Current-induced magnetic vortex core switching in a Permalloy nanodisk

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We report on the switching of a magnetic vortex core in a sub-micron Permalloy disk, induced by a short current pulse applied in the film plane. Micromagnetic simulations including the adiabatic and non-adiabatic spin-torque terms are used to investigate the current-driven magnetization dynamics. We predict that a core reversal can be triggered by current bursts a tenth of a nanosecond long. The vortex core reversal process is found to be the same as when an external field pulse is applied. The control of a vortex core’s orientation using current pulses introduces the technologically relevant possibility to address individual nanomagnets within dense arrays.

Patterned soft-magnetic thin film elements with lateral extension above a critical size naturally form flux-closure patterns, which contain magnetic vortices, i.e., small regions where the magnetization direction circulates in the film plane around a nanometer-sized core. At the center of this core, the magnetization points perpendicular to the plane. In the search for smaller and faster devices, such magnetic patterns have mostly been avoided favoring samples with uniform magnetizations. The study of the static and dynamic properties of vortices and vortex cores in particular has, however, recently emerged as a dynamic field of investigation. Magnetic vortex cores have indeed recently been considered as possible candidates for magnetic data storage due to several attractive properties: Their size is of only a few tens of nanometers, they exhibit perfect bi-stability (pointing either upwards or downwards, defining the vortex polarization), they form naturally and ultimately have a high thermal stability. All these features represent important prerequisites for possible applications to data storage. In order to store information using a vortex core, mechanisms for a controlled switching of its orientation are required. The direct reversal of vortex cores by means of an applied field oriented perpendicular to the plane requires large field values in the order of 500 mT, which gives an idea of the high stability of these structures. Recently, it has been shown that the vortex core could be switched by means of low fields applied in the plane of the sample. Experimentally, it has been shown that a sinusoidal in-plane field pulse as low as 2 mT could be used to reverse the core of a vortex in a sample excited at the gyrotrropic frequency, where the vortex is brought into a stationary orbit. However, the reversal process takes a few nanoseconds, due to the fact that the steady gyrotrropic orbit motion is in the order of 100 MHz. Although the gyrotrropic frequency depends on the sample size, this dependence is weak and this frequency is practically always in the sub-GHz range, so that switching speeds well below 1 ns are not possible using this resonant scheme. Moreover, the core switching only occurs if the frequency of the sinusoidal field is within a narrow range close to the gyrotrropic frequency. Based on micromagnetic simulations, an ultra-fast core reversal mechanism has been proposed recently, which is initiated by applying a suitably shaped unipolar in-plane magnetic field pulse only a few picoseconds long. The required amplitude of the field pulse is larger (ca. 70 mT) than in the case of resonant switching, but this switching scheme is much faster. In spite of their respective advantages (low fields, high speed) both the resonant and the non-resonant switching modes exhibit a common problem in terms of applicability: The lack of selectivity of the individual elements. Reliably addressing a single nanodisk inside a dense array is very difficult using external fields. In this letter, we present a fast and simple method to switch magnetic vortex cores by applying short electric current pulses, only one hundred picoseconds long. The electric current pulse is applied in the plane of the element. We thus show that a fast toggle core switching mechanism can be triggered in a relatively simple way which is compatible with integrated circuits, thereby solving the issue of selectivity.

The results were obtained using micromagnetic finite-element simulations based on the Landau-Lifshitz-Gilbert equation. Our micromagnetic code used in previous simulations has been extended in order to consider the spin torque exerted by an electric current flowing through the sample. This effect of current-driven magnetization dynamics is modelled by including the adiabatic and the non-adiabatic spin torque terms into the Gilbert equation:

$$\frac{dm}{dt} = -\gamma m \times H_{eff} + \alpha m \times \frac{dm}{dt} - (u \nabla) m + \beta m \times [(u \nabla) m],$$

(1)

where $m = M/M_s$ is the normalized local magnetization ($M_s$: saturation magnetization), $H_{eff}$ is the effective field containing the exchange and the dipolar field, $\beta$ is a dimensionless parameter describing the strength of the non-adiabatic term, and $\alpha$ is the Gilbert damp-
The blue and red ribbons represent the current density distribution is assumed, as was done recently in Ref. 13. The current-induced vortex core reversal is studied for short Gaussian-shaped current pulses ($\sigma = 100$ ps) of varying strengths. To obtain a core reversal, we found that for the considered sample and for 100 ps pulse duration, the pulse amplitude must exceed a minimum value of $j = 4.7 \times 10^{12}$ A/m$^2$. Although such a high current density might endanger the structural stability of the sample if it was applied continuously, the damaging effects of the current should be small in the present case where only ultrashort pulses are used.

