Reverse magnetic vortex curling direction of ferromagnetic nanodisk

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Abstract

We reverse the magnetic vortex curling direction of ferromagnetic nanodisk by applying a circular Oersted field. The nanodisk is fabricated without breaking its symmetry. The Oersted field is induced by passing current through an atomic force microscope tip placed at the center of the disk. Micromagnetic simulation indicates that compared to the uniformly distributed current throughout the cross section of disk, the line current concentrated in the center can reverse the chirality more easily, which is in accordance with our experimental results.

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Ferromagnetic nanodisks have attracted attention over the past few years due to its unique closed-flux vortex state [1–5]. The curling direction of the in-plane vortex state is either clockwise or counter-clockwise. This degree of freedom is defined as chirality. In the center, the magnetization pops out, pointing either up or down, and we denote this degree of freedom as polarity. The resulting four degenerate states are independent, and have remarkably stability against thermal fluctuations. The control of both polarity and chirality could stimulate the use of vortex state in nonvolatile data storage and random access memory devices. Polarity switching has been realized in a lot of studies by using various techniques, including out-of-plane perpendicular current or magnetic filed [6, 7], in-plane spin-polarized current [4, 8] and magnetic field [9–11]. However, it is still hard to manipulate the second degree of freedom due to the high symmetry of the structure. In some studies, the nanodisk is modified somehow to break the symmetry, so the chirality is able to be switched in the nanodisk with notch, truncated edge or with asymmetrical magnetic properties in lateral direction [12–15].

We present here that we can switch the chirality without breaking the symmetry of the nanodisk. We realize this by applying a circular Oersted field that is induced by passing current through an atomic force microscope tip placed at the center of the disk, and we get the information of curling direction by magnetic force microscopy (MFM) images of the initial and final magnetization states with an in-plane uniform magnetic field applied. Micromagnetic simulation is also conducted to help explain the underlying mechanism.

Permalloy nanodisks are fabricated on a gold-coated silicon wafer by using standard electron-beam lithography and lift-off process. The diameter and thickness of the disk are 1 µm and 50 nm, respectively, to ensure the vortex magnetization distribution for the ground state. The magnetic dipole moments have the in-plane closed form around the center in the vortex state, so MFM image presents no contrast for the disk except the center, and one can not tell the curling direction for the time being. However, if we apply an in-plane uniform magnetic field, it is expected that more and more magnetic moments will be aligned with the magnetic field to minimize Zeeman energy, then the vortex core will be ”pushed” away from the center to the edge of the disk. Furthermore, if the disk has an opposite chirality, the core will move to the edge on the other side. So by knowing the direction of the external uniform magnetic field and observing the moving direction of the vortex core, we learn the chirality information. Fig. 1 shows the simulation and experimental verification of this
conception. We can clearly see, from the MFM images (1st and 2nd row) that with the in-plane uniform magnetic field increased from 0 to 400 Gauss, the vortex cores of the two disks move from center to the right and left edges step by step, respectively, showing that they have clockwise and counter-clockwise curling directions, respectively. The third row is the simulation results which simulate the process of the second row. Experimental and simulation results are in good accordance with each other.

Since the curling direction is known, we can then try to reverse the chirality. The idea is to apply current to the center of disk vertically via atomic force microscope (AFM) tip. If the current-induced circular magnetic field has the opposite curling direction to that of the disk and is large enough, then the curling direction of the magnetic moments in the disk is expected to be reversed. The experimental setup is shown in Fig. 2. The platinum AFM tip is in contact with the disk in the sample. The sample is connected to a resistor with resistance $R_0 = 40 \, \Omega$ by copper wire and is grounded. We apply voltage $V$ to the circuit, ramp it up from 0 to 8 Volts at a constant rate, and read out the response voltage of the resistor $V_0$. We can simply calculate the current according to $I = V_0/R_0$ and get a plot of $I$ versus $V$. When applying the voltage, no external filed is applied in order for the magnetization distribution of the disk to be in vortex-state. Before and after ramping up the voltage, 600 Gauss in-plane uniform magnetic field is applied to get chirality information by MFM scan.

