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Nanocavity-Mediated Fast Magnetic Vortex Core *In-Situ* Switching by Local Magnetic Field

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Fast *in situ* switching of magnetic vortex core in a ferromagnetic nanodisk assisted by a nanocavity, with diameter comparable to the dimension of a vortex core, is systematically investigated by changing the strength as well as the diameter of the effective circular region of the applied magnetic field. By applying a local magnetic field within a small area at the nanodisk center, fast switching time of about 35 ps is achieved with relatively low field strength (70 mT) which is beneficial for fast data reading and writing. The reason for this phenomenon is that the magnetic spins around the nanocavity is aligned along the cavity wall due to the shape anisotropy when the perpendicular field is applied, which deepens the dip around the vortex core, and thus facilitates the vortex core switching.

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Magnetic vortices in micro- or nano-scale magnetic structures have attracted significant interest in recent years because of their potential applications in spintronic and information processing technology.[1,2] A magnetic vortex can be characterized by two components, its circular domain structure and the out-of-plane component of magnetization at the center of the vortex, which is called the vortex core (VC). A vortex-based memory has been suggested before based on the control of these two quantities, where the information could be stored in either the polarity or the circulation and read via a magnetoresistance measurement. The application of vortex-based devices requires the perfect controllability of the polarity and/or the circulation. Attempts have been made to reverse the vortex circulation deterministically by lifting the degeneracy between the clockwise and counterclockwise circulation through the use of shape-engineered nanomagnets,[3−6] inhomogeneous magnetic field,[7,8] current induced Oersted field[9,10] and bi-component magnetic nanodisks.[11]

For a VC memory,[12,13] an energy efficient as well as fast VC switching process needs to be provided.[14] It has been reported that the energy efficient switching of VC can be achieved under an in-plane oscillating magnetic field (or spin polarized current)[15−17] or a pulsed magnetic field (or pulsed current)[18,19] through the creation and annihilation of vortex-antivortex pairs. However, during the VC polarity switching, the movement trajectory of the core is complex and the amplitude of the motion is large (a few 10 to 100 nm), which create a severe obstacle for bit reading in magnetic data storage driven by in-plane field.

Recently, an *in situ* VC switching mechanism was proposed, in which the magnetic field is applied perpendicularly to the disk plane, involving static field,[20,21] oscillating field with resonant frequency,[22−24] global pulsed field[25] and local pulsed field.[26] It is a technical challenge to achieve an ultrafast, energy efficient and controllable VC switching. For example, while using a static global magnetic field which is energy inefficient, the threshold switching field is around 0.5 T.[20,21] Another example is that when applying a perpendicular oscillating field (or global field pulse), the radial spin waves are excited, which dominates the reversal process. However, after the VC switching, other spin waves are generated, through them a large amount of exchange energies can be released. For this reason, the final core polarity is very sensitive to the field strength and duration (or pulse amplitude and width), although it has turned out that switching the VC by resonantly oscillating field (or global field pulse) is an energy efficient way (a few 10 mT field). One more example is that by applying a local field pulse within a small area at the disk center, the excitation of the spin waves can be dramatically suppressed. With this approach, fast VC reversal time of about a few 10 ps was achieved, which

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is ten times faster compared to that in a global magnetic field, but much larger field strength is required (e.g., 1.6 T in Ref. [26]).

More recently, a geometry-dependent fast switching of VC has been reported under in-plane rotating magnetic field, which is assisted by a nanocavity positioned at the center of a nanodisk.[27] Mediated by the nanocavity, it is found that the VC can be switched well below 200 ps with less than 10 mT driving field and over a wide range of field frequency. This provides a new possibility for picosecond level fast switching of VC. In this Letter, the VC switching is investigated in a ferromagnetic nanodisk by applying a local magnetic field. To assist the VC switching, a cylindrical nanocavity is placed at the center of the nanodisk. Driven by the local perpendicular magnetic field, combining with the shape anisotropy effect of the nanocavity structure, a fast, energy efficient and polarity controllable *in situ* VC switching is expected.

