Inhomogeneous states in permalloy nanodisks with point defects

Afranio R. Pereira
Departamento de Física, Universidade Federal de Viçosa, Viçosa, 36570-000 Minas Gerais, Brazil
(Received 26 August 2004; revised manuscript received 2 February 2005; published 1 June 2005)

We investigate the effects that lithographically defined defects cause on the vortex structure in magnetic submicron-size disks. It is shown that the vortex is attracted and pinned by point defects. The pinning potential is estimated taking into account both exchange and magnetostatic effects. The influence of an external magnetic field is also considered.

DOI: 10.1103/PhysRevB.71.224404 PACS number(s): 75.75.+a, 75.60.Ch, 75.70.Rf

Recent progresses of nanotechnology have resulted in materials with large potential applications, which include high-density magnetic storage using an array of dot structures[1,2] as well as high-resolution magnetic field sensors.[3] As a consequence, there is a great interest in the micromagnetic properties of nanostructured magnetic thin films. The application of magnetic particle in devices requires reproducible controllable switching behavior between well-defined magnetic configurations. In this respect, magnetic vortex structures, which are frequently observed in submicron-sized ferromagnetic particles, may play an important role. Many features of vortex behavior in nanodots of several shapes have been studied experimentally and theoretically by many authors.[4–9] In general, these works do not consider possible irregularities on the dot structure. Influence of defects on the magnetization distribution may also lead to interesting applications. For instance, it might be advantageous to keep the magnetic nanoparticle of proper shape in the vortex state and to move the vortex core between artificial pinning sites, instead of reversing the magnetization of the nanoparticle as a whole. Recently, it has become possible the fabrication of disk-shaped permalloy particle, which contain a single or more lithographically defined defects.[10–12] Measurements of the magnetization reversal in these nanodisks with holes indicate that the magnetic vortex structure can be manipulated intentionally.[10–12] In fact, micromagnetic simulations and experiments of Refs. 10 and 11 have shown that a vortex core can be pinned at a point defect if the trajectory of the vortex core moves toward the defect. However, to the author's knowledge, there are not any analytical results concerning the vortex-hole interactions for this problem. Of course, any attempts to develop an analytical approach for studying magnetic vortices in a submicrodisk is worthwhile. The object of this paper is to study the vortex behavior near such hole defects using analytical calculations. We employed a model that combines the rigid vortex model[7,13] and a recent impurity model proposed to study the vortex-vacancy interactions in layered magnets.[14–16] This combination is not so simple since the impurity model has to be adjusted to the magnetostatic energy present in a finite system such a nanoparticle. It should be noted that the rigid vortex model is considered effective for qualitative understanding for the case of small enough vortex displacements.[7,13] At the same time, the impurity model[14–16] can make reasonable predictions about the behavior of the interactions between topological excitations and nonmagnetic impurities in two-dimensional magnets. Concerning the vortex behavior near the point defect in a nanodisk, our calculations are in qualitative agreement with experiments and micromagnetic simulations of Ref. 11.

We shall start describing the magnetic dot as a small cylinder having thickness L and radius R, with aspect ratio $L/R \ll 1$. Therefore we can assume that the magnetization $\vec{M}$ along the z axis (the cylinder symmetry axis) is uniform. Thus, in the continuum limit, the energy can be approximated by an integral over the dot plane as follows:

$$W = \frac{1}{2}L \int \int_D [A(\partial_\mu \vec{m})(\partial^\mu \vec{m}) - M_s^2 \vec{m} \cdot \vec{h}_m] U(\vec{r} - \vec{r}_0) d^2 r, \tag{1}$$

