Current induced switching of vortex polarity in magnetic nanodisks

Denis D. Sheka[a)]
National Taras Shevchenko University of Kiev, 03127 Kiev, Ukraine

Yuri Gaididei
Institute for Theoretical Physics, 03143 Kiev, Ukraine

Franz G. Mertens
Physics Institute, University of Bayreuth, 95440 Bayreuth, Germany

(Received 22 June 2007; accepted 31 July 2007; published online 24 August 2007)

It is shown that the vortex polarity can be irreversibly switched by injecting a spin-polarized direct electrical current, which flows perpendicular to the disk plane. Intensive numerical spin-lattice simulations demonstrate that the switching process involves a vortex-antivortex pair creation. This differs from magnets with no dipolar interaction, where the spin dc acts similar to a static magnetic field. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2775036]

The spin torque effect, which is the change of magnetization due to the interaction with an electrical current, was predicted by Slonczewski[1] and Berger[2] in 1996. During the last decade, this effect was tested in different magnetic systems[3–5] and, nowadays, it plays an important role in spintronics.[6,7] Recently, the spin torque effect was observed in vortex state nanoparticles. In particular, circular vortex motion can be excited by an ac (Ref. 8) or a dc (Ref. 9) spin-polarized current. Very recently, it was predicted theoretically[10] and observed experimentally[11] that the vortex polarity can be controlled using a spin-polarized current. This opens up the possibility of realizing electrically controlled magnetic devices, changing the direction of modern spintronics.[12]

In this letter, we study the magnetic vortex dynamics in nanodots excited by the spin-polarized current, using the pillar structure.[10] In Ref. 10, we considered the case of infinitesimally thin nanomagnets when the role of the demagnetization field (dipolar interaction) is reduced to an effective uniaxial anisotropy.[13] In the present study, we consider a more realistic model with account of a nonlocal dipolar interaction. Qualitatively speaking, in addition to the effective uniaxial anisotropy of the easy-plane type, there appears here a nonhomogeneous effective in-plane anisotropy (surface anisotropy).[14] Due to the surface anisotropy, the magnetization near the disk edge is constrained to be tangential to the boundary, which prevents its precession near the edge. That is why a simple picture of rotational vortex, which perfectly works for the Heisenberg magnet[10] should be revised for the nanodot with account of the dipolar interaction.

The magnetic energy of nanodots consists of two parts: Heisenberg exchange and dipolar interactions:[15]

$$\mathcal{H} = -\frac{\ell}{2}\sum_{(n,\delta)} \boldsymbol{S_n}\cdot\boldsymbol{S_{n+\delta}} + \frac{1}{8\pi}\sum_{\substack{n,m\\ n\neq m}} \frac{\boldsymbol{S_n}\cdot\boldsymbol{S_m} - 3(\boldsymbol{S_n}\cdot\boldsymbol{e_{nm}})(\boldsymbol{S_m}\cdot\boldsymbol{e_{nm}})}{|\boldsymbol{n}-\boldsymbol{m}|^3}. \quad (1)$$

Here, $\boldsymbol{S_n}$ is a unit vector which determines the spin direction at the lattice point $\boldsymbol{n}$, $\ell=\sqrt{A/(\mu_0 M_S^2)}$ is the exchange length (A is the exchange constant, μ_0 is the vacuum permeability, and M_S is the saturation magnetization), the vector δ connects nearest neighbors, and $\boldsymbol{e_{mn}}\equiv(\boldsymbol{n}-\boldsymbol{m})/|\boldsymbol{n}-\boldsymbol{m}|$ is a unit vector. The lattice constant is chosen as a unity length.

It is known that as a result of competition between the exchange interaction and the dipolar one, the ground state of a thin magnetically soft nanodisk is a vortex state: the magnetization lies in the disk plane XY in the main part of the disk being parallel to the disk edge, forming the magnetic flux-closure pattern characterized by the vorticity $q=+1$. At the disk center, the magnetization distribution forms a vortex core, which is oriented either parallel or antiparallel to the z axis. The former is characterized by a polarity $p=+1$ and the latter $p=-1$. When electrical current is injected in the pillar structure, perpendicular to the nanodisk plane, it influences locally the spin $\boldsymbol{S_n}$ of the lattice through the spin torque,[1,2]

$$\boldsymbol{T_n} = j\sigma\mathcal{A}\frac{\boldsymbol{S_n}\times[\boldsymbol{S_n}\times\hat{z}]}{1+\sigma\mathcal{B}\boldsymbol{S_n}\cdot\hat{z}}. \quad (2)$$

Here, $j=J_e/J_p$ is a normalized spin current, J_e is the electrical current density, $J_p=\mu_0 M_S^2|e|d/\hbar$, d is the disk thickness, e is the electron charge, $\mathcal{A}=4\eta^{3/2}/[3(1+\eta)^3-16\eta^{3/2}]$, $\mathcal{B}=(1+\eta)^3/[3(1+\eta)^3-16\eta^{3/2}]$, and $\eta\in(0;1)$ denotes the degree of the spin polarization; $\sigma=\pm1$ gives two directions of spin-current polarization.