To investigate the geometry-dependent fast *in situ* VC switching, we performed the micromagnetic simulations using the MuMax package,[28] which is a finite element software, solving the Landau–Lifshitz–Gilbert equation. The geometry and dimension of the nanodisk with a nanocavity is shown detailedly in Fig. 1. The diameter of the nanodisk is 300 nm. On the top part is a flat disk with thickness 5 nm. A cylindrical nanocavity of diameter 10 nm, comparable to the dimension of a VC,[29] and height 25 nm is inserted in the center of the nanodisk bottom. Material parameters of permalloy are considered with the exchange stiffness coefficient $A = 13 \times 10^{-12}$ J/m, the saturation magnetization $M_s = 8.6 \times 10^5$ A/m. No magnetocrystalline anisotropy is considered. The unit cell dimensions of $2.5 \times 2.5 \times 2.5\,\text{nm}^3$ and the Gilbert damping constant $\alpha = 0.01$ are used. The vortex structure in the initial state is set to be an upward core with counterclockwise in-plane curling magnetization.

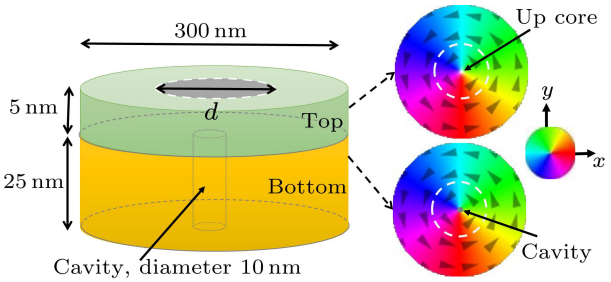

Fig. 1. The geometry and dimension of the nanodisk. The white dotted lines indicate the effective circular region of the local applied field with diameter d. Triangular arrows in the disks on the right part of the figure as well as the color map indicate the in-plane magnetization direction.

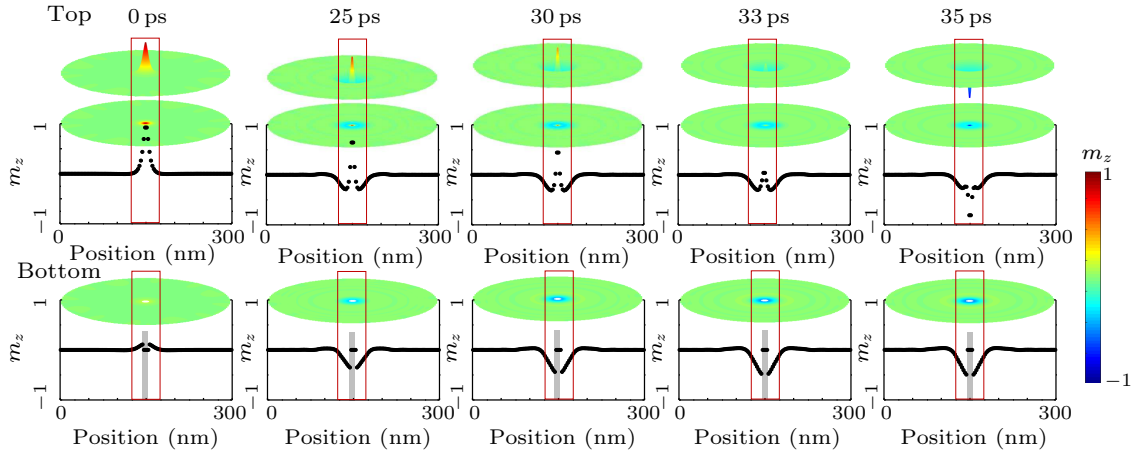

Fig. 2. Snapshots of local m_z distributions during the VC switching process driven by 70 mT perpendicular magnetic field. The dotted line plots show the m_z profiles across the disk center. The upper panel shows the perspective and top view of the top part of the nanodisk, and the panel below shows the top view of the bottom part of the nanodisk. The color bar in the middle represents the m_z value. The gray regions indicate the position of the nanocavity and the red rectangles highlight the effective regions of the local applied field.

