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1 Manipulation of Magnetic Monopole Injection for the Topological Transition

2
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1 Abstract

2 **Manipulating topological properties of spin textures in magnetic materials is of**
3 **great interest due to their rich physics and promising technological applications in**
4 **advanced electronic devices. A spin texture with desired topological properties can be**
5 **created by magnetic monopole injection resulting in the topological transitions**
6 **involving the change of topological charges. Therefore, controlling the magnetic**
7 **monopole injection is of paramount importance to obtaining desired spin textures, but**
8 **has not yet been reported. Here, we report reliably manipulated magnetic monopole**
9 **injection in the topological transition from stripe domains to skyrmions in Fe/Gd**
10 **multilayer. We reveal that an easily tunable in-plane magnetic field applied to Fe/Gd**
11 **multilayer plays a key role in the magnetic monopole injection by modulating the local**
12 **exchange energy. Our findings pave the way for efficient management of topological**
13 **transition by providing an important stepping-stone for controlling the magnetic**
14 **monopole injection.**

1 The spin textures such as skyrmions are classified by the non-zero topological charge

2 $Q = 1/4\pi \iint m \cdot \left(\frac{\partial m}{\partial x} \times \frac{\partial m}{\partial y} \right) d^2 r^{1,2}$. In a topology argument, a continuous transformation

3 between topologically distinct spin textures with different Q is not allowed, so spin textures

4 with $Q \neq 0$ have high stability in magnetic medium despite of their tiny size³⁻⁶. Due to the

5 topology-associated intriguing physical behaviors and unique features of spin textures with Q

6 $\neq 0$, such as skyrmion Hall effects^{7,8} and topological protection³⁻⁶, the topological transition

7 from topologically trivial spin textures ($Q = 0$) to non-trivial ones ($Q \neq 0$) has not only

8 attracted significant scientific interests, but also been considered to be important in the

9 development of advanced spin-based electronic devices such as memory, logic, and bio-

10 inspired computing devices⁹⁻¹².

11 The topological transition can occur by discontinuous deformation of the

12 magnetization configuration^{1,13,14}. Magnetic monopole (MP)-mediated topological transition is

13 a representative example. MP is the topological magnetic singularity with $|Q| = 1$ at which the

14 local magnetization vanishes, called Bloch point¹⁵⁻²¹. MP has been the key to elucidating

15 various topological transitions in nanomagnetism²²⁻²⁴. For instance, MP is responsible for the

16 topological transition from the vortex-antivortex pair characterized by $|Q| = 1$ to the

17 topologically trivial state of $|Q| = 0$ ²⁵⁻²⁸. The vortex-antivortex pair is annihilated through the

18 injection of MP from the surface of a magnetic medium, and thus $|Q|$ of the total system is

1 changed from $|Q| = 1$ to $|Q| = 0$. MP injection also plays an essential role in the merging of
2 two skyrmions ($|Q| \neq 0$) into the stripe domain ($|Q| = 0$) or breaking the stripe domain ($|Q| =$
3 0) into multiple skyrmions ($|Q| \neq 0$)^{29,30}.

4 Despite of the central importance of MP in topological transitions, an efficient means
5 of injecting MP in a controlled manner has not been addressed yet. In addition, the
6 mechanism for topological transition associated with MP injection and relevant physics have
7 not been comprehensively understood. Here, we demonstrate a simple yet robust method for
8 the controlled MP injection that efficiently triggers the topological transition from the stripe
9 domains with $Q = 0$ to the skyrmions with $|Q| = 1$ in $[\text{Fe}(0.34 \text{ nm})/\text{Gd}(0.4 \text{ nm})]_{120}$
10 ferrimagnetic multilayer film (hereafter, Fe/Gd multilayer). We reveal that the slight in-plane
11 magnetic field results in an intense concentration of local exchange energy, boosting the
12 easier MP injection. The Fe/Gd multilayer was chosen based on the fact that this material
13 hosts different types of spin textures: topologically trivial stripe domains and magnetic
14 bubbles (hereafter, bubbles) as well as topologically non-trivial skyrmions stabilized by
15 **dipole-dipole interactions** without Dzyaloshinskii-Moriya interaction (DMI)^{6,31-34}.