The spin dynamics of the system is described by the modified Landau-Lifshitz-Gilbert equation,

$$\dot{\boldsymbol{S}}_{\boldsymbol{n}} = -\boldsymbol{S_n}\times\frac{\partial\mathcal{H}}{\partial\boldsymbol{S_n}} - \alpha\boldsymbol{S_n}\times\dot{\boldsymbol{S}}_{\boldsymbol{n}} + \boldsymbol{T_n}. \quad (3)$$

Here, the overdot indicates the derivative with respect to the dimensionless time $\tau=\omega_0 t$ with $\omega_0=4\pi\gamma M_S$, $\alpha\ll1$ is a damping coefficient, and $\mathcal{H}$ is the Hamiltonian [Eq. (1)].

To study the vortex dynamics, we have performed numerical simulations of the discrete spin-lattice Eq. (3). We consider the case of thin nanodots where the magnetization does not depend on the z coordinate. We have integrated numerically the set of Eq. (3) over the square lattice using the fourth-order Runge-Kutta scheme with the time step $\Delta\tau$

[a)]Author to whom correspondence should be addressed; electronic mail: denis_sheka@univ.kiev.ua

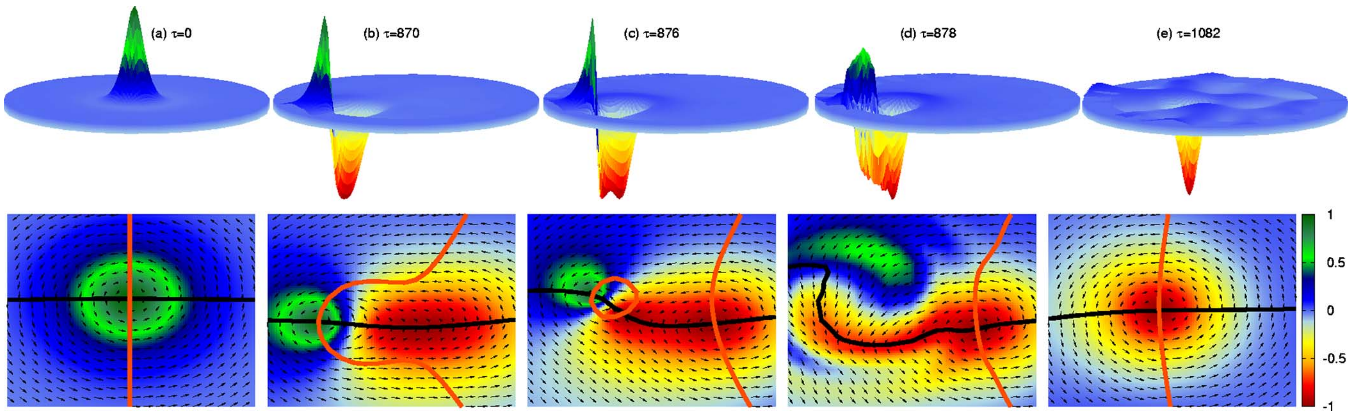

FIG. 1. (Color online) Time evolution of the vortex switching process from simulations: the top row shows the three-dimensional distribution of the magnetization z component, the bottom row corresponds to the in-plane magnetization distribution near the vortex core. Isosurfaces $S_x=0$ (black curve) and $S_y=0$ (orange curve) are plotted to determine the vortex position. The current $j=-0.1$.

$=0.01$.[16] The lattice is bounded by a circle of diameter $2L$. In most of the simulations, $2L=100$, $h=10$, $\ell=2.65$, $\alpha=0.01$, $\sigma=+1$, and $\eta=0.26$.

