# Static and dynamic properties of vortices in anisotropic magnetic disks

Tiago S. Machado,[1] Tatiana G. Rappoport,[2] and Luiz C. Sampaio[1,a)]
[1]*Centro Brasileiro de Pesquisas Físicas, Xavier Sigaud, 150, Rio de Janeiro 22.290-180, Brazil*
[2]*Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro 68.528-970, Brazil*

(Received 30 July 2008; accepted 28 August 2008; published online 19 September 2008)

We investigate the effect of the magnetic anisotropy ($K_z$) on the static and dynamic properties of magnetic vortices in small disks. Our micromagnetic calculations reveal that for a range of $K_z$ there is an enlargement of the vortex core. We analyze the influence of $K_z$ on the dynamics of the vortex core magnetization reversal under the excitation of a pulsed field. The presence of $K_z$, which lead to better resolved vortex structures, allows us to discuss in more details the role played by the in-plane and perpendicular components of the gyrotropic field during the vortex-antivortex nucleation and annihilation. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2985901]

The manipulation of magnetization in nanostructured materials by means of magnetic field and/or spin polarized current has attracted substantial attention in the past decade. More recently, a special focus on the study of magnetization reversal dynamics in magnetic disks[1] and lines[2] has been motivated mainly by their potential importance in the implementation of memory and logical operations.

Microsized Permalloy (Py) disks can exhibit a magnetic vortex with a core (~10–20 nm) magnetized perpendicular to the disk plane.[3] The vortex core magnetization reversal can be achieved by applying an in-plane magnetic field or spin polarized current in the form of short pulses[4] and/or alternating (ac) resonant excitation.[1,5,6]

It is usually considered that the size of the vortex core depends on parameters such as exchange constant, thickness, and diameter of the magnetic disk. Most of the research on vortices in magnetic systems neglects the effect of magnetic anisotropy. On the other hand, it has been demonstrated that a uniaxial magnetic anisotropy in Permalloy particles can be induced by the deposition process.[7] Experiments and simulations have also shown that the presence of anisotropy in thick magnetic disks gives rise to a diversity of domain patterns.[7,8]

In this letter, we study the role played by the magnetic anisotropy in the magnetic properties of disks. Using micromagnetic simulations, we consider a magnetic anisotropy ($K_z$) perpendicular to the disk plane and analyze how it modifies the magnetization pattern and the dynamics of the vortex core under action of an in-plane pulsed magnetic field. We also discuss the influence of $K_z$ on the gyrotropic field and the magnetization reversal time.

The simulations were performed with a code we developed, which employs the Landau–Lifshitz–Gilbert equation. We used the typical magnetic parameters of Py: the saturation magnetization is given by $M_s=8.6\times10^5$ A/m, the exchange coupling is $A=1.3\times10^{-11}$ J/m, and the Gilbert damping constant is $\alpha=0.2$. The magnetic anisotropy was included in the total effective magnetic field $\boldsymbol{h}_{\text{eff}}$ and is given by $(2K_z/\mu_0M_s^2)m_z\hat{z}$.[9] $K_z$ varies from 0 to $10^6$ J/m$^3$. We have simulated Py disks with the diameter of 300 nm and thickness of 12 nm. The disk is discretized in cells of $3\times3\times3$ nm$^3$.

Let us first consider the vortex core structure in static equilibrium. The magnetization pattern of the Py disk presents three characteristic regimes, as can be seen in Figs. 1(b)–1(f): for $K_z$ below $2.5\times10^5$ J/m$^3$ the main consequence of increasing $K_z$ is an increase in the vortex core diameter. The size of the vortex core is measured at half of the maximum value of $m_z$ and its dependence with $K_z$ is shown in Fig. 1(a). For $K_z$ between $2.5\times10^5$ and $4.0\times10^5$ J/m$^3$, $m_z$ exhibits concentric regions with $+M_s$ and $-M_s$, still preserving the core at the center of the disk. For $K_z$ between $4\times10^5$ and $6\times10^5$ J/m$^3$ the core disappears and the number of concentric rings increases, which also happens for larger disks. Moreover, in these two ranges, the in-plane magnetization still preserves the vorticity [see Figs. 1(d) and 1(e)]. The similarity between these patterns and previous observed patterns in Co nanomagnets[10] and thick NiFe nanodisks[7] is noteworthy. For $K_z$ above $6\times10^5$ J/m$^3$, the vortex structure is lost and we see what amounts to a single domain in $m_z$ [Fig. 1(f)]. For larger and thinner disks, the magnetization pattern is composed by stripes.