16 Figure 1 shows illustrations of representative spin textures in Fe/Gd multilayer: stripe
17 domains, bubble, and skyrmion. The stripe domains are topologically trivial, thus $Q = 0$ (Fig.
18 1a). It has been reported that, by applying external stimuli such as electrical currents or
19 magnetic fields, the stripe domains can be transformed into dot-like spin textures^{6,29-32,35-38}:

1 bubble (Figure 1b) or skyrmion (Figure 1c). The bubble has two Bloch lines (BLs), denoted
2 by red and blue arrows, in the boundary between bubble core and outer domain (hereafter,
3 boundary of the bubble). Topologically, like stripe domains, Q of the bubble is zero. In
4 contrast, the skyrmion is a chiral spin texture characterized by $|Q| = 1$. It should be noted that
5 the structural inversion symmetry is only broken on the top and bottom surfaces of Fe/Gd
6 multilayers, but its contribution to emergence of DMI is negligibly small due to its significant
7 thickness close to 90 nm^{32,34,39}. Instead of DMI, the dipole-dipole interaction arising from the
8 significant thickness of Fe/Gd multilayers can stabilize the skyrmion in Fe/Gd multilayers³¹⁻³⁴.
9 As seen in Fig. 1b and c, the shapes of bubble and skyrmion created in Fe/Gd multilayer are
10 distinguishable^{6,33-36}. We confirmed that, in Fe/Gd multilayer, the elliptical and circular-
11 shaped spin textures are bubbles and skyrmions, respectively by micromagnetic simulations.
12 Additionally, we confirmed that the annihilation fields of circular-shaped spin textures are
13 greater than those of elliptical-shaped spin textures by experiments and micromagnetic
14 simulation, supporting that bubbles and skyrmions are in elliptical and circular shapes,
15 respectively. Additionally, we confirmed that the magnetization configuration of the
16 elliptical- and circular-shaped spin textures are bubbles and skyrmions. Although it is
17 reported that the elliptical skyrmion can be stably formed under anisotropic DMI and
18 perpendicular magnetic anisotropy (PMA)⁴⁰, the elliptical-shaped spin textures correspond to
19 bubbles in our work since DMI is negligibly small and PMA is isotropic in our Fe/Gd

1 **multilayers.** The transition from stripe domains to bubbles, where the Q remains unchanged,
2 is a topologically trivial process. It can be achieved through the continuous transformation of
3 the magnetization configuration in the same homotopy class^{1,14}. On the other hand, the
4 skyrmion is a chiral spin texture characterized by $|Q| = 1$. Therefore, the transition from stripe
5 domains to skyrmions is the topological transition where Q of the entire system changes from
6 $|Q| = 0$ to $|Q| = 1$.

7 For an in-depth understanding of the topological transition, we experimentally
8 realized the process of the transition from stripe domains to skyrmions. The initial stripe
9 domains were set by applying a saturation magnetic field of $\mathbf{H} = -0.3$ mT, i.e., downward
10 out-of-plane magnetic fields, and then reducing the magnetic field to zero. Considering a
11 previous report predicting the contribution of the IP magnetic field component to skyrmion
12 generation^{6,38,41}, we applied magnetic fields slightly tilted by $\theta = 1^\circ$ with respect to the film
13 normal direction as schematically illustrated in Fig. 2a. In this geometry, due to the tilting
14 angle of magnetic fields with respect to the z -axis, a slight magnetic field is also applied to the
15 film plane, i.e., in-plane (IP) magnetic field. Figure 2b shows the spin textures observed by
16 the magnetic transmission soft X-ray microscopy (MTXM) with increasing \mathbf{H} . **All MTXM**
17 **images are taken at room temperature.** The black and white contrasts in MTXM images
18 represent downward and upward magnetizations, respectively. As \mathbf{H} increases from 0 mT to
19 162 mT, the stripe domains are transitioned into circular-shaped skyrmions. As shown in Fig. 1,

1 the circular-shaped skyrmions can be distinguished from bubbles, which are elliptical-
2 shaped^{16,35,36}. As \mathbf{H} increases further to 223 mT, skyrmions are reduced in size, but all
3 skyrmions remain without annihilation. This indicates the high stability of skyrmions ensured
4 by the non-trivial topology of skyrmions. Figures 2c and 2d show three-dimensional
5 magnetization configurations of simulated stripe domains and skyrmion, respectively. The
6 transparent gray surfaces indicate the isosurfaces for $m_z = 0$, which indicates the boundary
7 between upward and downward magnetizations. In the stripe domains (Fig. 2c), the flux-
8 closure domain structures are created with respect to the domain walls to reduce the
9 demagnetization energy (Supplementary information 1), which makes the domain walls on
10 the top and bottom surfaces of the film become right- and left-handed Néel walls,
11 respectively. Interestingly, however, in the middle region of the film, Bloch walls where the
12 magnetizations are oriented towards the x -axis are generated to avoid the high exchange
13 energy in the region. In the stripe domain created by applying magnetic fields with the tilting
14 angle of 1° with respect to the z -axis, magnetizations of domain walls in the middle region of
15 the film are found to be aligned in the $-x$ -direction, as seen in Fig. 2c. For the skyrmion (Fig.
16 2d), the flux-closure domain structures leads to the Néel configurations on top and bottom
17 surfaces with opposite chirality, while the middle region of the film shows the Bloch
18 configuration (Supplementary information 1).

