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Manipulation of Magnetic Monopole Injection for the Topological Transition

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Abstract

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

The spin textures such as skyrmions are classified by the non-zero topological charge $Q = 1/4\pi \iint m \cdot \left(\frac{\partial m}{\partial x} \times \frac{\partial m}{\partial y}\right) d^2r$[1,2]. In a topology argument, a continuous transformation between topologically distinct spin textures with different Q is not allowed, so spin textures with $Q \neq 0$ have high stability in magnetic medium despite of their tiny size[3-6]. Due to the topology-associated intriguing physical behaviors and unique features of spin textures with $Q \neq 0$, such as skyrmion Hall effects[7,8] and topological protection[3-6], the topological transition from topologically trivial spin textures ($Q = 0$) to non-trivial ones ($Q \neq 0$) has not only attracted significant scientific interests, but also been considered to be important in the development of advanced spin-based electronic devices such as memory, logic, and bio-inspired computing devices[9-12].

The topological transition can occur by discontinuous deformation of the magnetization configuration[1,13,14]. Magnetic monopole (MP)-mediated topological transition is a representative example. MP is the topological magnetic singularity with $|Q| = 1$ at which the local magnetization vanishes, called Bloch point[15-21]. MP has been the key to elucidating various topological transitions in nanomagnetism[22-24]. For instance, MP is responsible for the topological transition from the vortex-antivortex pair characterized by $|Q| = 1$ to the topologically trivial state of $|Q| = 0$[25-28]. The vortex-antivortex pair is annihilated through the injection of MP from the surface of a magnetic medium, and thus $|Q|$ of the total system is changed from |Q| = 1 to |Q| = 0. MP injection also plays an essential role in the merging of two skyrmions (|Q| ≠ 0) into the stripe domain (|Q| = 0) or breaking the stripe domain (|Q| = 0) into multiple skyrmions (|Q| ≠ 0)[29,30].

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

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

bubble (Figure 1b) or skyrmion (Figure 1c). The bubble has two Bloch lines (BLs), denoted by red and blue arrows, in the boundary between bubble core and outer domain (hereafter, boundary of the bubble). Topologically, like stripe domains, Q of the bubble is zero. In contrast, the skyrmion is a chiral spin texture characterized by $|Q| = 1$. It should be noted that the structural inversion symmetry is only broken on the top and bottom surfaces of Fe/Gd multilayers, but its contribution to emergence of DMI is negligibly small due to its significant thickness close to 90 nm[32,34,39]. Instead of DMI, the dipole-dipole interaction arising from the significant thickness of Fe/Gd multilayers can stabilize the skyrmion in Fe/Gd multilayers[31-34]. As seen in Fig. 1b and c, the shapes of bubble and skyrmion created in Fe/Gd multilayer are distinguishable[6,33-36]. We confirmed that, in Fe/Gd multilayer, the elliptical and circular-shaped spin textures are bubbles and skyrmions, respectively by micromagnetic simulations. Additionally, we confirmed that the annihilation fields of circular-shaped spin textures are greater than those of elliptical-shaped spin textures by experiments and micromagnetic simulation, supporting that bubbles and skyrmions are in elliptical and circular shapes, respectively. Additionally, we confirmed that the magnetization configuration of the elliptical- and circular-shaped spin textures are bubbles and skyrmions. Although it is reported that the elliptical skyrmion can be stably formed under anisotropic DMI and perpendicular magnetic anisotropy (PMA)[40], the elliptical-shaped spin textures correspond to bubbles in our work since DMI is negligibly small and PMA is isotropic in our Fe/Gd multilayers. The transition from stripe domains to bubbles, where the Q remains unchanged, is a topologically trivial process. It can be achieved through the continuous transformation of the magnetization configuration in the same homotopy class[1,14]. On the other hand, the skyrmion is a chiral spin texture characterized by $|Q| = 1$. Therefore, the transition from stripe domains to skyrmions is the topological transition where Q of the entire system changes from $|Q| = 0$ to $|Q| = 1$.