As an initial condition, we use the vortex centered in the disk origin [see Fig. 1(a)]. To identify precisely the vortex position we use, similar to Ref. 17, the cros section of isosurfaces $S_x=0$ and $S_y=0$ (see the bottom row of Fig. 1). The vortex dynamics results from the force balance between a driving force (by the current), a dipolar force, a gyroscopical force, and a dissipative force. In the simulations, we observe that when the vortex and the spin current have the same polarization ($j\sigma p>0$) the vortex does not quit the center of the disk. However, for $j\sigma p<0$ ($p=+1$, $\sigma=+1$ and $j<0$ in our case), the vortex under the action of the current starts to move out of the disk center following a spiral trajectory [see Fig. 2(a)]. The spiral type of motion is caused by the gyroscopical force, which acts on a moving vortex perpendicular to its velocity in the same way as a Lorentz force acts on a charged particle in a magnetic field. The role of the charge plays a π_2 topological charge $Q=qp/2$. The sign of Q determines the direction of the vortex motion, which is clockwise for $p=+1$. At some point (marked on Figs. 2 by the green symbol), the vortex switches its polarity ($p=-1$). As is seen from Fig. 1, the mechanism of the vortex switching is very similar to the one observed in other systems.[11,18–22] The moving vortex excites a nonsymmetric magnon mode with a dip situated toward the disk center. When the vortex moves away from the center, the amplitude of the dip increases [see Fig. 1(b)]. When the depth of the dip reaches a minimum ($S_z=-1$), a pair of a new vortex and antivortex is created [see Fig. 1(c)]. The reason why the newborn vortex tears off his partner has a topological origin. The gyroscopic force depends on the total topological charge Q. Therefore, it produces a *clockwise* motion for the original vortex ($q=1$, $p=1$, $Q=1/2$) and the newborn antivortex ($q=-1$, $p=-1$, $Q=1/2$) while the newborn vortex ($q=1$, $p=-1$, $Q=-1/2$) moves in the *anticlockwise* direction. As a result, the new vortex separates from the vortex-antivortex pair and rapidly moves to the origin [see Figs. 1(e) and 2(b)]. The attractive force between the original vortex ($q=1$) and the antivortex ($q=-1$) facilitates a binding and subsequent annihilation of the vortex-antivortex pair [see Fig. 1(d)]. The supplementary video illustrates the whole evolution during the switching process.[23]

The switching process has a threshold behavior. It occurs when the current $|j|>j_{sw}$, which is about 0.0102 in our simulations [see Fig. 3]. For stronger currents, the switching time rapidly decreases. Using typical parameters for Permalloy disks[10,22] ($\eta=0.26$, $A=26$ pJ/m, $M_S=860$ kA/m, and $\alpha=0.01$), we estimate that the time unit $1/\omega_0=50$ ps and the critical current density is about 0.1 A/μm^2 for a nanodot of 20 nm thickness. The total current for a disk with diameter of 200 nm is about 10 mA.

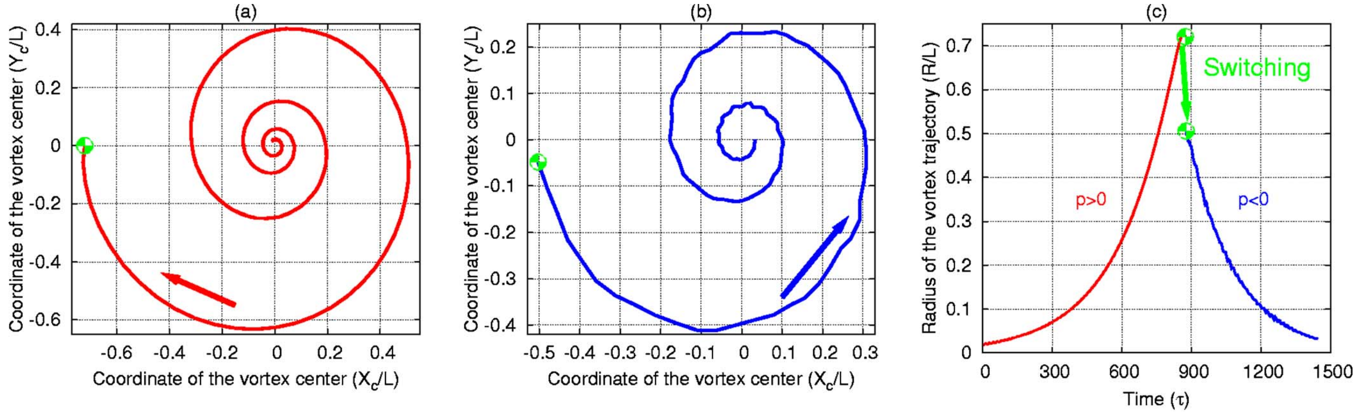

FIG. 2. (Color online) Vortex dynamics for $j=-0.1$. The vortex trajectory before the switching (a) and after it (b). The radius of the vortex trajectory as a function of time (c). At $\tau=877$ the vortex polarity is switched.

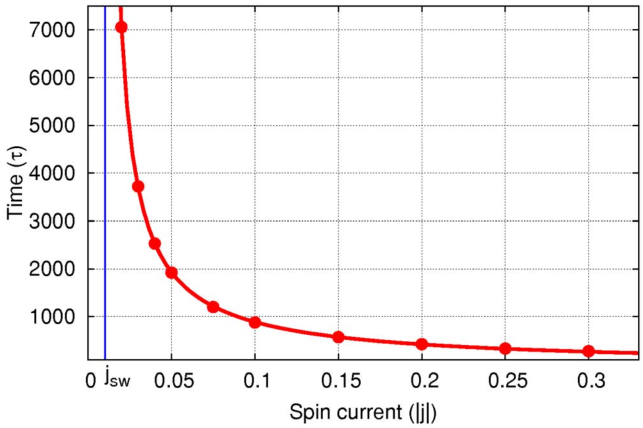

FIG. 3. (Color online) Switching time as a function of the applied current.

