structures dictated by topology, which is also highly relevant to the
5 technological applications of topological magnetic structures.

1 **SUPPLEMENTARY MATERIALS**

2 See supplementary material for the details of MTXM measurements and
3 micromagnetic simulations, the detailed description to calculate the topological charge of V-
4 AV structures, the additional micromagnetic simulation results for the stability of V-AV
5 structures with different topologies, and the discussion of the stability of V-AV structures in
6 the topological and energetic perspective.

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1 DATA AVAILABILITY

2 The data that support the findings of this study are available from the corresponding
3 author upon reasonable request.

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1 FIGURE CAPTIONS

2 FIG. 1. (a) Schematic diagram of magnetic imaging utilizing magnetic transmission soft X-
3 ray microscopy (MTXM). (b)-(g) Out-of-plane magnetic structures in various $\text{Ni}_{80}\text{Fe}_{20}$
4 rectangular-patterned elements observed by (b)-(d) MTXM measurements and (e)-(g)
5 micromagnetic simulations with consideration of magnetic grains. The black and white
6 contrasts in (b)-(g) indicate the upward and downward out-of-plane (OOP) magnetic
7 components, respectively. The zoomed images for detailed magnetic configurations near the
8 kinked area of domain walls are inserted. The red and blue dotted lines represent domain wall
9 segments with upward and downward magnetizations, respectively. (h)-(j) Three-dimensional
10 illustrations of magnetic structures in the yellow dotted boxes of (b)-(g). The red and blue
11 colors represent volumes with the normalized magnetizations of with $m_z \geq +0.8$ and $m_z \leq$
12 -0.8 , respectively. The black streamlines with arrows indicate the direction of the in-plane
13 magnetization. The cross-section images of magnetic configurations on the plane at the center
14 of element ($x = 0$) in (h) and on the planes at $x = -120$ nm and $x = +120$ nm in (i) and (j) are
15 added.

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17 FIG. 2. Field-driven motion of the $\text{V-AV}_{q=0}$ structure observed by (a) MTXM measurements
18 and (b) micromagnetic simulations with consideration of magnetic grains. The magnetic field
19 was applied in y -axis. The black and white contrasts indicate the upward and downward
20 magnetic components, respectively. In (a) and (b), the vortex and antivortex constituting the
21 vortex-antivortex structure together are indicated by V and AV, respectively. (c) The
22 annihilation process of $\text{V-AV}_{q=0}$ structure (yellow dotted boxes in (b)) and the internal

magnetic configuration of the structure during the process are illustrated. q_V , q_{AV} and q_{V-AV} indicate q of the vortex, antivortex, and V-AV _{$q=0$} structure, respectively.

FIG. 3. Field-driven motion of the V-AV _{$q=-1$} structure observed by (a) MTXM measurements and (b) micromagnetic simulations with consideration of magnetic grains. The magnetic field was applied in x -axis. The black and white contrasts indicate the upward and downward magnetic components, respectively. (c) The internal magnetic configurations of the vortex and antivortex structures at $H_x = 2$ mT and $H_x = 7$ mT are illustrated. q_V , q_{AV} and q_{V-AV} indicate q of the vortex, antivortex, and V-AV structure, respectively.

FIG. 4. (a) Three-dimensional illustration of the annihilation of the V-AV _{$q=-1$} structure by applying the magnetic field in y -axis, and (b) their out-of-plane magnetic structure where the black and white contrasts indicate upward and downward magnetic components, respectively. q_{V-AV} indicates the q of the V-AV structure. (c) The annihilation process of the V-AV _{$q=-1$} structure by the injection of the Bloch point. The green sphere in (a) and (c), represents the Bloch point. Transparency indicates sequential order of the V-AV _{$q=-1$} annihilation.

1 **FIGURE**

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4