For an in-depth understanding of the topological transition, we experimentally realized the process of the transition from stripe domains to skyrmions. The initial stripe domains were set by applying a saturation magnetic field of $\mathbf{H} = -0.3$ mT, i.e., downward out-of-plane magnetic fields, and then reducing the magnetic field to zero. Considering a previous report predicting the contribution of the IP magnetic field component to skyrmion generation[6,38,41], we applied magnetic fields slightly tilted by $\theta = 1°$ with respect to the film normal direction as schematically illustrated in Fig. 2a. In this geometry, due to the tilting angle of magnetic fields with respect to the z-axis, a slight magnetic field is also applied to the film plane, i.e., in-plane (IP) magnetic field. Figure 2b shows the spin textures observed by the magnetic transmission soft X-ray microscopy (MTXM) with increasing $\mathbf{H}$. All MTXM images are taken at room temperature. The black and white contrasts in MTXM images represent downward and upward magnetizations, respectively. As $\mathbf{H}$ increases from 0 mT to 162 mT, the stripe domains are transited into circular-shaped skyrmions. As shown in Fig. 1, the circular-shaped skyrmions can be distinguished from bubbles, which are elliptical-shaped[6,35,36]. As **H** increases further to 223 mT, skyrmions are reduced in size, but all skyrmions remain without annihilation. This indicates the high stability of skyrmions ensured by the non-trivial topology of skyrmions. Figures 2c and 2d show three-dimensional magnetization configurations of simulated stripe domains and skyrmion, respectively. The transparent gray surfaces indicate the isosurfaces for $m_z = 0$, which indicates the boundary between upward and downward magnetizations. In the stripe domains (Fig. 2c), the flux-closure domain structures are created with respect to the domain walls to reduce the demagnetization energy (Supplementary information 1), which makes the domain walls on the top and bottom surfaces of the film become right- and left-handed Néel walls, respectively. Interestingly, however, in the middle region of the film, Bloch walls where the magnetizations are oriented towards the x-axis are generated to avoid the high exchange energy in the region. In the stripe domain created by applying magnetic fields with the tilting angle of 1° with respect to the z-axis, magnetizations of domain walls in the middle region of the film are found to be aligned in the $-x$-direction, as seen in Fig. 2c. For the skyrmion (Fig. 2d), the flux-closure domain structures leads to the Néel configurations on top and bottom surfaces with opposite chirality, while the middle region of the film shows the Bloch configuration (Supplementary information 1).

The mechanism of the experimentally observed topological transition from stripe domains to skyrmions was investigated in detail using micromagnetic simulations (Figure 3a and Supplementary Movie 1). The initial stripe domain starts breaking as **H** increases. However, we found that the stripe domain is not directly transformed into the skyrmion. Surprisingly, the bubble with two BLs, indicated by blue and red arrows, transiently appears immediately after the stripe domain breaks (snapshot at t = 2.45 ns). The magnetizations at the blue and red BLs are aligned in the same $-x$ direction as those of domain walls in the stripe domain. It is worth noting that the magnetization configurations around the two BLs are different on the top and bottom surfaces. On the top surface, the spatial variation of the magnetization around the red BL is more drastic than the magnetizations around the blue BL. On the other hand, on the bottom surface, the magnetizations around the blue BL are spatially more inhomogeneous than the magnetizations around the red BL. We found that the difference between magnetizations around the red and blue BLs on the top and bottom surfaces is closely associated with the dipole-dipole interactions (Supplementary information 2). Once the bubble is formed, however, two MPs, denoted by blue and red spheres, are injected at the BLs with drastically varying magnetization (i.e., the red BL on the top surface and the blue BL on the bottom surface). By the injection of the MPs, which involves the annihilation of the red BL on the top surface and the blue BL on the bottom surface, the magnetization configurations on the top and bottom surfaces are changed to that of the skyrmion as depicted in the 2D schematic images of the snapshot at t = 2.60 ns. It was found that the MPs injected from the top and bottom surfaces have convergent and divergent magnetization configurations, which are topologically characterized by $\mathrm{Q}_{\mathrm{Top}}^{\mathrm{MP}} = -1$ and $\mathrm{Q}_{\mathrm{Bot}}^{\mathrm{MP}} = +1$, respectively. The injected MPs propagate through the boundary of the bubble as indicated by cyan and magenta lines (snapshot at t = 5.10 ns). When the MPs reach the middle region of the film, they start moving towards each other in the middle region of the film (snapshot at t = 5.68 ns). The movement of the MPs is accompanied by the magnetization switching that converts magnetizations in the boundary of the bubble to those of the skyrmion in the middle region of the film. The micromagnetic simulation results for the detailed magnetization switching process in the middle region of the film are illustrated in Supplementary information 3. Interestingly, despite of non-trivial topology of MPs, when the MPs collide with each other, the MPs are annihilated together, completing the topological transition from the stripe domain to the skyrmion (snapshot at t = 6 ns). Since two MPs have opposite topological charges ($\mathrm{Q}_{\mathrm{Bot}}^{\mathrm{MP}} + \mathrm{Q}_{\mathrm{Top}}^{\mathrm{MP}} = 0$), the pair annihilation of MPs is a topologically trivial process as shown in Fig. 3b. The results in Fig. 3 clearly show that the topological transition from the stripe domain to the skyrmion is achieved through the sequential processes of the injection, propagation, and pair annihilation of MPs.

