Research articles

Unidirectional switching of magnetic vortex core in a nanocavity mediated nanodisk: Looking for a reliable low-power-driven and fast switching in terms of geometric parameters

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1. Introduction

The dynamics of magnetic vortex core (VC) reversal in micro- and nanosized circular magnetic disks have been a hot subject of research in the fields of nanomagnetism and spintronics [1,2]. The ground states of these magnetic disks are defined by the polarization of the VC (up, \( p = 1 \); down, \( p = -1 \)) together with the sense of the in-plane flux closure (counterclockwise (CCW), \( c = 1 \); clockwise (CW), \( c = -1 \)) [3–5]. Since the state of VC polarization is naturally binary, arrays of circular disks (platelets) may be used as nonvolatile magnetic random access memories (MRAMs) [6–9], if it is possible to reverse the VC in a well-defined manner with low power.

Low-power-driven unidirectional VC switching is known to be achievable through the resonant excitation of the azimuthal-spin-wave (ASW) mode [10–13]. Because the core couples differently with two azimuthal modes (\( \pm m \), positive/negative corresponding to CCW/CW spin wave rotation sense), which leads to an observable frequency splitting [14–19]. However, to obtain selective unidirectional switching, the frequency and the duration as well as the amplitude of the excitation field should be carefully chosen. Otherwise, the multiple VC switching events occur due to the excitation field transfers a sufficient amount of energy to the magnetic system.

Two different modes of the core motion (divergence/convergence mode) [20–25] exist if it is excited by a rotating magnetic field. Since the eigenfrequencies for these two modes are different, one can get an unidirectional switching through the frequency splitting. We can go a step further and get a reliable unidirectional switching by widening the threshold field (\( H_{th} \)) splitting. As reported in previous work [10], the ‘dip’ (localized area where magnetization is opposite to the core), which is the key point for VC reversal, is strongly developed in convergence mode (\( pm = -1 \)), but relatively weakly developed in divergence mode (\( pm = 1 \)). Hence, the threshold switching field in convergence mode is smaller. It is revealed in our previous work [26] that for convergence mode the \( H_{th} \) can be reduced by inserting a nanocavity in the center of the magnetic disk, which is used to decrease the potential energy when the core locates at the disk center, and thus to confine the core. We found that in convergence mode the \( H_{th} \) can be further reduced by carefully choosing a proper value of the nanocavity height. Hence, an optimized unidirectional switching behavior is expected through the threshold switching field splitting together with the frequency splitting.

Keywords: Unidirectional vortex core switching, Convergence/divergence mode, Nanostructured magnetic material

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ABSTRACT

Reliable unidirectional switching of magnetic vortex core driven by continuous rotating magnetic field is investigated using a permalloy nanodisk with a nanocavity inserted in the center in combination with micromagnetic simulations. It is reported that once the vortex core is confined in a nanocavity of diameter is comparable to the core size, the modes of the core motion (divergence/convergence modes) are modulated differently by the nanocavity; the threshold field amplitude required for vortex core switching is reduced for convergence mode, but not for divergence mode. We found that the confinement of the nanocavity to the core is mediated by the cavity height as well. Low-power-driven fast unidirectional switching is found to be achievable by carefully choosing the value of the nanocavity height.
2. Sample and simulation method

To explore the unidirectional VC switching behavior, the micromagnetic simulations [27] were performed. The sample we used is a permalloy disk with diameter 500 nm and thickness varies from 10 to 40 nm. A cylindrical nanocavity with diameter $d = 10$ nm and height $h$ varies from 5 to 35 nm is placed in the bottom center of the nanodisk, as detailed dimensions illustrated in Fig. 1(a). Material parameters of permalloy are considered with the exchange stiffness coefficient of $A = 13 \times 10^{-12}$ J/m, the saturation magnetization of $M_s = 8.6 \times 10^5$ A/m. No magnetocrystalline anisotropy is considered. In all simulations, the unit cell dimension 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 the CCW in-plane curling magnetization around a downward core, as indicated in Fig. 1(a). In order to investigate the reliable unidirectional switching, instead of pulsed field, a continuous CCW rotating magnetic field expressed as $\vec{H} = H_0 [\sin(2\pi f t) \hat{x} - \cos(2\pi f t) \hat{y}]$ is used in this work, where $H_0$ is the amplitude of the field and $f$ is the frequency. The profile of the rotating field is illustrated in Fig. 1(b). The field amplitude varies from 2 to 4 mT, and the frequency is chosen to be the eigenfrequency. The same method is adopted to get the eigenfrequency of convergence/divergence mode as used in previous work [26].