The prospect of having large vortex cores has clear advantages for magnetization detection. Still, in order to consider the practical aspects it is necessary to study the stability of these vortex cores and the possibility of switching their

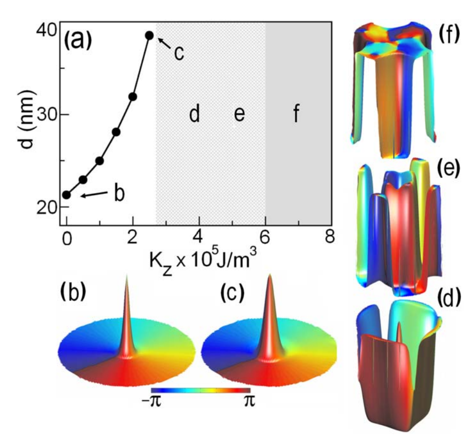


FIG. 1. (Color online) (a) The diameter $d$ of the vortex core as a function of $K_z$ for a disk with diameter of 300 nm and thickness of 12 nm. Panels (b)–(f) show the magnetization pattern for increasing values of $K_z$, illustrating the different regimes of (a). The colors represent the direction of the in-plane component of the magnetization $m_{xy}$. A vortex structure is given by a clockwise color sequence of blue-green-red.

a)Electronic mail: sampaio@cbpf.br.

 

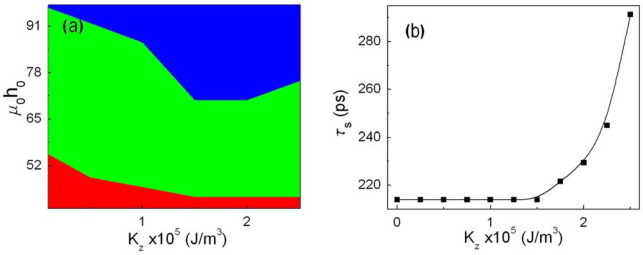


FIG. 2. (Color online) (a) Switching vortex core magnetization diagram for magnetic field pulse strength $B_0$ and $K_z$. Red, green, and blue colors represent no, one, and multiple switches, respectively. (b) Switching time $\tau_s$ as a function of $K_z$ for $B_0$=64 mT.

magnetization. For this purpose, we studied the dynamics of the system under short in-plane magnetic field pulses. We simulated the magnetic reversal process and constructed a switching diagram. Similar diagrams have been constructed recently for magnetic disks.[4,6] They show that the operating field range is narrow: low fields do not produce core switching. On the other hand, higher fields can give rise to multiple switchings.

In order to discuss the influence of $K_z$ on this process, we built the diagram sketched in Fig. 2(a). We use a Gaussian pulse with a fixed duration ($\tau_p$=263 ps), a variable field strength $B_0$, and direction $-\hat{x}$. For each value of $K_z$, we count the number of core magnetization inversions during a single pulse length. Figure 2(a) shows three different dynamical regimes in response to the exciting field. In the absence of magnetic anisotropy, the field that is necessary to switch the core magnetization is $B_0$=60 mT. However, for fields higher than 95 mT undesirable multiple switches are produced. For disks with $K_z \neq 0$, the pulse necessary to induce the switching process has a strength comparable to the $K_z$=0 case. As can be seen in Fig. 2(a), an important consequence of increasing $K_z$ is the decrease in the minimum field necessary to produce a single switch. Such dependence on $K_z$, for this minimal field, opens the possibility of producing selective vortex inversions in a group of magnetic disks with different $K_z$'s.

Another interesting aspect of the influence of $K_z$ can be seen in the switching time $\tau_s$, which is the interval between the pulse start and the complete reversal of the vortex core magnetization. We have calculated $\tau_s$ for $B_0$=64 mT in the single switching regime. $\tau_s$ for $K_z$=0 is 213 ps and it increases monotonically with $K_z$, reaching values $\simeq$1.4 times larger than $\tau_s(K_z=0)$ [Fig. 2(b)]. For thinner disks (6 nm) $\tau_s$ can reach up to $2.5\tau_s(K_z=0)$.

A closer look at the core reversal dynamics for disks with $K_z \neq 0$ shows that the intermediate processes leading to the switching are similar to the ones obtained in previous analysis for $K_z$=0.[1,4,5,11,12] The vortex core magnetization, reversal, its switching time, the core motion, and its deformations can be understood in terms of the gyrotropic field,[1,11] which acts on the vortex core only during its movement. The gyrotropic field is given by $\mathbf{h}_g=(1/\gamma)\mathbf{m}\times(\mathbf{v}\cdot\nabla\mathbf{m})$,[1,11] where $\gamma$ and $\mathbf{v}$ are the gyromagnetic factor and the core velocity, respectively. Indeed, using Thiele's equation[13] in its original form, $\mathbf{h}_g$ can be simplified using $\dot{\mathbf{m}}$ instead of $\mathbf{v}$, and it is reduced to $\mathbf{h}_g=-(1/\gamma)\mathbf{m}\times\dot{\mathbf{m}}$. All calculations shown below were performed with this last expression of $\mathbf{h}_g$.