A typical example of the simulated vortex core reversal process is shown in Fig. 1, starting with a vortex whose core is pointing in the positive $z$-direction. The micromagnetic processes leading to the vortex core reversal are identical to the ones described in Ref. 13, where field pulses were used to trigger a vortex core switching. The isosurface representation introduced in Ref. 13 has been used to precisely locate the vortex core. It can be seen that the in-plane magnetization is first heavily distorted as a result of the applied current, which is running through the sample. After ca. 460 ps the distortion eventually leads to the creation of a vortex-antivortex pair, which can unambiguously be recognized by the two additional crossings of the $m_x = 0$ and $m_y = 0$ isosurfaces. Both cores of the new pair are pointing in the opposite $z$-direction of the initial core. The newly formed antivortex and the oppositely polarized initial vortex subsequently annihilate as described in Ref. 13. The latter subprocess unfolds over approximately 10 ps and leaves a single vortex core, which is oppositely polarized with respect to the initial one. The formation of vortex-antivortex pairs after application of short current pulses is consistent with recent experimental observations by Klau{"u} et al. on the domain wall mobility in thin magnetic strips.

FIG. 1: Current-induced vortex core reversal in a Py nanodisk of 200 nm in diameter and 20 nm thickness. A Gaussian current pulse is applied in the sample plane with a strength of $5.2 \times 10^{12}$ A/m$^2$ and a width $\sigma = 100$ ps. On the left, the magnetic structure of the whole sample is shown at equilibrium. In the three frames on the right, the evolution of the magnetization is shown for a small region around the vortex core, where a new vortex-antivortex pair nucleates. As the vortex is shifted in the direction of the electron flow prior to the pair creation, the frames are not taken in the same areas of the sample. The green arrows represent the $x$ and $y$ components of the magnetization, while the cross-sections of the bottom surface of the sample are shown for the $z$ component of the magnetization. The green area represents $m_x = +1$, whereas $m_x = -1$ in the orange area. The blue and red ribbons represent the $m_x = 0$ and $m_y = 0$ isosurfaces, respectively.

The current-pulse induced gyrotropic vortex core motion was investigated.

The current-induced vortex core reversal is studied for short Gaussian-shaped current pulses ($\sigma = 100$ ps) of varying strengths. To obtain a core reversal, we found that for the considered sample and for 100 ps pulse duration, the pulse amplitude must exceed a minimum value of $j = 4.7 \times 10^{12}$ A/m$^2$. Although such a high current density might endanger the structural stability of the sample if it was applied continuously, the damaging effects of the current should be small in the present case where only ultrashort pulses are used.

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FIG. 2: Evolution as a function of time of the total, magnetostatic and exchange energy densities in the Py disk following a current pulse of a duration of $\sigma = 100$ ps and a peak value of $5.2 \times 10^{12}$ A/m$^2$.
By increasing the pulse strength, it is possible to produce multiple switches, as shown in Fig. 3. Such multiple switches are a repeated series of vortex-antivortex pair creation and annihilation processes. In all cases, the total energy is seen to immediately decrease following each core reversal. However, if the energy provided by the current pulse after a core reversal is strong enough to overcompensate the energy dissipation, the energy can still increase before further switches occur. A double core switching is obtained with current pulses of about $6 \times 10^{12}$ A/m$^2$, while triple and quadruple switches occur with pulses of $7 \times 10^{12}$ A/m$^2$ and $9 \times 10^{12}$ A/m$^2$, respectively. Ultimately, for very large currents (above $14 \times 10^{12}$ A/m$^2$), the vortex core is expelled from the sample.