A local magnetic field is applied perpendicularly (opposite to the VC direction) to a circular region at the nanodisk center. By varying the local field strength from 60 to 200 mT as well as the diameter (d) of the effective circular region of the applied magnetic field from 20 to 300 nm (global field), the VC switching behaviors were systematically investigated in shaped nanodisk. The snapshots of local out-of-plane magnetization (m_z) distributions driven by 70 mT magnetic field in the case of $d = 50$ nm are illustrated in Fig. 2. At the initial state, the VC has positive polarization ($m_z = 0.92$ at the apex of the VC), as shown in 0 ps snapshot at top part of Fig. 2. In the bottom part of the disk (the part with nanocavity), the $m_z = 0$ inside the cavity and $m_z > 0$ near the cavity (see the 0 ps snapshot as well as the line plot at the bottom of Fig. 2), which means that the spins around the nanocavity tilt up slightly along the cavity wall due to the shape anisotropy. The gray regions in Fig. 2 indicate the position of the nanocavity. After

the local magnetic field is applied, the spins around the nanocavity are aligned along the field direction, see the m_z values at both sides of the gray bars in 25–35 ps line plots. The m_z values around the nanocavity at 25, 30 and 33 ps are −0.35, −0.44 and −0.48, respectively. The tilting down spins in the bottom part of the disk are just under the dip (the local area around the VC with out-of-plane magnetization opposite to the core) on the top part of the disk, which deepens the dip when the field is applied. The m_z values of the dips at 25, 30 and 33 ps are −0.29, −0.31 and −0.30, respectively. With the deepening of the dip, the upward VC is eventually sucked by the dip at 35 ps, completing the VC switching process.

To compare, further simulations in flat disk with thickness 5 nm, diameter 300 nm were performed as well. The applied diameter of the local magnetic field is the same as used in Fig. 2 (d = 50 nm). The results show that the threshold switching field is 390 mT, much higher than the value in the nanocavity shaped disk (70 mT).

The switching mechanism in the present work is completely different from the excitation of the radial spin waves, by which the VC experiences considerable expansion and compression, the so-called breathing-like motion. To confirm that, we plot the variation of m_z distribution across the disk center of the top part of the nanodisk with 5 ps per step, as shown in Fig. 3. The dip becomes deeper and deeper with time, leading to the decrease of the m_z value of the VC (from 0.92 to 0.44). No breathing-like motion is observed before the VC reversal, no radial spin wave excitation is observed in the nanodisk as well. We have $m_z = 0$ in the whole region of the nanodisk except the region around the VC.

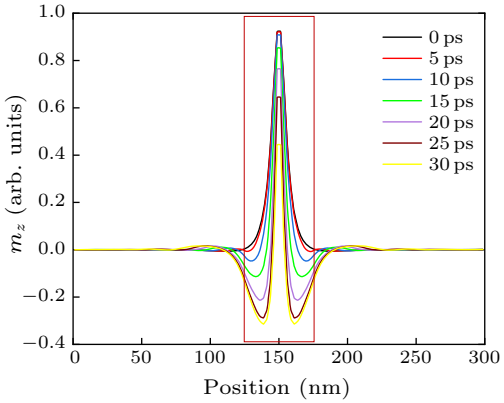

Fig. 3. Profiles of local out-of-plane magnetization (m_z) across the nanodisk center at different times. The red rectangle indicates the effective region of local applied magnetic field.