1 The mechanism of the experimentally observed topological transition from stripe
2 domains to skyrmions was investigated in detail using micromagnetic simulations (Figure 3a
3 and Supplementary Movie 1). The initial stripe domain starts breaking as \mathbf{H} increases.
4 However, we found that the stripe domain is not directly transformed into the skyrmion.
5 Surprisingly, the bubble with two BLs, indicated by blue and red arrows, transiently appears
6 immediately after the stripe domain breaks (snapshot at $t = 2.45$ ns). The magnetizations at
7 the blue and red BLs are aligned in the same $-x$ direction as those of domain walls in the
8 stripe domain. It is worth noting that the magnetization configurations around the two BLs
9 are different on the top and bottom surfaces. On the top surface, the spatial variation of the
10 magnetization around the red BL is more drastic than the magnetizations around the blue BL.
11 On the other hand, on the bottom surface, the magnetizations around the blue BL are spatially
12 more inhomogeneous than the magnetizations around the red BL. We found that the
13 difference between magnetizations around the red and blue BLs on the top and bottom
14 surfaces is closely associated with the dipole-dipole interactions (Supplementary information
15 2). Once the bubble is formed, however, two MPs, denoted by blue and red spheres, are
16 injected at the BLs with drastically varying magnetization (i.e., the red BL on the top surface
17 and the blue BL on the bottom surface). By the injection of the MPs, which involves the
18 annihilation of the red BL on the top surface and the blue BL on the bottom surface, the
19 magnetization configurations on the top and bottom surfaces are changed to that of the

1 skyrmion as depicted in the 2D schematic images of the snapshot at $t = 2.60$ ns. It was found
2 that the MPs injected from the top and bottom surfaces have convergent and divergent
3 magnetization configurations, which are topologically characterized by $Q_{\text{Top}}^{\text{MP}} = -1$ and $Q_{\text{Bot}}^{\text{MP}} =$
4 $+1$, respectively. The injected MPs propagate through **the boundary of the bubble** as indicated
5 by **cyan** and **magenta** lines (snapshot at $t = 5.10$ ns). When the MPs reach the middle region
6 of the film, they start moving towards each other in the middle **region** of the film (snapshot at
7 $t = 5.68$ ns). The movement of the MPs is accompanied by the magnetization switching that
8 converts magnetizations in the **boundary** of the bubble to those of the skyrmion in the middle
9 region of the film. **The micromagnetic simulation results for the detailed magnetization**
10 **switching process in the middle region of the film are illustrated in Supplementary**
11 **information 3**. Interestingly, despite of non-trivial topology of MPs, when the MPs collide
12 with each other, the MPs are annihilated together, completing the topological transition from
13 the stripe domain to the skyrmion (snapshot at $t = 6$ ns). Since two MPs have opposite
14 topological charges ($Q_{\text{Bot}}^{\text{MP}} + Q_{\text{Top}}^{\text{MP}} = 0$), the pair annihilation of MPs is a topologically trivial
15 process as shown in Fig. 3b. The results in Fig. 3 clearly show that the topological transition
16 from the stripe domain to the skyrmion is achieved through the sequential processes of the
17 injection, propagation, and pair annihilation of MPs.

18 From extensive micromagnetic simulations with various configurations of applying
19 magnetic fields, we found that the topological transition from stripe domains to skyrmions is

1 most reliably achieved when the magnetic field slightly tilted along the $+x$ -axis was applied
2 than when only the magnetic field was applied along the $+z$ -axis (Supplementary information
3 4) as was done in the experiments shown in Fig. 2. It indicates that the IP magnetic field
4 induced by applying the magnetic fields at an angle tilted by 1° toward the $+x$ -axis (Fig. 2a)
5 might be a key to manipulating the MP injection. Indeed, the IP magnetic field has been
6 discussed as playing an important role in generating skyrmions and having a decisive
7 influence on the shape of spin textures^{6,41-43}.