$\mu = 1,2$, where A is the exchange constant, $\vec{m} = \vec{M}/M_s$ is a unit vector describing the magnetization distribution, M_s being the saturation magnetization, D is the area of the cylinder face, $\vec{r} = (x,y)$ is a point on the face, and $\vec{h}_m = \vec{H}_m / M_s$ is the demagnetizing field (a function of $\vec{m}$) created by the magnetization distribution. The function $U(\vec{r} - \vec{r}_0)$ describes a defect hole centralized at $\vec{r}_0$, and in the simplest and symmetric case, it can be defined as $U(\vec{r} - \vec{r}_0) = 0$ if $|\vec{r} - \vec{r}_0| < \rho$ and $U(\vec{r} - \vec{r}_0) = 1$ if $|\vec{r} - \vec{r}_0| \geq \rho$. In this definition, the defect is seen as a small cylindrical cavity of radius $\rho \ll R$, hallowed out from the nanodisk structure and centralized at distance r_0 away from origin (the disk center). Such disk-shaped permalloy particles with diameters between 300 and 800 nm and thickness from 20 to 60, which contain a single lithographically defined defect with an approximate diameter of 25 nm have been fabricated recently.[10,11] If the exchange length or the unit cell element size $a^2 = A/4\pi M_s^2$ is 4×4 nm, the hole with a diameter of 25 nm will contain many missing magnetic cells in each face of the nanodisk. One question is then opened: does a vortex in the face of a cylindrical nanodisk interact with j empty cells (neighbors or not) as it interacts with only one empty cell? This problem was first considered in Ref. 15, which studied the problem of interaction between a vortex and nonmagnetic impurities in layered magnetic systems. In fact, the presence of other nonmagnetic impurities in the system must affect the influence that an isolated nonmagnetic impurity has on a single vortex. It was proposed in Ref. 15 that the effects of two or more spin vacancies on the vortex configuration do not obey the principle of superposition. This assumption will be considered in this paper to estimate the vortex-defect interactions in magnetic nanodisks.

In Eq. (1), the sources of magnetostatic field $\vec{h}_m$ are both volume and surface magnetic charges arising from $\vec{\nabla}\cdot\vec{m}$, and from the discontinuity of the normal component of the magnetization on the surface $\vec{m}\cdot\hat{n}$, where the unit vector $\hat{n}$ is normal to the disk surfaces. In our case there are the external surfaces of the magnetic cylinder (lateral and the two faces) and a little internal surface inside the cavity (the walls of the cavity) of the artificial defect. Then the demagnetizing field can be expressed with the help of Maxwell equations through its magnetostatic potentials Φ_v, $\Phi_{\rm edge}^{\rm ext}$, and $\Phi_{\rm edge}^{\rm int}$, which are the magnetostatic potentials from volume, external edge, and internal edge, respectively. The potential is then $\Phi=\Phi_v+\Phi_{\rm edge}^{\rm ext}+\Phi_{\rm edge}^{\rm int}$ and the demagnetizing field is $\vec{h}_m=-\vec{\nabla}\Phi$. For consideration of the vortex state it is natural to express the magnetization $\vec{m}$ through angular variables in the polar coordinate system $\vec{m}=(\sin\theta\cos\varphi,\sin\theta\sin\varphi,\cos\theta)$. As justified above, for thin dots the magnetization is uniform along the z axis and is essentially two dimensional. The vortex state in a dot without defect hole and in the absence of an external magnetic field is given by the ansatz $\theta=\theta_v(r)$, $\varphi=\arctan(y/x)\pm\pi/2$, where the function $\theta_v(r)$ is determined numerically, having asymptotic solutions given as $\theta_v(r)\to 0$ for $r\to 0$ (near the disk center) and $\theta_v(r)\simeq\pi/2$ for $r_v\leqslant r\leqslant R$, where r_v is the vortex radius. For the determination of $\vec{h}_m$, the above vortex distribution in the absence of defects is very simple because $\vec{\nabla}\cdot\vec{m}=0$ and $\vec{m}\cdot\hat{n}|_{r=R}=0$, thereby giving neither edge nor volume contributions. The sole source of $\vec{h}_m$ in the ground state is the out-of-plane component of the magnetization $m_z=\cos\theta_v(r)$ in the cylinder faces. For a thin enough nanodot this gives the contribution to energy $-\vec{m}\cdot\vec{H}_m/2=2\pi m_z^2$,[17] which is an effective local easy-plane anisotropy. However, in the presence of a point defect, this is not the stable configuration because the vortex must be attracted to the hole,[14,15,18,19] which, in general, may not be located at the nanodisk center. To see this effect we consider first a simple calculation based only on the exchange energy, using a hole with radius a (the cell size). Later we generalize the calculations to larger defects and include the magnetostatic energy as well as the influence of an external magnetic field. For a vortex center located at origin in the presence of a hole (of radius $\rho=a$), which the center is placed at distance r_0 away, the effective potential experienced between the two defects due to the exchange energy is defined as $v_{\rm eff}(r_0)=\epsilon_{\rm hole}(r_0)-\epsilon$, where $\epsilon_{\rm hole}(r_0)$ and ϵ are the reduced vortex energies in the presence of the hole placed at r_0 and in the absence of a hole, respectively ($\epsilon_{\rm hole}=W_{\rm hole}^{\rm ex}/L$, $\epsilon=W^{\rm ex}/L$). If r_0 is large enough, i.e., $r_0>r_v\ll R$, the reduced effective potential can be approximated by[14]