The diagram in Fig. 3 (b) shows the number of core switches as a function of the applied current’s strength. Clear “steps” are observed. While the core reversal mechanism is mediated by the formation of a vortex-antivortex pair, it is the annihilation process which leaves the vortex with an oppositely-polarized core. As shown in Ref.18, such an annihilation is mediated by a magnetic singularity (Bloch point) which is injected through the sample. Since the energy of formation of a Bloch point is uniquely a function of the material exchange constant, the annihilation (and thus the reversal) process can only occur at specific energy values, resulting in the observed steps.

In conclusion, we have presented the possibility of reversing the polarization of a magnetic vortex core using short current pulses. The actual magnetization reversal process, which consists of a complicated sequence of vortex-antivortex pair creation and annihilation events, unfolds on a time scale of ca. 40 ps, i.e. shorter than the duration of the pulses applied in this study. Further investigations are required to explore the limits of the operational range for a controlled, single toggle switching in terms of pulse duration and pulse strength, and to determine how short a current pulse can be to trigger a vortex core reversal. The current-induced vortex core reversal opens the possibility of addressing individual magnetic elements in a vortex state within an array of nanoelements. This feature, in combination with the small size of magnetic vortex cores, their high thermal stability and the high speed of the reversal process could make vortex cores interesting candidates for data storage purposes in future devices.

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1. R. P. Cowburn, D. K. Koltssov, A. O. Adeyeye, M. E. Welland, and D. M. Tricker, Phys. Rev. Lett. 83, 1042 (1999).
2. J. Miltat and A. Thiaville, Science 298, 555 (2002).
3. T. Shinjo, T. Okuno, R. Hassdorf, K. Shigeto, and T. Ono, Science 289, 930 (2000).
4. T. Gerrits, H. van den Berg, J. Hohlfeld, L. Bär, and T. Rasing, Nature 418, 509 (2002).
5. S. B. Choe, Y. Acreman, A. Scholl, A. Bauer, A. Doran, J. Stohr, and H. A. Padmore, Science 304, 420 (2004).
6. J. P. Park, P. Eames, D. M. Engebretson, J. Berezovsky, and P. A. Crowell, Phys. Rev. B 67, 024003(R) (2003).
7. A. Wachowiak, J. Wiebe, M. Bode, O. Pietzsch, M. Morgenstern, and R. Wiesendanger, Science 298, 577 (2002).
8. B. Van Waeyenberge, A. Puzic, H. Stoll, K. W. Chou, T. Tyliszczak, R. Hertel, M. Fähnle, H. Brückl, K. Rott, G. Reiss, et al., Nature 444, 461 (2006).
9. R. Hollinger, A. Killinger, and U. Krey, J. Magn. Magn. Mater. 261, 178 (2003).
10. T. Okuno, K. Shigeto, T. Ono, K. Mibu, and T. Shinjo, J. Magn. Magn. Mater. 240, 1 (2002).
11. B. E. Argyle et al., Phys. Rev. Lett. 53, 190 (1984).
12. M. Fähnle, private communication.
13. R. Hertel, S. Gliga, M. Fähnle, and C. M. Schneider, cond-mat 0611668 (2006), (accepted for publication in Phys. Rev. Lett.).
14. R. Hertel, W. Wulfhekel, and J. Kirschner, Phys. Rev. Lett. 93, 257202 (2004).
15. S. Zhang and Z. Li, Phys. Rev. Lett. 93, 127204 (2004).
16. A. Thiaville, Y. Nakatani, J. Miltat, and Y. Suzuki, Europhys. Lett. 69, 990 (2005).
17. S. Kassai, Y. Nakatani, K. Kobayashi, H. Kohno, and T. Ono, Phys. Rev. Lett. 97, 107204 (2006).
18. R. Hertel and C. M. Schneider, Phys. Rev. Lett. 97, 177202 (2006).
19. M. Klüui, M. Laufenberg, L. Heyne, D. Backes, U. Rüdiger, C. A. F. Vaz, J. A. C. Bland, L. J. Heyderman, S. Cherifi, A. Locatelli, et al., Appl. Phys. Lett. 88, 232507 (2006).
20. O. A. Tretiakov and O. Tchernyshyov, Phys. Rev. B 75, 012408 (2007).