8 To clearly verify the role of the IP magnetic field in the MP injection, we examined
9 the transition from the bubble to the skyrmion by directly applying a magnetic field, H_x , along
10 the film plane (x -direction). To stably form the bubble in magnetic medium, we applied the
11 out-of-plane magnetic field of $H_z = 280$ mT. Under the fixed H_z , the IP magnetic fields
12 increases from $H_x = -20$ mT. Figure 4a shows the magnetization configurations of the bubble
13 (snapshots at $H_x = -20$ mT, 0 mT, and 1.4 mT) and skyrmion (snapshot at $H_x = 1.5$ mT),
14 along with the exchange energy density of these configurations (Fig. 4b). Here, the
15 magnetization at the BL in the bubble is also aligned in the $-x$ -direction. When the IP
16 magnetic field increases from $H_x = -20$ mT to $H_x = 0$ mT, the magnetizations at the BLs
17 become more inhomogeneous (snapshot at $H_x = 0$ mT). As a result, the corresponding
18 exchange energy become much higher at the red BL on the top surface and the blue BL on
19 the bottom surface. When the IP magnetic field is applied in the $+x$ -direction, opposite to the

1 magnetization at the BLs, and increased to 1.4 mT, the exchange energy at those BLs
2 increases significantly (snapshot at $H_x = 1.4$ mT) because of the drastic spatial inhomogeneity
3 of the magnetizations at those BLs. A further increase of H_x to 1.5 mT finally leads to the
4 transition from the bubble to the skyrmion with relaxing the exchange energy. In the
5 transition process, MPs are injected from the surfaces while annihilating BLs. It is interpreted
6 that the exchange energy at the BLs is converted into energy for the injection of MP to reduce
7 the total energy of the system²². The results in Fig. 4 clearly confirm that the IP magnetic field
8 triggers MP injection by concentrating the local exchange energy at the BLs. Additionally,
9 Figure 4 shows that a certain strength of the IP magnetic field, $H_x = 1.5$ mT, is required for
10 MP injection, suggesting that the MP injection can be manipulated by adjusting the strength
11 of the IP magnetic fields.

12 To experimentally confirm if the MP injection is controllable by varying the strength
13 of the IP magnetic field, we applied magnetic fields tilted toward the $+x$ -axis with various θ to
14 manipulate the strength of IP magnetic field and observed spin textures (Fig. 2a). The θ is
15 varied from 1° to 10° in the step of 1° (Supplementary information 5). Figure 5a shows spin
16 textures observed at $\mathbf{H} = 0$ mT, 162 mT, and 206 mT with $\theta = 1^\circ, 3^\circ, 5^\circ, 7^\circ,$ and 9° . The H_x
17 corresponds to the strength of IP magnetic fields induced by \mathbf{H} with θ . We observed that the
18 stripe domains break into dot-like spin textures at $\mathbf{H} = 162$ mT. It can be seen that some of
19 the dot-like spin textures at $\mathbf{H} = 162$ mT are circular-shaped skyrmions, while others are

1 elliptical-shaped bubbles (for example, $\theta = 7^\circ$ and 9°). As \mathbf{H} increases to 206 mT, the
2 topologically protected circular-shaped skyrmions remain stable while the elliptical-shaped
3 bubbles are annihilated, which supports the higher stability of skyrmions than that of bubble.
4 The experimentally observed differences in the annihilation fields of skyrmion and bubble
5 were also confirmed by micromagnetic simulations (Supplementary information 6).
6 Remarkably, the populations of skyrmions and bubbles are strongly dependent on the θ ,
7 which can be determined by counting the number of dot-like spin textures remaining at $\mathbf{H} =$
8 206 mT. At $\theta = 1^\circ$, one can find that only skyrmions are formed, whereas only bubbles are
9 formed at $\theta \geq 7^\circ$, as can be seen with no remaining spin texture. Note that the circular-
10 shaped structures at $\theta = 7^\circ$ and 9° and at $\mathbf{H} = 206$ mT were confirmed to be defects
11 (Supplementary information 7). At $1^\circ < \theta < 7^\circ$, the skyrmions and bubbles coexist, and as θ
12 increases, the population of skyrmions decreases while the population of bubbles increases.
13 The results in Fig. 5a show that the topological transition from stripe domains into skyrmions
14 occurs only at weak IP magnetic fields ($\theta = 1^\circ$ and $H_x = 2.83$ mT), which implies that MP
15 injection is triggered when the applied IP magnetic field is relatively weak ($\theta = 1^\circ$ and $H_x =$
16 2.83 mT), but is hindered when the strong IP magnetic field ($\theta > 7^\circ$ and $H_x > 19.7$ mT) is
17 applied.