With the sample structure illustrated in Fig. 3(a), there is always a linear relationship between $I$ and $V$ (Fig. 3(b)), and the chirality can not be reversed, as MFM images captured before and after the voltage application show no difference. However, after the sample structure is slightly altered, the result turns out to be what is expected. This time, based on the previous sample, a 10 nm thick Ti layer is deposited on top of Permalloy disk. Then a thin layer of TiO$_2$ is grown on Ti layer via plasma-enhanced chemical vapor deposition (PECVD) (Fig. 3(c)). The following MFM measurement and voltage application process are the same as before. The $I - V$ curve is shown in Fig. 3(d) (note that this time the voltage is ramped up from 0 to -8 Volts because the disk has an opposite chirality as compared to the previous one). As we can see, initially, the current is almost 0 as the voltage is ramped up. At some voltage $V_B$, the current suddenly jumps from 0 to $V_B/R_0$. Afterwards, it increases linearly as the voltage increases, with a slope the same as that in Fig. 3(b). This phenomenon is explainable: When the "jump" happens, the TiO$_2$ layer as a dielectric
is penetrated so that the disk transforms from an insulator to a conductor. Experimental trials show that everytime the voltage is applied to the disk with the Ti and TiO$_2$ capping layers, a jump appears in the $I - V$ curve. In addition, when the breakdown voltage $V_B$ is above some value (approximately 5 Volts), the chirality can be reversed since the vortex core is at opposite sides of the disk before and after the voltage application with the same in-plane uniform magnetic field applied (Fig. 4, disk 1 and 2). When $V_B$ is below 5 Volts, the vortex core presents at the same side (Fig. 4, disk 3), illustrating that the chirality is not reversed.

To explain the phenomenon that only a jump appearing at voltage above 5 Volts approximately in the $I - V$ curve can lead to chirality switch, we conduct micromagnetic simulation based on OOMMF. In the simulation, we assume two cases of current distribution: 1. Uniformly distributed all over the cross section of the disk, then according to Ampere’s law, magnetic field $B \propto Jr$, where $J$ is current density, $r$ is the distance between disk center and point investigated; 2. Concentrated in the center, like a line-current, so $B \propto I/r$. We then calculate the magnetic field at each simulation cell and generate field file to run simulation for the two current-distribution cases with various $I$ and $J$. The results show that in the uniform distribution case, the threshold current density $J_t$ for the chirality to switch is $1 \times 10^{12}$ A/m$^2$. The corresponding threshold current is $I_{t1} = \pi R^2 J_t = 0.64$ A where $R = 450$ nm is the radius of disk, whereas in the line distribution case, in order for the chirality to switch, the threshold current is $I_{t2} = 0.03$ A, which is much smaller than $I_{t1}$. Consequently, we think that for disk without dielectric capping layer, when $I$ is steadily increasing with $V$, the current spreads out when going through the disk, and the extreme situation for this scenario is the uniform distribution case. However, the maximum current applied in our experiment is 0.20 A, which is smaller than the threshold current $I_{t1}$ for this case, so the chirality can not be reversed. On the other hand, for disk with dielectric capping layer, the current increases a lot within a very short time when the dielectric is penetrated, thus the current is more concentrated in the disk, and more like a line current. In other words, when we compare the two points in Fig.3 (denoted as Point 1 and 2) with the same magnitude of current and resort to the equation $I = envA$, where $I$ is the current flowing in disk, $e$ the charge of an electron, $n$ the charge density, $v$ the drift speed, $A$ the cross-sectional area, we know that $I$, $e$, and $n$ are the same for the two points. However, $A$ is much smaller in the second point as $v$ is much larger in the breakdown case. Accordingly, current is more
concentrated. Simply speaking, the dielectric penetration creates a conducting channel that is much narrower than that formed by direct contact between MFM tip and ferromagnetic disk. When the jump happens at $V_B \simeq 5$ Volts, the current immediately after the jump is $I = V_B/R_0 = 0.125$ A. This is larger than the threshold value $I_{t2}$ for the line distribution case, so the chirality is able to be reversed. Moreover, when the jump happens at $V_B < 5$ Volts, the chirality cannot be reversed, meaning that the actual threshold current is about 0.125 A, larger than $I_{t2}$. This is reasonable because although the current is distributed more concentratively after the breakdown of the dielectric layer, it is not an ideal line current. Thus, larger threshold current is required to switch the chirality.