To summarize, we have studied the magnetic vortex switching under the action of a dc electrical current. We showed that the switching mechanism is essentially the same as in the cases when it is induced by a magnetic field pulse,[18–20] by an ac oscillating[21] or rotating field,[22] or by an in-plane electrical current.[11] There are two key points in this process: (i) the dipolar interaction causes the deformation of the magnetization profile for the fast moving vortex, which finally results in the creation of an additional vortex-antivortex pair, and (ii) the topological charge structure of these three excitations secures the survival of the vortex with the new polarity direction or, in other words, the polarity switching. The detailed study of the vortex dynamics including the switching process is under construction.

The authors thank S. Komineas and V. Kravchuk for helpful discussions. Two of the authors (D.D.S. and Y.G.) thank the University of Bayreuth, where this work was performed, for kind hospitality and acknowledge the support from DLR Grant No. UKR 05/055. One of the authors (D.D.S.) acknowledges the support from the Alexander von Humboldt Foundation.

[1]J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
[2]L. Berger, Phys. Rev. B **54**, 9353 (1996).
[3]M. Tsoi, A. G. M. Jansen, J. Bass, W.-C. Chiang, M. Seck, V. Tsoi, and P. Wyder, Phys. Rev. Lett. **80**, 4281 (1998).
[4]E. B. Myers, D. C. Ralph, J. A. Katine, R. N. Louie, and R. A. Buhrman, Science **285**, 867 (1999).
[5]I. N. Krivorotov, N. C. Emley, J. C. Sankey, S. I. Kiselev, D. C. Ralph, and R. A. Buhrman, Science **307**, 228 (2005).
[6]Y. Tserkovnyak, A. Brataas, G. E. W. Bauer, and B. I. Halperin, Rev. Mod. Phys. **77**, 1375 (2005).
[7]C. H. Marrows, Adv. Phys. **54**, 585 (2005).
[8]S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, and T. Ono, Phys. Rev. Lett. **97**, 107204 (2006).
[9]V. S. Pribiag, I. N. Krivorotov, G. D. Fuchs, P. M. Braganca, O. Ozatay, J. C. Sankey, D. C. Ralph, and R. A. Buhrman, Nat. Phys. **3**, 498 (2007).
[10]J.-G. Caputo, Y. Gaididei, F. G. Mertens, and D. D. Sheka, Phys. Rev. Lett. **98**, 056604 (2007).
[11]K. Yamada, S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, A. Thiaville, and T. Ono, Nat. Mater. **6**, 270 (2007).
[12]R. P. Cowburn, Nat. Mater. **6**, 255 (2007).
[13]G. Gioia and R. D. James, Proc. R. Soc. London, Ser. A **453**, 213 (1997).
[14]J.-G. Caputo, Y. Gaididei, V. P. Kravchuk, F. G. Mertens, and D. D. Sheka, e-print arXiv:0705.1555.
[15]A. I. Akhiezer, V. G. Bar'yakhtar, and S. V. Peletminskiĭ, *Spin Waves* (North-Holland, Amsterdam, 1968).
[16]Note that the discrete Eqs. (3), being ODEs, require only initial conditions.
[17]R. Hertel and C. M. Schneider, Phys. Rev. Lett. **97**, 177202 (2006).
[18]V. B. Waeyenberge, A. Puzic, H. Stoll, K. W. Chou, T. Tyliszczak, R. Hertel, M. Fahnle, H. Bruckl, K. Rott, G. Reiss, I. Neudecker, D. Weiss, C. H. Back, and G. Schutz, Nature (London) **444**, 461 (2006).
[19]Q. F. Xiao, J. Rudge, B. C. Choi, Y. K. Hong, and G. Donohoe, Appl. Phys. Lett. **89**, 262507 (2006).
[20]R. Hertel, S. Gliga, M. Fahnle, and C. M. Schneider, Phys. Rev. Lett. **98**, 117201 (2007).
[21]K.-S. Lee, K. Y. Guslienko, J.-Y. Lee, and S.-K. Kim, e-print arXiv:cond-mat/0703538.
[22]V. P. Kravchuk, D. D. Sheka, Y. Gaididei, and F. G. Mertens, J. Appl. Phys. (to be published).
[23]Supplementary video, http://www.phy.uni-bayreuth.de/~btp315/publ/Sheka.arXiv.0706.3172.html