18 To understand the MP injection that occurs as a function of the strength of the IP
19 magnetic field, we investigated the process by which the stripe domain is converted into the

1 bubble in detail. Figures 5b and 5c illustrate the magnetization process in which the stripe
2 domain converts to the transient bubble at $\theta = 1^\circ$ and $\theta = 9^\circ$, respectively. By applying the
3 magnetic field at $\theta = 1^\circ$, the magnetizations of domain walls in the stripe domain on the top
4 and bottom surfaces are tilted into $-x$ -direction along with the ones in the middle region of
5 the film. The magnetization direction of domain walls and that at the BLs in the transient
6 bubble remains the same in the $-x$ -direction. On the other hand, with the applied magnetic
7 field at $\theta = 9^\circ$, due to a relatively strong IP magnetic field induced, the magnetizations of
8 domain walls in the stripe domain on the top and bottom surfaces and in the middle region of
9 the film are flipped from the $-x$ -direction into the $+x$ -direction. As a result, in the transient
10 bubble formed at $\theta = 9^\circ$, the magnetizations **in the boundary** and BLs in the transient bubble
11 are aligned in the $+x$ -direction. Since the magnetization at the BLs in the transient bubble
12 formed at $\theta = 1^\circ$ is aligned in the $-x$ -direction, opposite to the direction of the IP magnetic
13 field ($+x$ -direction), the exchange energy at BLs in the bubble is highly localized and
14 increased with increasing the IP magnetic field, and thus MP injection is triggered at the BLs,
15 as described in Fig. 4. However, the magnetization at the BLs in the transient bubble formed
16 at $\theta = 9^\circ$ is parallel to the direction of the IP magnetic field ($+x$ -direction). Therefore, the
17 applied IP magnetic field reduces the exchange energy at the BLs, unlike the case of $\theta = 1^\circ$,
18 and thus the bubble is stabilized as the final spin texture without MP injection. The
19 experimental results in Fig. 5 strongly support that MP injection can be effectively and

1 simply controlled by adjusting the tilting angle of applied magnetic field, i.e., the strength of
2 IP magnetic fields.

3 In summary, we report a well-manipulated injection of MPs leading to the topological
4 transition from the stripe domain to skyrmion by applying a slightly tilted magnetic field to
5 the film surface of Fe/Gd multilayer. The mechanism of MP injection during the topological
6 transition was thoroughly understood, and it was found that the MP injection strongly
7 depends on the strength of the IP magnetic field. We experimentally demonstrate that MP
8 injection can be effectively controlled by engineering IP magnetic fields in Fe/Gd multilayer.
9 Our findings on the controllable MP injection can be extended to manipulating and
10 understanding the topological transition between various topological spin textures.

1 **Methods**

2 **Sample fabrication.**

3 The [Fe(0.34 nm)/Gd(0.4 nm)]₁₂₀ ferrimagnetic multilayer film were fabricated by
4 magnetron sputtering. 0.34 nm-thick Fe and 0.4 nm-thick Gd layers were alternately
5 deposited on 100 nm-thick X-ray transparent Si₃N₄ membrane substrate.

6

7 **X-ray imaging technique.**

8 The magnetic components in the [Fe(0.34 nm)/Gd(0.4 nm)]₁₂₀ ferrimagnetic
9 multilayer film were directly observed by utilizing full-field magnetic transmission X-ray
10 microscopy (MTXM) at the beamline 6.1.2 in the Advanced Light Source (ALS)⁴⁴. Out-of-
11 plane magnetic components were imaged at the Fe L₃ X-ray absorption edge (708 eV). All
12 MTXM measurements were performed at room temperature. To apply the IP magnetic field,
13 the sample holder was tilted with respect to the out-of-plane magnetic field.