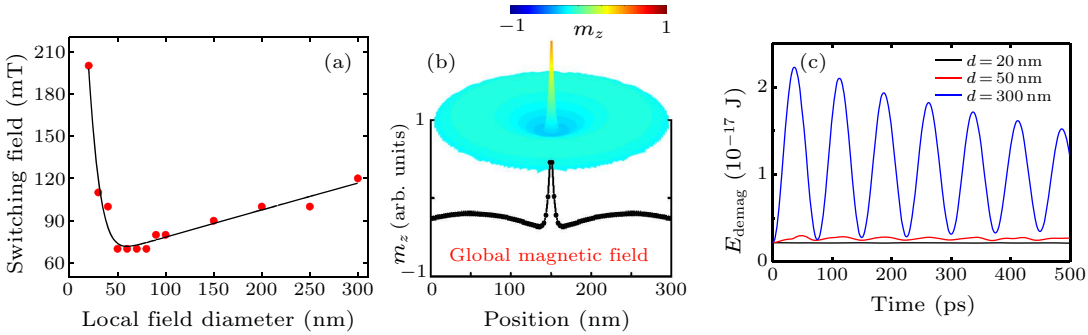

Fig. 4. (a) The threshold switching field of VC driven by the local field with different applied diameters. The black curve is a guide line. (b) The snapshot of local m_z distribution on the top part of the nanodisk driven by 120 mT global magnetic field (d = 300 nm) before the VC switching. The line plot below shows the m_z profile across the disk center. The color bar on the top represents the m_z value. (c) The magnetostatic energy $E_{\rm demag}$ profile driven by the local magnetic field with different d.

We further changed the applied diameter of the local magnetic field to see how the variation of d affects the VC switching behavior. The threshold switching fields by the local magnetic field with different d are plotted in Fig. 4(a), from which we can see that the threshold switching field achieves its minimum (70 mT) when the local field diameter of 50–80 nm is chosen. The reason why the required field strength for the core reversal is much larger when the local field diameter less than 50 nm (e.g., 200 mT in the case of d = 20 nm) is that the total amount of energy is smaller due to the limited area where the field is applied.[26] The threshold switching field is high as well when the local field diameter is larger than 80 nm (e.g., 120 mT in the case of d = 300 nm). The reason is the excitation of the radial spin waves, which dissipate part of the total energy when the global field (or local field with large applying area) is applied. The excitation of the spin wave can be clearly seen from the snapshot of local m_z distribution shown in Fig. 4(b), where the driving field is 120 mT global magnetic field (d = 300 nm). The snapshot is obtained at 25 ps after the field is turned on. The excitation of the spin waves can be further confirmed from the energy perspective. Normally, the vortex structure avoids the creation of surface magnetic charges and reduces the magnetostatic energy ($E_{\rm demag}$). The magnetostatic energy here is mostly generated from the spins tilting out of the disk pane when the magnetic field is applied. As plotted in Fig. 4(c), the $E_{\rm demag}$ is barely changed

when the local field with small d (e.g., $d = 20\,\text{nm}$) is applied. As d is increased to 300 nm (global field), the E_{demag} oscillates with much larger amplitude compared to the values in the cases of $d = 20\,\text{nm}$ and 50 nm [see Fig. 4(c)], which indicates the spin waves generation by the global field.

It is straightforward to get even more fast VC switching time by increasing the field strength. For instance, under the same condition as used in Fig. 2 but the magnetic field is up to 200 mT, the VC can be switched within 20 ps. However, the switching time cannot be reduced linearly with simply increasing the field strength, since there exists an ultimate speed of magnetic switching.[30] Under this circumstance, it is essential to seek a more energy efficient as well as fast VC switching approach, as provided in this work. In addition, the simulations with varied cavity diameter were also performed. The results show that, to get a nanocavity assisted VC switching, the diameter of the nanocavity should be comparable to the dimension of the VC, e.g., 10 nm in the present sample.

In conclusion, we have performed micromagnetic simulations to investigate the magnetic VC switching driven by a local out-of-plane magnetic field. The application of the local field allows a fast (20 ps) *in situ* VC switching by suppressing the excitation of the spin waves. Assisted with a nanocavity, an energy efficient *in situ* VC switching is achieved. The field strength required for the VC switching (a few 10 mT) in the present work is 20 times lower than that in disks without nanocavity, e.g., 1.6 T in Ref. [26]. Furthermore, without excitation of the spin waves, the final polarity of the VC is controllable and reliable, which is beneficial for fast data reading and writing based on the VC switching.

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