In summary, we have demonstrated magnetic vortex chirality switch of ferromagnetic nanodisk. This is realized by applying a current induced circular Oersted field. Simulation shows that the current density needs to be at least $1 \times 10^{12}$ A/m² to accomplish the switch in the case that the current is uniformly distributed throughout the cross section of the disk. The corresponding current is about 0.6 A. The actual current applied to switch the chirality in our experiment is no more than 0.2 A. According to the simulation, we think that our capacitor-like sample is able to concentrate the current enormously and thus less current is required to realize the switch. We hope our study can bring fresh notion for magnetic states manipulation and relevant application.

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References

[1] T. Shinjo, T. Okuno, R. Hassdorf, K. Shigeto, and T. Ono, Science 289, 930 (2000).
[2] W. Scholz, K. Y. Guslienko, V. Novosad, D. Suess, T. Schrefl, R. W. Chantrell, and J. Fidler, J. Magn. Magn. Mater. 266, 155 (2003).
[3] S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, and T. Ono, Phys. Rev. Lett. 97, 107204 (2006).
[4] K. Yamada, S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, A. Thiaville, and T. Ono, Nature Mater. 6, 270 (2007).
[5] K. Y. Guslienko, K.-S. Lee, and S.-K. Kim, Phys. Rev. Lett. 100, 027203 (2008).
[6] J.-G. Caputo, Y. Gaididei, F. G. Mertens, and D. D. Sheka, Phys. Rev. Lett. 98, 056604 (2007).
[7] D. D. Sheka, Y. Gaididei, and F. G. Mertens, Appl. Phys. Lett. 91, 082509 (2007).
[8] K. Yamada, S. Kasai, Y. Nakatani, K. Kobayashi, and T. Ono, Appl. Phys. Lett. 93, 152502 (2008).
[9] B. Van Waeyenberge, A. Puzic, H. Stoll, K. W. Chou, T. Tyliszczak, R. Hertel, M. Fähnle, H. Brückl, K. Rott, G. Reiss, I. Neudecker, D. Weiss, C. H. Back, and G. Schütz, Nature (London) 444, 461 (2006).
[10] R. Hertel, S. Gliga, M. Fähnle, and C. M. Schneider, Phys. Rev. Lett. 98, 117201 (2007).
[11] Y.-S. Yu, K.-S. Lee, H. Jung, Y.-S. Choi, M.-W. Yoo, D.-S. Han, M.-Y. Im, P. Fischer, and S.-K. Kim, Phys. Rev. B 83, 174429 (2011).
[12] T. Kimura, Y. Otani, H. Masaki, T. Ishida, R. Antos, and J. Shibata, Appl. Phys. Lett. 90, 132501 (2007).
[13] M. Schneider, H. Hoffmann, and J. Zweck, Appl. Phys. Lett. 79, 3113 (2001).
[14] Z. Zhong, H. Zhang, X. Tang, Y. Jing, L. Jia, and S. Liu, J. Magn. Magn. Mater. 321, 2345 (2009).
[15] V. Cambel and G. Karapetrov, Phys. Rev. B 84, 014424 (2011).
[16] T. Yang, N. R. Pradhan, A. Goldman, A. S. Licht, Y. Li, M. Kemei, M. T. Tuominen, and K. E. Aidala, Appl. Phys. Lett. 98, 242505 (2011).
FIG. 1: Experimental and simulation verification of vortex core motion. Each column corresponds to one specific external uniform magnetic field applied in the sample plane with its magnitude shown on the bottom. (a). MFM images showing vortex core motion of a nanodisk with counterclockwise (1st row) and clockwise (2nd row) curling directions, respectively, as shown by the curling arrows. (b). Magnetization images from OOMMF simulation showing the process of the second row in (a).
FIG. 2: Schematic illustration of the experimental setup.
FIG. 3: (a), (c). Schematic illustrations of the sideview of two different disk structures investigated in our study. (b), (d). $I - V$ curves for samples (a) and (c), respectively.
FIG. 4: MFM images of six nanodisks before (a) and after (b) applying current to three of them as indicated by "1", "2" and "3". The same external uniform magnetic field is applied to both images in sample plane. "+" and "-" signs illustrate positive and negative voltage application, respectively. All the disks have the same structure as that in Fig. 3(c).