14

15 **Micromagnetic simulation.**

16 To specify the detailed magnetization configurations in the Fe/Gd multilayer film, we
17 performed the micromagnetic simulation utilizing MuMax³ code, and typical material
18 parameters of Fe/Gd multilayer films were used, i.e., a saturation magnetization $M_s = 400$ kA/
19 m, an exchange stiffness $A_{ex} = 5$ pJ/m, a uniaxial anisotropy $K_u = 40$ kJ/m³. We solved
20 numerically the Landau-Lifshitz-Gilbert (LLG) equation:
21 $\partial \mathbf{M} / \partial t = -\gamma_0 (\mathbf{M} \times \mathbf{H}_{eff}) + (\alpha / |\mathbf{M}|) (\mathbf{M} \times \partial \mathbf{M} / \partial t)$ with the local magnetization vector \mathbf{M} , the
22 gyromagnetic ratio γ_0 , the effective field \mathbf{H}_{eff} , and the phenomenological damping constant α
23 using MuMax³ code⁴⁵⁻⁴⁷. To study the MP injection process, we carried out the quasistatic

1 calculation where the precessional effects are excluded, the damping constant α was set to
2 0.5. We used a $300 \times 300 \times 100 \text{ nm}^3$ films with periodic boundary conditions.
3 **Data availability.** The data that support the findings of this study are available from the
4 corresponding author upon reasonable request.

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12

13 **Author Contributions**

14 H.-S.H., S.-G.J., K.-S.L. M.-Y.I. designed and planned the research. H.-S.H., S.-G.J., W.C.,
15 M.-Y.I. carried out magnetic transmission soft x-ray microscopy experiments. S.A.M., E.E.F.
16 prepared the samples. H.-S.H., S.-G.J. analyzed data. H.-S. H. carried out the micromagnetic
17 simulations. H.-S.H., S.-G.J., M.-Y.I., K.-S.L. prepared the manuscript, which incorporates
18 critical input from all authors.

19

20 **Competing financial interests**

21 The authors declare no competing financial interests.

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1 **Figure legends**

2 **Figure 1. Representative spin textures in Fe/Gd multilayer.** (a) Magnetization
3 configurations of the topologically trivial stripe domain (a), bubble (b), and topologically
4 non-trivial skyrmion (c). The changes of the topological charges Q of spin textures are
5 inserted as the stripe domains are transited to the bubble and skyrmion, respectively.

6

7 **Figure 2. The topological transition from stripe domains to skyrmions.** (a) Schematic
8 illustration of the model system applying the magnetic field tilted by θ with respect to the z -
9 axis. (b) The spin textures are observed by MTXM as increasing \mathbf{H} at $\theta = 1^\circ$ (scale bars: 500
10 nm). (c,d) The three-dimensional illustrations of the stripe domain (c) and skyrmion (d) with
11 schematic images of the magnetization configurations on the top surface, middle region, and
12 bottom surface of films. The transparent gray surfaces indicate the boundary between upward
13 and downward magnetizations, corresponding to the isosurfaces for $m_z = 0$.

14

15 **Figure 3. The MP injection in the topological transition.** (a) The process of the topological
16 transition from the stripe domain to the skyrmion at $\theta = 1^\circ$ (scale bar: 30 nm). The schematic
17 images of the magnetization configurations on the top surface, middle region, and bottom
18 surface of films are inserted below the three-dimensional illustration of the magnetization
19 configurations. The red and blue arrows indicate the BLs in the bubble. The red and blue
20 spheres indicate the MPs injected from the bottom and top surfaces, which are topologically
21 characterized by $Q_{\text{Top}}^{\text{MP}} = -1$ and $Q_{\text{Bot}}^{\text{MP}} = +1$, respectively. The trajectories of red and blue MPs
22 are denoted by magenta and cyan lines, respectively. (b) The schematic illustrations of the
23 pair annihilation of the injected MPs.

1

2 **Figure 4. The role of IP magnetic fields in MP injection.** (a-b) The magnetization
3 configuration of the spin texture (a) and exchange energy density ($E_{exch. dens.}$) (b) under
4 perpendicular magnetic fields of $H_z = 280$ mT as sweeping the IP magnetic field of H_x from
5 -20 mT to 1.5 mT (scale bars: 30 nm). The schematic images describing the magnetization
6 configuration on the top and bottom surfaces were inserted below the three-dimensional
7 illustration of the spin textures. The red and blue arrows indicate the BLs. The green dashed
8 boxes indicate the BLs having relatively large inhomogeneous magnetizations.

9

10 **Figure 5. Manipulating the MP injection by IP magnetic fields.** (a) The transitions from
11 stripe domains to dot-like spin textures, skyrmions and bubbles, are observed by MTXM with
12 varying θ as increasing \mathbf{H} (scale bars: 500 nm). (b-c) Three-dimensional illustration of the
13 transition from the stripe domains to the transient bubble at $\theta = 1^\circ$ and $\theta = 9^\circ$ (scale bar: 30
14 nm). The strengths of the applied IP magnetic fields, H_x , are inserted.