From extensive micromagnetic simulations with various configurations of applying magnetic fields, we found that the topological transition from stripe domains to skyrmions is most reliably achieved when the magnetic field slightly tilted along the +x-axis was applied than when only the magnetic field was applied along the +z-axis (Supplementary information 4) as was done in the experiments shown in Fig. 2. It indicates that the IP magnetic field induced by applying the magnetic fields at an angle tilted by 1° toward the +x-axis (Fig. 2a) might be a key to manipulating the MP injection. Indeed, the IP magnetic field has been discussed as playing an important role in generating skyrmions and having a decisive influence on the shape of spin textures[6,41-43].

To clearly verify the role of the IP magnetic field in the MP injection, we examined the transition from the bubble to the skyrmion by directly applying a magnetic field, H_x, along the film plane (x-direction). To stably form the bubble in magnetic medium, we applied the out-of-plane magnetic field of H_z = 280 mT. Under the fixed H_z, the IP magnetic fields increases from $H_x = -20$ mT. Figure 4a shows the magnetization configurations of the bubble (snapshots at $H_x = -20$ mT, 0 mT, and 1.4 mT) and skyrmion (snapshot at H_x = 1.5 mT), along with the exchange energy density of these configurations (Fig. 4b). Here, the magnetization at the BL in the bubble is also aligned in the $-x$-direction. When the IP magnetic field increases from $H_x = -20$ mT to H_x = 0 mT, the magnetizations at the BLs become more inhomogeneous (snapshot at H_x = 0 mT). As a result, the corresponding exchange energy become much higher at the red BL on the top surface and the blue BL on the bottom surface. When the IP magnetic field is applied in the +x-direction, opposite to the magnetization at the BLs, and increased to 1.4 mT, the exchange energy at those BLs increases significantly (snapshot at H_x = 1.4 mT) because of the drastic spatial inhomogeneity of the magnetizations at those BLs. A further increase of H_x to 1.5 mT finally leads to the transition from the bubble to the skyrmion with relaxing the exchange energy. In the transition process, MPs are injected from the surfaces while annihilating BLs. It is interpreted that the exchange energy at the BLs is converted into energy for the injection of MP to reduce the total energy of the system[22]. The results in Fig. 4 clearly confirm that the IP magnetic field triggers MP injection by concentrating the local exchange energy at the BLs. Additionally, Figure 4 shows that a certain strength of the IP magnetic field, H_x = 1.5 mT, is required for MP injection, suggesting that the MP injection can be manipulated by adjusting the strength of the IP magnetic fields.

To experimentally confirm if the MP injection is controllable by varying the strength of the IP magnetic field, we applied magnetic fields tilted toward the +x-axis with various θ to manipulate the strength of IP magnetic field and observed spin textures (Fig. 2a). The θ is varied from 1° to 10° in the step of 1° (Supplementary information 5). Figure 5a shows spin textures observed at **H** = 0 mT, 162 mT, and 206 mT with θ = 1°, 3°, 5°, 7°, and 9°. The H_x corresponds to the strength of IP magnetic fields induced by **H** with θ. We observed that the stripe domains break into dot-like spin textures at **H** = 162 mT. It can be seen that some of the dot-like spin textures at **H** = 162 mT are circular-shaped skyrmions, while others are elliptical-shaped bubbles (for example, θ = 7° and 9°). As **H** increases to 206 mT, the topologically protected circular-shaped skyrmions remain stable while the elliptical-shaped bubbles are annihilated, which supports the higher stability of skyrmions than that of bubble. The experimentally observed differences in the annihilation fields of skyrmion and bubble were also confirmed by micromagnetic simulations (Supplementary information 6). Remarkably, the populations of skyrmions and bubbles are strongly dependent on the θ, which can be determined by counting the number of dot-like spin textures remaining at **H** = 206 mT. At θ = 1°, one can find that only skyrmions are formed, whereas only bubbles are formed at $\theta \geq 7°$, as can be seen with no remaining spin texture. Note that the circular-shaped structures at θ = 7° and 9° and at **H** = 206 mT were confirmed to be defects (Supplementary information 7). At $1° < \theta < 7°$, the skyrmions and bubbles coexist, and as θ increases, the population of skyrmions decreases while the population of bubbles increases. The results in Fig. 5a show that the topological transition from stripe domains into skyrmions occurs only at weak IP magnetic fields (θ = 1° and H_x = 2.83 mT), which implies that MP injection is triggered when the applied IP magnetic field is relatively weak (θ = 1° and H_x = 2.83 mT), but is hindered when the strong IP magnetic field ($\theta > 7°$ and $H_x > 19.7$ mT) is applied.