3. Results and discussion

We first investigated the VC switching behaviors in flat disk (diameter 500 nm and thickness 20 nm) under CCW rotating magnetic field with field amplitude $H_0 = 4$ mT and frequency $f = 7$ GHz. Soon after the excitation field is switched on, a dip is generated near the core (see 0.44 ns snapshot in Fig. 2). Followed the CCW motion of the VC, the dip gyrates CCW as well. Although the dip is significantly developed, because the dip cannot meet the core, so that the core cannot be switched until at 10.58 ns. At 10.57 ns, the dip is divided into two parts (inner dip and outer dip) by the spin waves. The inner dip annihilates the core at 10.58 ns and the outer dip becomes the new core (10.57–10.58 ns), making the complete switching of the magnetic VC. The phenomenon that a dip with a significant amplitude is excited but the core still cannot be reversed because the dip is relatively far from the original core has already been previously reported [12]. This indicates that to speed up the VC switching, increasing the magnetic field strength is not the only way. Alternatively, fast VC switching can be achieved by improving the possibility of the dip meets the core.

Considering that the diameter of VC in permalloy disk is around 10 nm [3,28], we inserted a nanocavity of diameter 10 nm and height $h$ into the lower-center of the disk (Fig. 1(a)) to confine the VC. The potential energy when the core locates at different position of the disk is plotted in Fig. 3(a), where $x$-axis represents the distance the core deviates from the center of the disk. Overall, the potential energy when the core at the center of the disk is lowered by the nanocavity compare to the corresponding flat disk (the disk without nanocavity). In the case of $h = 15$ nm (green dots), the potential energy when the core at the cavity wall ($x = \pm 5$ nm) is much higher compare to the case that the core at the same position but in flat disk (black solid line). This means that to escape from the nanocavity, the VC must overcome an energy barrier. The difference of the potential energy $\Delta E_{\text{potential}}$ (= the potential energy when the core at the cavity wall - the potential energy when the core at the center of the disk) is plotted in the upper part of Fig. 3(b), from which one can see that the $\Delta E_{\text{potential}}$ increases with $h$ until $h = 15$ nm, then it goes to a saturation state ($h = 15–25$ nm), and then decreases with $h$. This indicates that the confinement when the core is trapped in the nanocavity of $h = 15–25$ nm is stronger than in other cases.

We further applied an in-plane static field (step 0.1 mT) to the nanocavity mediated disks to see under how much field strength the core can escape from the trapping of the nanocavity. The results are shown in the lower part of Fig. 3(b). To push the core out of the nanocavity, 14.7 mT field is required when the core is confined in the nanocavity of $h = 15$ nm, which is the most strongest field among all the cases ($h = 5–35$ nm). The $\Delta E_{\text{potential}}$ is almost the same in the cases of $h = 15–25$ nm, but the escaping field decreases almost linearly from $h = 15–35$ nm. This is possibly because the core diameter in flat disk increases with the disk thickness, while the diameter of the nanocavity is fixed to be 10 nm, so that the confinement of the nanocavity to the core decreases when $h$ increases (the disk thickness increases as well). We checked and found that the diameter of the VC (measured at the position where the $m_y$ value equals to half of the maximum value of $m_y$) is around 15 nm in flat disk of thickness 10–20 nm, and the core diameter is larger than 15 nm in disks of thickness 25–35 nm, and it is larger than 20 nm in thickness 40 nm disk. Another possible reason is the potential energy density decreases with $h$ increases. The data shown in Fig. 3(b) reveals that to confine the core and then increase the possibility of the dip meets the core, $h = 15$ nm is the most preferred value.

We then applied a CCW rotating field with $H_0 = 3$ mT and $f = 7$ GHz during a period of 100 cycles (15 ns) to a nanocavity mediated disk with cavity height $h = 15$ nm. To determine the switching time of the VC, we evaluate the time derivative of the out-of-plane magnetization ($dm_y/dt$) for each cell in the simulation and the maximum value of this quantity ($\max(dm_y/dt)$) varies with time is plotted in Fig. 4(a). The peak in the $\max(dm_y/dt)$ profile shown in Fig. 4(a) indicates that the switching time is 0.47 ns. The amplitude of the $\max(dm_y/dt)$ goes to a stable value after the core switching, which reveals that the afterwards core motion enters a periodic and stable state and the core cannot be reversed further. The snapshots of local $m_y$ distributions in top and bottom part of the disk at different moments are illustrated in Fig. 4(b). A dip can be observed at 0.4 ns, which grows stronger at 0.45 ns and the downward core shrinks.

![Fig. 1.](image_url) (a) The geometry and dimension of the nanodisk with a cylindrical cavity. The black arrow on the top of the nanodisk indicates a downward VC. Arrows inside the two disks on the right part as well as the color code represent the magnetization direction on $xy$ plane. The black dot in the center of the upper disk represents a downward VC, and the gray hole with diameter $d$ in the center of the bottom disk is the cylindrical cavity. (b) CCW rotating field profile.
The downward core is totally annihilated at 0.47 ns and the value of the dip grows to \( m_z = 1 \), that means the core is switched at this moment. Through the comparison of the bottom and top images of the disk, one can see that the downward core is confined in the nanocavity before it is switched. After switching, the upward core remains outside of the cavity. Once the core is reversed, the mode of the core motion changes to divergence. But 3 mT excitation field is too weak for divergence mode switching, in addition, 7 GHz is not the eigenfrequency of divergence mode (8 GHz), hence the unidirectional switching behavior occurs.