$$v_{\rm eff}(r_0)=\frac{\pi A}{2}\ln\left(1-\frac{a^2}{r_0^2+b^2}\right), \qquad (2)$$

where b is a constant of the order of the cell size a introduced to avoid spurious divergence in the vortex energy when the vortex center coincides with the hole center.[14] Indeed, this constant can be obtained assuming that the pinning energy (the vortex energy when its center coincides with the hole center) is of the order of $-3.54A$.[14] However, this value for the pinning energy is valid in the limit of an infinite lattice. Therefore, in Refs. 14,19, it was shown that this value does not vary very much as the lattice is decreased and then we will use this inferior limit, which leads to $b\simeq 1.054a$. In our approximations, we also assume that the potential given by Eq. (2) is valid for all range of distances of separation vortex hole. It is based on the results of Zaspel *et al.*[20] and also Wysin.[19] They have shown that the easy-plane anisotropy in layered magnets necessary to keep the vortex in the in-plane form is drastically increased by a vacancy. In nanodisks, the exchange energy density increases rapidly toward the vortex center and then the magnetization turns out of the plane in order to minimize the energy. Hence, for defect holes with sizes of the order of 25 nm, which is of the same order of the vortex radius r_v for many dot sizes R, it is expected that out-of-plane magnetization is not so necessary to minimize the exchange energy.

Now, we want to know what happens to Eq. (2) when the defect hole is larger, containing many neighbor cells ($\rho\simeq ja, j>1$). The arguments used here generalize that of Ref. 15: imagine j empty cells (j holes with size a) distributed around the disk face and keeping fixed distances among them. If the vortex is pinned on an individual hole, the presence of other holes must decrease the pinning energy because they also attract the vortex. Indeed, each hole attracts the vortex center through an effective potential similar to that of Eq. (2), but now the constant b should be different in order to give a new pinning energy. It is estimated considering the j hole centers and the vortex center placed at the same point. In the limit that the separation vanishes, the system is equivalent to a simpler problem of a vortex on a single vacancy, but now, to conserve the number of holes, the total pinning energy is $(\pi A/2)\ln(1-a^2/b_j^2)^j$, which must be equal to $-3.54A$. It means that $b_j=a[1-\exp(-2.254/j)]^{-1/2}$ and as a good approximation we can use $\rho\sim b_j$. Essentially, the pinning energy now depends not only on the number of holes but also on their distribution on the space. However, our interest is in the case of only one hole with arbitrary size (of course, $\rho\ll R$). Here, a typical defect hole is then composed by j neighbor empty cells of radius a preferentially ordered to form a larger empty circle with radius ρ. Volumetrically, it is a cylindrical cavity inside the dot, which the symmetry axis is parallel to the dot axis [see definition of $U(\vec{r}-\vec{r}_0)$ in Eq. (1)]. We will assume that the defect hole is placed along the x axis at $r_0=x_0>0$.

The above calculations only consider part of the exchange energy. In this case, if a vortex is initially located at the dot center, the hole placed at $\vec{r}_0=x_0\hat{x}$ will make the vortex to dislocate in its direction, pinning the vortex center on its center, minimizing the system energy. Based on the "rigid" vortex model, Guslienko *et al.*[7] have shown that, for small displacement d ($d\ll R$) of the vortex center from the disk center, the reduced exchange energy is also decreased by

$$w(d) = \frac{\pi A}{2}\ln\left(1 - \frac{d^2}{R^2}\right). \quad (3)$$

Thus, a displacement of the vortex center towards the defect hole center decreases the exchange energy as follows:

$$v_{\text{ex}}(s,r_0) = \frac{\pi A}{2}\ln\left[(1 - s^2)\left(1 - \frac{a^2}{(r_0 - sR)^2 + b_j^2}\right)\right], \quad (4)$$

where $s = d/R$. However, for a nanodisk, if the vortex is shifted from the dot center due to the potential in Eq. (4), a restoring force acts on it. Of course, the restoring force appears due to finite dot in-plane size and is directed toward the dot center. It is calculated by considering magnetostatic contribution to the total vortex magnetic energy in the dot and is related only to surface magnetic charges $\vec{m}\cdot\hat{n}$ appearing along the envelop of the disk and along the wall of the hole cavity. The contribution along the disk envelop was calculated in Ref. 7 and is given by

$$v_{1m}(s) = w_{1m}(s) - w_m(0) = 2M_s^2(R^2 - \rho^2)\sum_{\gamma>0} F_\gamma(\beta_{1m})I_\gamma^2(s), \quad (5)$$

where

$$F_\gamma(\beta_{1m}) = \int_0^\infty \frac{dt}{t} f(\beta_{1m}t)J_\gamma^2(t), \quad f(q) = 1 - \frac{1 - e^q}{q}, \quad (6)$$

$$I_\gamma(s) = 2\int_0^\pi d\tau \frac{\sin(\tau)\sin(\gamma\tau)}{\sqrt{1 - 2s\cos(\tau) + s^2}}, \quad (7)$$

$\gamma = 1,2,\ldots$, J_γ are Bessel's functions and $\beta_{1m} = L/R$. The contribution of the cavity surface is estimated considering two distinct regions: $|s - r_0/R| < \rho/R$ and $|s - r_0/R| \geqslant \rho/R$. Due to the symmetry, if the vortex center coincides with the hole center $|s - r_0/R| = 0$, this contribution vanishes. Then, for the first region $|s - r_0/R| < \rho/R$, the contribution of the magnetostatic energy can be written as

$$v_{2m}(s) = 2M_s^2(R^2 - \rho^2)(s - r_0/R)^2\sum_{\gamma>0} F_\gamma(\beta_{2m})I_\gamma^2(s - r_0/R), \quad (8)$$

where $\beta_{2m} = L/\rho$. By the other hand, in the second region $|s - r_0/R| \geqslant \rho/R$, in which the vortex center is outside the hole, the product $\vec{m}\cdot\hat{n}$ will be negative on one half of the cavity surface and positive on the other half. In this circumstance, the symmetric distribution of "magnetic charges" in the cavity wall does not change appreciably as the distance between the vortex and the hole centers changes. Thus, we approximate the contribution of the second region as

$$v_{2m}(s) \simeq 2M_s^2(R^2 - \rho^2)(\rho/R)^2\sum_{\gamma>0} F_\gamma(\beta_{2m})I_\gamma^2(\rho/R). \quad (9)$$

For small displacement ($s \ll 1$), the total effective interaction vortex-defect-surface can be written as

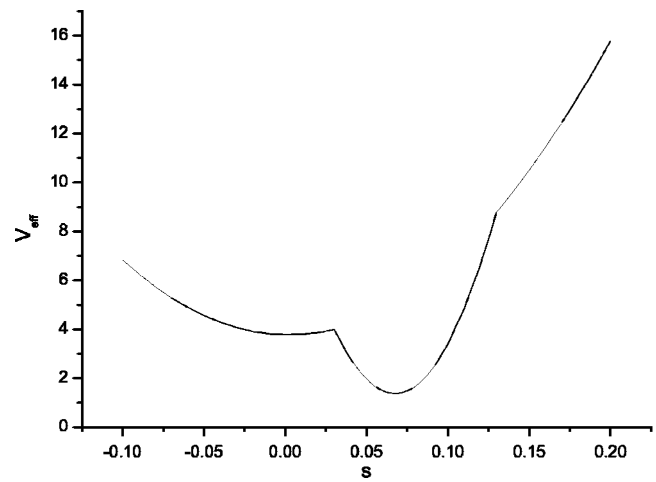

FIG. 1. The effective interaction (in units of the exchange constant A) of a vortex with a hole and the disk surfaces in a permalloy nanodisk. the origin of the coordinate system is the center of the disk and the hole center is placed at $r_0 = 20$ nm (or $s = 0.08$) along the x axis. The material is described in the text. At the hole border (the points $s \sim 0.03$ and $s \sim 0.13$), the potential suffers a strong change.