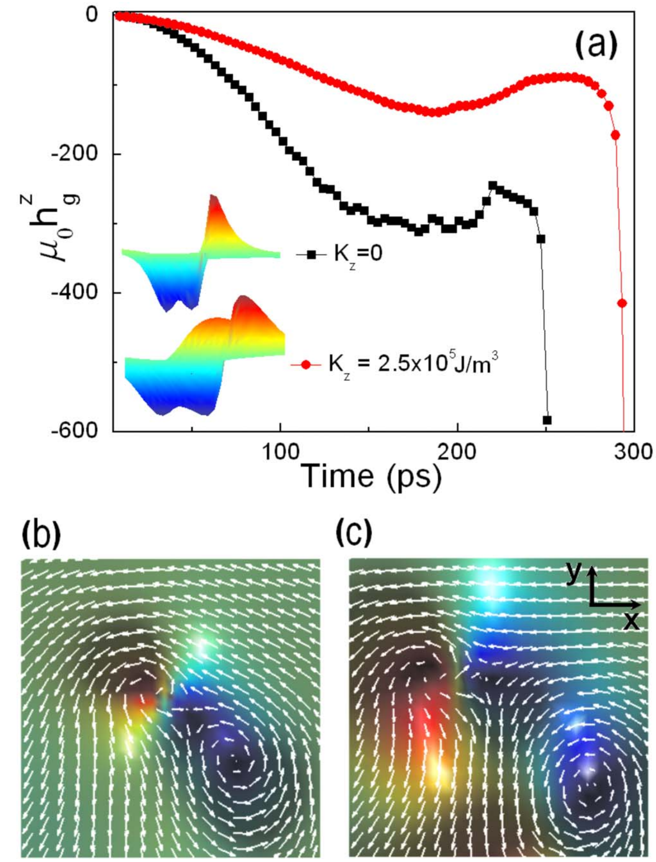


FIG. 3. (Color online) (a) Time evolution of the gyrotropic field (perpendicular component). Snapshots of vortices and antivortex for (b) $K_z$=0 at the maxima of the gyrotropic field and (c) $K_z=2.5\times10^5$ J/m$^3$. The color map represents $m_z$ and the arrows show the in-plane component. The inset of panel (a) gives a transverse view of $m_z$.

Previous discussions on $\mathbf{h}_g$ have emphasized the role of the perpendicular component of this effective field in the reversal process.[11] To further investigate this, we have calculated the perpendicular $\mathbf{h}_g^z$ and the in-plane $\mathbf{h}_g^{xy}$ component as well. First, we discuss the time evolution of the perpendicular component $\mathbf{h}_g^z$ for $K_z$=0 and $2.5\times10^5$ J/m$^3$, which is shown in Fig. 3(a). Following the application of the field pulse, the core moves and $\mathbf{h}_g^z$ acts on the core at the side opposite to the movement direction leading to the formation of a peak with negative magnetization. At this stage, it is just a peak without a vortex structure. $\mathbf{h}_g^z$ increases (in modulus) until the point where the peak is so wide that it leads to the nucleation of a vortex-antivortex pair, labeled as $V^-$-$AV^-$, respectively. In conjunction with this $V^-$-$AV^-$ nucleation there is a decrease in $|\mathbf{h}_g^z|$. Subsequently, the $AV^-$-$V^+$ annihilation takes place at the $\mathbf{h}_g^z$ divergence. This divergence is in agreement with Ref. 11. Such behavior is independent of $K_z$ but it is worth noticing that the separation of the $V^-$-$AV^-$ is better resolved spatially and takes place after an interval that is longer than the one for $K_z$=0. This can be seen in the inset of Fig. 3(a), and in the comparison of Figs. 3(b) and 3(c). On the right, one sees the $V^+$ with a close neighbor at its left, which is the $AV^-$. Further on the left, one sees the $V^-$. As can be gathered from the figures, $|\mathbf{h}_g^z|$ decreases for increasing values of $K_z$ and that is the reason for the increase of $\tau_s$.