To understand the MP injection that occurs as a function of the strength of the IP magnetic field, we investigated the process by which the stripe domain is converted into the bubble in detail. Figures 5b and 5c illustrate the magnetization process in which the stripe domain converts to the transient bubble at θ = 1° and θ = 9°, respectively. By applying the magnetic field at θ = 1°, the magnetizations of domain walls in the stripe domain on the top and bottom surfaces are tilted into −*x*-direction along with the ones in the middle region of the film. The magnetization direction of domain walls and that at the BLs in the transient bubble remains the same in the −*x*-direction. On the other hand, with the applied magnetic field at θ = 9°, due to a relatively strong IP magnetic field induced, the magnetizations of domain walls in the stripe domain on the top and bottom surfaces and in the middle region of the film are flipped from the −*x*-direction into the +*x*-direction. As a result, in the transient bubble formed at θ = 9°, the magnetizations in the boundary and BLs in the transient bubble are aligned in the +*x*-direction. Since the magnetization at the BLs in the transient bubble formed at θ = 1° is aligned in the −*x*-direction, opposite to the direction of the IP magnetic field (+*x*-direction), the exchange energy at BLs in the bubble is highly localized and increased with increasing the IP magnetic field, and thus MP injection is triggered at the BLs, as described in Fig. 4. However, the magnetization at the BLs in the transient bubble formed at θ = 9° is parallel to the direction of the IP magnetic field (+*x*-direction). Therefore, the applied IP magnetic field reduces the exchange energy at the BLs, unlike the case of θ = 1°, and thus the bubble is stabilized as the final spin texture without MP injection. The experimental results in Fig. 5 strongly support that MP injection can be effectively and simply controlled by adjusting the tilting angle of applied magnetic field, i.e., the strength of IP magnetic fields.

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

Methods

Sample fabrication.

The $[Fe(0.34\ nm)/Gd(0.4\ nm)]_{120}$ ferrimagnetic multilayer film were fabricated by magnetron sputtering. 0.34 nm-thick Fe and 0.4 nm-thick Gd layers were alternately deposited on 100 nm-thick X-ray transparent Si_3N_4 membrane substrate.

X-ray imaging technique.

The magnetic components in the $[Fe(0.34\ nm)/Gd(0.4\ nm)]_{120}$ ferrimagnetic multilayer film were directly observed by utilizing full-field magnetic transmission X-ray microscopy (MTXM) at the beamline 6.1.2 in the Advanced Light Source (ALS)[44]. Out-of-plane magnetic components were imaged at the Fe L_3 X-ray absorption edge (708 eV). All MTXM measurements were performed at room temperature. To apply the IP magnetic field, the sample holder was tilted with respect to the out-of-plane magnetic field.

Micromagnetic simulation.

To specify the detailed magnetization configurations in the Fe/Gd multilayer film, we performed the micromagnetic simulation utilizing MuMax^3 code, and typical material parameters of Fe/Gd multilayer films were used, i.e., a saturation magnetization $M_s = 400$ kA/m, an exchange stiffness $A_{ex} = 5$ pJ/m, a uniaxial anisotropy $K_u = 40$ kJ/m^3. We solved numerically the Landau-Lifshitz-Gilbert (LLG) equation: $\partial \mathrm{M}/\partial t = -\gamma_0(\mathrm{M}\times \mathrm{H}_{eff})+(\alpha/|\mathrm{M}|)(\mathrm{M}\times\partial \mathrm{M}/\partial t)$ with the local magnetization vector $\mathbf{M}$, the gyromagnetic ratio γ_0, the effective field $\mathbf{H}_{eff}$, and the phenomenological damping constant α using MuMax^3 code[45-47]. To study the MP injection process, we carried out the quasistatic calculation where the precessional effects are excluded, the damping constant α was set to 0.5. We used a $300 \times 300 \times 100$ nm^3 films with periodic boundary conditions.

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

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Author Contributions

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., M.-Y.I. carried out magnetic transmission soft x-ray microscopy experiments. S.A.M., E.E.F. prepared the samples. H.-S.H., S.-G.J. analyzed data. H.-S. H. carried out the micromagnetic simulations. H.-S.H., S.-G.J., M.-Y.I., K.-S.L. prepared the manuscript, which incorporates critical input from all authors.

Competing financial interests

The authors declare no competing financial interests.

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Figure legends

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

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

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

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

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