$$V_{\text{eff}} = \frac{\pi A}{2}\ln\left[(1 - s^2)\left(1 - \frac{a^2}{(r_0 - sR)^2 + b_j^2}\right)\right] + 2\pi^2 M_s^2 \times (R^2 - \rho^2)F_1(\beta_{1m})s^2 + 2\alpha\pi^2 M_s^2(R^2 - \rho^2)F_1(\beta_{2m}) \times (s - r_0/R)^2 + 2\nu\pi^2 M_s^2(R^2 - \rho^2)F_1(\beta_{2m})(\rho/R)^2, \quad (10)$$

where $\alpha = 1$, $\nu = 0$ if $|s - r_0/R| < \rho/R$ and $\alpha = 0$, $\nu = 1$ if $|s - r_0/R| \geqslant \rho/R$. For estimates we use typical parameters for permalloy, $A^{1/2}/M_s = 17$ nm, giving $a = 4.8$ nm. Considering $R = 250$ nm, $L = 30$ nm, $\rho \simeq 12.5$ nm, one gets $F_1(\beta_{1m}) \simeq 0.07$ and $F_1(\beta_{2m}) \simeq 0.364$. In Fig. 1, we plotted the effective potential well as a function of s for $r_0 = 20$ nm. As expected, the equilibrium value for the vortex center s_0 inside the hole (the bottom of the well), obtained by minimizing $V_{\text{eff}}(s)$, is not located at the hole center r_0. In fact, in this case, the magnetostatic energy pushes the vortex toward the dot center, dislocating the vortex center from $\vec{r}_0$ by a distance that depends on the size and position of the defect (for instance, for $r_0 = 20$ nm, the vortex center is shifted from the hole center by a distance ~ 3 nm). For $r_0 < \rho$ there is essentially only one minimum in Eq. (10). In contrast, for $r_0 > \rho$, there are two minima (an absolute minimum and a local minimum) due to the competition between exchange and magnetostatic energies. Indeed, for r_0 smaller than a critical distance r_c, the absolute minimum is inside the hole and the local one is located at origin, while for $r_0 > r_c$, one has the oppositive situation. The critical size r_c is estimated taking $V_{\text{eff}}(s_0) = V_{\text{eff}}(0)$. For the above example, $V_{\text{eff}}(0) \sim 3.79A$, giving $r_c \simeq 31$ nm. At zero field, it is conceivable that, for $r_0 < r_c$, vortex configurations would preferentially nucleate about the hole. Figure 2 shows how the reduced vortex center equilibrium position s_0 varies as a function of the hole center position r_0.

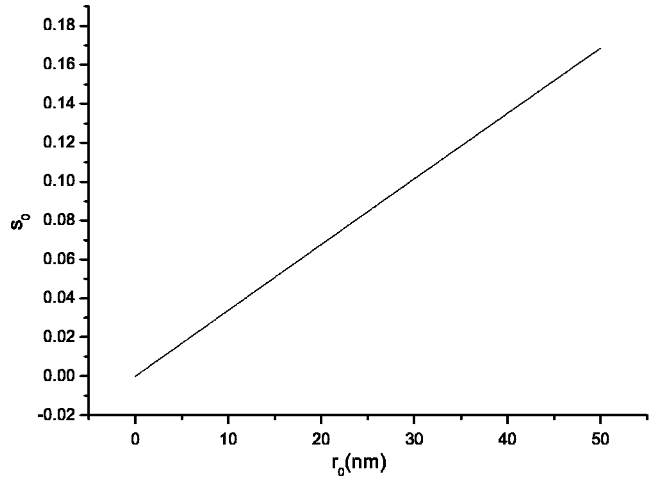

FIG. 2. The dependence of the equilibrium position for the vortex center (inside the hole) on the hole position is linear.