One of the main advantages of considering $K_z \neq 0$ in our calculations is the large separation between the V's and AV's

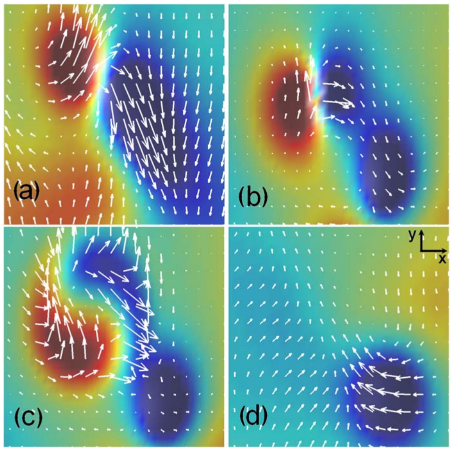


FIG. 4. (Color online) In-plane component of the gyrotropic field (arrows) just (a) before and [(b)–(d)] after the nucleation and separation of the vortex and antivortex with negative magnetizations. The color map represents the out-of-plane magnetization.

involved in the switching process. This allows us to analyze the structure of the gyrotropic field in between these vortex structures. We calculated the $\mathbf{h}_g^{xy}$ component during the $V^-$-$AV^-$ nucleation and separation, which are fundamental steps in the process of core magnetization reversal. Figure 4(a) shows $\mathbf{h}_g^{xy}$ for an instant just before the $V^-$-$AV^-$ nucleation and separation. The color map and the arrows illustrate $m_z$ and $\mathbf{h}_g^{xy}$, respectively. The red circle is the original $V^+$ and the blue one is the negative peak. We can see from Figs. 4(a) and 4(b) that $\mathbf{h}_g^{xy}$ is responsible for the transformation of this wide negative peak into a $V^-$-$AV^-$ pair and acts as a driving force that pushes $V^-$. As can be seen in Fig. 4(b), $\mathbf{h}_g^{xy}$ pushes the $AV^-$ in the direction of $V^+$, producing the pair annihilation. In Fig. 4(c) it is also possible to observe spin waves generated by the $AV^-$-$V^+$ annihilation. In Fig. 4(d), we can see the remaining $V^-$. The analysis of the two components of $\mathbf{h}_g$ shows explicitly the dynamics responsible for the $V^-$-$AV^-$ nucleation, *its separation* and the $AV^-$-$V^+$ annihilation. Considering only the perpendicular component of $\mathbf{h}_g$, together with the vorticity conservation, one is able to explain the $AV^-$-$V^+$ annihilation but not the $V^-$-$AV^-$ nucleation and separation process.

In conclusion, we presented a detailed analysis of the influence of $K_z$ on static and dynamic properties of magnetic vortices in disks. We showed that increasing values of $K_z$ produce a growth of the vortex core and a change in the magnetization pattern. We then obtained, by means of dynamical calculations, that both in-plane and perpendicular components of the gyrotropic field ($\mathbf{h}_g^z$ and $\mathbf{h}_g^{xy}$) contribute and are fundamental to the understanding of the vortex core magnetization reversal process.

We thank Flávio Garcia for useful discussions and the Brazilian agencies CNPq and FAPERJ for financial support.

[1] K. Yamada, S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, A. Thiaville, and T. Ono, Nat. Mater. **6**, 269 (2007).
[2] S. S. P. Parkin, M. Hayashi, and L. Thomas, Science **320**, 190 (2008), and references therein.
[3] T. Shinjo, T. Okuno, R. Hassdorf, K. Shigeto, and T. Ono, Science **289**, 930 (2000); A. Wachowiak, J. Wiebe, M. Bode, O. Pietzsch, M. Morgenstern, and R. Wiesendanger, *ibid.* **298**, 577 (2002).
[4] R. Hertel, S. Gliga, M. Fähnle, and C. M. Schneider, Phys. Rev. Lett. **98**, 117201 (2007).
[5] B. Van Waeyenberge, A. Puzic, H. Stoll, K. W. Chou, T. Tyliszczak, R. Hertel, M. Fhnle, H. Brckl, K. Rott, and G. Reiss, Nature (London) **444**, 461 (2006).
[6] K.-S. Lee, K. Y. Guslienko, J.-Y. Lee, and S.-K. Kim, Phys. Rev. B **76**, 174410 (2007).
[7] P. Eames and E. Dan Dahlberg, J. Appl. Phys. **91**, 7986 (2002).
[8] C. Moutafis, S. Komineas, C. A. F. Vaz, J. A. C. Bland, and P. Eames, Phys. Rev. B **74**, 214406 (2006).
[9] J. Fidler and T. Schrefl, J. Phys. D: Appl. Phys. **33**, 135 (2000).
[10] M. Hehn, K. Ounadjela, J. P. Bucher, F. Rousseaux, D. Decanini, B. Bartelian, and C. Chappert, Science **272**, 1782 (1996).
[11] K. Y. Guslienko, K.-S. Lee, and S.-K. Kim, Phys. Rev. Lett. **100**, 027203 (2008).
[12] Q. F. Xiao, J. Rudge, B. C. Choi, Y. K. Hong, and G. Donohoe, Appl. Phys. Lett. **89**, 262507 (2006).
[13] A. A. Thiele, Phys. Rev. Lett. **30**, 230 (1973).