The \( m_z \) values of the peak of the dip as well as the core before the core switching are plotted in Fig. 4(c), where we ignore the dips whose peak value less than 0.2. The \( m_z \) of the dip increases from 0.2 at 320 ps to the maximum value 1 at 460 ps, while the \( m_z \) of the core maintains the value -1 until the dip closes to the core at 450 ps, and the core shrinks leading to it’s \( m_z = -0.6 \) at 450 ps and -0.2 at 460 ps. We also tracked the position of the dip, and the position of it’s peak is illustrated in Fig. 4(d).

In the simulations, the dimension of the cell is \( 2.5 \times 2.5 \times 2.5 \) nm\(^3\). In other words, there are 200 \( \times \) 200 cells in xy plane. We first find out the peak of the dip locates at which cell and plot it at the center of this cell in Fig. 4(d), where each grid represents 4 cells. It is shown that the dip is developed around 25 nm far from the center of the disk (point (250 nm, 250 nm)), and it approaches the center of the disk with it’s gyration.

To compare, simulations in cavity height \( h = 20 \) nm disk were performed as well. The field parameter is the same as used above (CCW rotating field, \( H_0 = 3 \) mT and \( f = 7 \) GHz). The profile of the maximum \( m_z \) is plotted in Fig. 5(a), where the peak indicates that the switching time of the VC is 0.82 ns, which is longer than the switching time in case of \( h = 15 \) nm (0.47 ns). This can be explained that in present case the potential energy density is larger when the core (or dip) in the center of the disk, which leads to the dip approach the center of the disk not as easily as in \( h = 15 \) nm case. This explanation can be confirmed by the snapshots of local \( m_z \) distributions shown in Fig. 5(b) and the trajectory of the dip illustrated in Fig. 5(d). The first dip can be observed at 0.4 ns (Fig. 5(b)), which fails to meet the core and becomes weaker at 0.45 ns. At 0.78 ns a new dip is generated, which grows rapidly and the core shrinks (0.8 ns). Eventually, the downward core is annihilated and the dip becomes the new upward core at 0.82 ns. The \( m_z \) value of the peak of the core as well as the dip is plotted in Fig. 5 (c) before the core switching. The dip is firstly formed at 230 ps with \( m_z = 0.2 \), and the \( m_z \) value increases to it’s maximum (0.64), then decreases until the dip vanishes at around 600 ps.

The switching time of the VC excited by CCW rotating field with eigenfrequency in nanocavity mediated disks is shown in Fig. 6. As we focus on low-power-driven VC switching, only the excitation field with amplitude 2–4 mT is investigated. In the cases of \( h = 5 \) and 35 nm, the VC cannot be switched under 2–4 mT field. For low-power-driven and fast unidirectional switching, \( h = 15 \) nm is the most desirable height.
value. In this case, the VC can be unidirectionally switched within 0.34, 0.47 and 0.86 ns under the excitation field with amplitude 4, 3 and 2 mT, respectively. For \( h = 25 \) and 30 nm cases, the VC cannot be switched if the field amplitude lower than 4 mT. It is worth to mention that for flat disk (thickness 20 nm) the switching time under 4 mT field is 10.58 ns (Fig. 2). In addition, the unidirectional VC switching can be obtained

Fig. 4. (a) The maximum \( \frac{dm_n}{dt} \) vs. time under \( H_0 = 3 \) mT, \( f = 7 \) GHz CCW rotating field applied in cavity mediated disk of \( h = 15 \) nm. (b) The snapshots of local \( m_z \) distributions in the top and bottom part of the disk (only the center part of the disk is shown). The white hole in the bottom part of the disk is the nanocavity. The color bar represents the \( m_z \) value. (c) The \( m_z \) value of the peak of the dip as well as the core varies with time. (d) The trajectory of the dip before the core is switched. The arrow indicates the gyration direction of the dip.

Fig. 5. (a) The maximum \( \frac{dm_n}{dt} \) vs. time under \( H_0 = 3 \) mT, \( f = 7 \) GHz CCW rotating field applied in cavity mediated disk of \( h = 20 \) nm. (b) The snapshots of local \( m_z \) distributions in the top and bottom part of the disk. The white hole in the bottom part of the disk is the nanocavity. The color bar represents the \( m_z \) value. (c) The \( m_z \) value of the peak of the dip as well as the core varies with time. (d) The trajectory of the dips before the core is switched. The arrows indicate the gyration direction of the dips.
over a wide range of field frequency as reported in our previous work [26]. Since we focus on low-power-driven VC switching, only the VC switching driven by resonant magnetic field is presented in this work.

4. Conclusion

In conclusion, the reliable unidirectional VC switching in nanodisk with a cylindrical nanocavity inserted in the center has been systematically explored. Low-power-driven and fast VC switching can be obtained by carefully choosing the diameter (comparable to the core’s diameter, 10 nm here) as well as the height of the nanocavity. We expect that our finding can propose an additional method for fast dynamical manipulation and application of the magnetic VC.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References