The presence of an external magnetic field along the direction perpendicular to the line joining the disk-hole centers can also contribute to the vortex dislocation along the x direction. Supposing that the field is applied along the y direction, the Zeeman energy contribution can be approximated to be $w_{h_{\text{ext}}} \simeq -\pi M_s^2 (R^2-\rho^2) h_{\text{ext}}[(s-s_0)+O(s^3)]$, where $\vec{h}_{\text{ext}} = \vec{H}_{\text{ext}}/M_s$ is the external magnetic field. The energy is now given by $V=V_{\text{eff}}+w_{h_{\text{ext}}}$. Here, if the magnetic field is positive ($h_{\text{ext}}>0$), the new equilibrium position is $s_h > s_0$ (right shift). On the other hand, i.e., if $h_{\text{ext}}<0$, the new equilibrium value obeys $s_h < s_0$ (left shift). Figure 3 shows the interaction potential vortex defects in the presence of a magnetic field applied along the y axis ($h_{\text{ext}}=-0.05$ and $h_{\text{ext}}=0.05$). It was used the same parameters for the case without a field. Note that an external magnetic field can control the depth of the potential well induced by the defect, permitting a convenient control of the trapped state for a vortex in nanodisks. The attractive well generated by the point defect (in the presence or absence of an external field) suggests that such defect may induce interesting magnetization dynamics. It is possible that a vortex develops small amplitude oscillations around the bottom of the well. Possible oscillatory motion was predicted for topological excitations around a nonmagnetic impurity in layered magnets.[16,21,22]

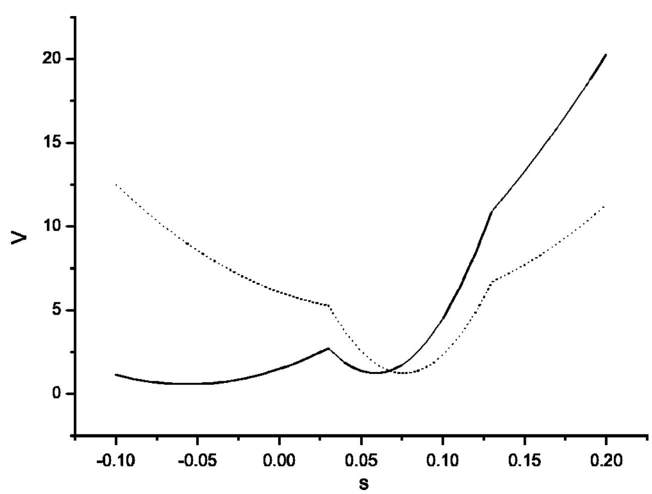

FIG. 3. The potential well (in units of A) induced by the point defect in the presence of an external magnetic field applied perpendicularly to the line joining the disk-hole centers. Solid and dotted lines correspond to $h_{\text{ext}}=-0.05$ and $h_{\text{ext}}=0.05$, respectively. The field can control the depth and the position of the bottom of the well.

In summary, we have investigated analytically the problem of vortices (in the presence and absence of an external magnetic field) interacting with a lithographically defined defect in submicron-sized disk-shaped magnetic elements. Such disk permalloy particles were fabricated recently.[10,11] We have used the rigid vortex model combined with an impurity model employed to study vortex-vacancy[14–16] and soliton-vacancy[21,22] interactions in two-dimensional magnets. The rigid vortex model is based on the assumption that vortices are rigid objects that do not deform as they move. A detailed discussion of the applicability of this model is presented in a recent interesting paper by Sarvel'ev and Nori.[23] These authors have used the rigid magnetic vortex model to develop a substantially modified Landau theory approach for analytically studying phase transitions between different spin arrangements in circular submicron magnetic dots subject to an applied magnetic field. Some predictions of their work are consistent with recent and earlier micromagnetic computations.[24–26] At the same time, the impurity model is based on a support manifold being not simply connected and has been shown to be very useful to predict some features of the vortex-vacancy interactions in layered magnets.[14,16] However, in reality, the vortex configuration suffers small changes when the vortex moves and when the vortex is around large holes.[16] Nevertheless we believe that our approach is a good approximation and useful for qualitative understanding of the mechanism of the vortex-defect interactions in nanodisks in the case of a hole (or holes) near the disk center (and hence, involving small vortex displacements). In fact, concerning the vortex-defect interactions, the analytical results obtained here indicate that the vortex core can be pinned by a point defect, in qualitative agreement with recent experiments and micromagnetic simulations of Refs. 10 and 11. Our calculations give the vortex-hole effective interaction potential as a function of the relevant disk parameters and the defect position. Only the case in which a magnetic field is applied perpendicularly to the line joining the hole center and the disk center was considered. Of course, the path of the vortex core depends on the direction of the external field and it can lead to interesting new situations not investigated here.

We acknowledge support from CNPq and FAPEMIG (Brazil).

[1] A. Maeda, M. Kume, T. Ogura, K. Kukkori, T. Yamada, M. Nishikawa, and Y. Harada, J. Appl. Phys. **76**, 6667 (1994).
[2] J. F. Smyth, S. Schultz, D. R. Fredkin, D. P. Kern, S. A. Rishton, H. Schmid, M. Cali, and T. R. Koehler, J. Appl. Phys. **69**, 5262 (1991).
[3] J. N. Chapman, P. R. Aitchison, K. J. Kirk, S. McVitie, J. C. S. Kools, and M. F. Gillies, J. Appl. Phys. **85**, 5828 (1999).
[4] M. Schneider, H. Hoffmann, and J. Zweck, Appl. Phys. Lett. **77**, 2909 (2000).
[5] T. Shinjo, T. Okuno, R. Hassdorf, K. Shigeto, and T. Ono, Science **289**, 930 (2000).
[6] J. Raabe, R. Pulwey, R. Suttler, T. Schweinbock, J. Zeweck, and D. Weiss, J. Appl. Phys. **88**, 4437 (2000).
[7] K. Y. Guslienko, V. Novosad, Y. Otani, H. Shima, and K. Fukamichi, Appl. Phys. Lett. **78**, 3848 (2001).
[8] B. A. Ivanov and C. E. Zaspel, Appl. Phys. Lett. **81**, 1261 (2002).
[9] N. A. Usov and S. E. Peschany, J. Magn. Magn. Mater. **118**, L290 (1993).
[10] M. Rahm, J. Biberger, V. Umansky, and D. Weiss, J. Appl. Phys. **93**, 7429 (2003).
[11] M. Rahm, R. Höllinger, V. Umansky, and D. Weiss, J. Appl. Phys. **95**, 6708 (2004).
[12] M. Rahm, J. Stahl, W. Wegscheider, and D. Weiss, Appl. Phys. Lett. **85**, 1553 (2004).
[13] K. Y. Guslienko, V. Novosad, Y. Otani, H. Shima, and K. Fukamichi, Phys. Rev. B **65**, 024414 (2002).
[14] A. R. Pereira, L. A. S. Mól, S. A. Leonel, P. Z. Coura, and B. V. Costa, Phys. Rev. B **68**, 132409 (2003).
[15] F. M. Paula, A. R. Pereira, and L. A. S. Mól, Phys. Lett. A **329**, 155 (2004).
[16] A. R. Pereira, S. A. Leonel, P. Z. Coura, and B. V. Costa, Phys. Rev. B **71**, 014403 (2005).
[17] B. A. Ivanov and C. E. Zaspel, J. Appl. Phys. **95**, 7444 (2004).
[18] A. R. Pereira, J. Magn. Magn. Mater. **279**, 396 (2004).
[19] G. M. Wysin, Phys. Rev. B **68**, 184411 (2003).
[20] C. E. Zaspel, C. M. McKennan, and S. R. Snaric, Phys. Rev. B **53**, 11 317 (1996).
[21] A. R. Pereira, Phys. Lett. A **314**, 102 (2003).
[22] L. A. S. Mól, A. R. Pereira, and W. A. Moura-Melo, Phys. Rev. B **67**, 132403 (2003).
[23] S. Savel'ev and F. Nori, Phys. Rev. B **70**, 214415 (2004).
[24] M. Rahm, M. Schneider, J. Biberger, R. Pulwey, J. Zweck, and D. Weiss, Appl. Phys. Lett. **82**, 4110 (2003).
[25] J. K. Ha, R. Hertel, and J. Kirschner, Phys. Rev. B **67**, 224432 (2003); **67**, 064418 (2003).
[26] Yu. B. Grebenshchikov, N. A. Usov, and K. S. Pestchanyi, J. Appl. Phys. **94**, 6649 (2003).