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Dynamics of the vortex core in magnetic nanodisks with a ring of magnetic impurities

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In this work, we used numerical simulations to study the effect of a ring of magnetic impurities on the vortex core dynamics in nanodisks of Permalloy. The presence of the ring not only allowed us to modulate the gyrotropic frequency but also provided us a way to confine the vortex core. We observed that the gyrotropic frequency depends on the ring parameters. Moreover, we have noticed that the switching of the vortex core polarity can be obtained from the vortex core-impurity interaction under peculiar conditions, in particular, when the ring works for pinning the vortex core. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4772071]

Nowadays, nanomagnets can be fabricated to present different magnetization states, depending on its geometric characteristics and the material of which it is made of. In particular, a soft nanomagnet in the shape of a disk can exhibit a magnetic vortex in the remanent state.[1–5] The competition between the exchange and dipolar energies is responsible for the curl configuration of the magnetic moments that arises as an intermediate state between mono and multidomain.[6] At the core of the magnetic vortex a magnetization perpendicular to the plane of disk can be developed; the vortex polarity determines the sense of this out-of-plane magnetization (up or down). From the technological point of view, these discrete states can be useful to store information, so that, a nanodisk containing a vortex configuration could store up to 2 bits of data.[7]

It is well known that the simplest effect induced by an in-plane external magnetic field is the vortex core displacement. Since the vortex core is polarized, it describes an elliptical trajectory around some fixed point. This motion is known as the gyrotropic mode. The sense of rotation depends only on the vortex core polarity. The frequency of the gyrotropic mode is of order of 10^2 MHz being determined by the disk aspect ratio.[8,9]

In the last few years, much effort has been dedicated to control the polarity switching. It has been experimentally observed that applying a small-amplitude field pulse[10] or a spin polarized current[11] can switch the polarity.

Some works reported that defects can influence the vortex core dynamics. One can distinguish two classes of defects, magnetic and nonmagnetic. The vortex core pinning by nonmagnetic defects (vacancy or cavity) was predicted theoretically[12] and observed experimentally.[13] Such defects can attract and capture the vortex core. Corresponding analytical and micromagnetic calculations, modelling the vacancy defects, are in good agreement with reported experiments.[14–16] Furthermore, it was observed that the gyrotropic frequency at low excitation amplitudes was significantly influenced by intrinsic defects.[17,18] If the vortex core is captured by artificial defects in the form of cavities, its out-of-plane component is substantially reduced or even vanishes. In this case, the commonly observed gyrotropic mode is suppressed.[19,20] The basic physics behind the mechanism of the vortex core pinning by nonmagnetic defects is widely discussed in Ref. 21. Nevertheless, for some special conditions, it has been observed in simulations that the vortex core switching can occur due to the interaction between the vortex core and the nonmagnetic defects.[22] A model for structural defects in nanomagnets was proposed in Ref. 23; the authors discussed two possible types of pointlike defects acting as pinning or scattering sites for the vortex core. There, the following question is pointed out: It is known that nonmagnetic impurities act as pinning sites, but what could act as scattering sites? In a recent work,[24] the answer to this question was addressed. Numerical results indicate that a possible origin of the pinning or scattering defects in nanomagnets could be the local reduction or increase in the exchange constant, respectively. In another recent work,[25] it was shown that the gyrotropic frequency is affected by the magnetic impurities. From the experimental point of view, magnetic impurities can be lithographically inserted in nanomagnets.

The main goal in this paper is to investigate how the dynamics of the vortex core is influenced by an arrangement of magnetic impurities in nanodisks. In particular, we study a circular distribution of the impurities as shown in Fig. 1.

In an early work, we have presented a Hamiltonian model describing two types of pointlike magnetic impurities that can behave as pinning and scattering sites for the vortex core.[24] We have considered a classical ferromagnet model described by the following Hamiltonian:

$$H = J\Bigg\{ -\frac{1}{2}\sum_{<i\neq i',j>} \hat{m}_i\cdot\hat{m}_j - \frac{J'}{2J}\sum_{<i',j>} \hat{m}_{i'}\cdot\hat{m}_j + \frac{D}{2J}\sum_{i,j}\left[\frac{\hat{m}_i\cdot\hat{m}_j - 3(\hat{m}_i\cdot\hat{r}_{ij})(\hat{m}_j\cdot\hat{r}_{ij})}{(r_{ij}/a)^3}\right] - \frac{Z}{J}\sum_i \hat{m}_i\cdot\vec{b}_i^{ext}\Bigg\}, \quad (1)$$

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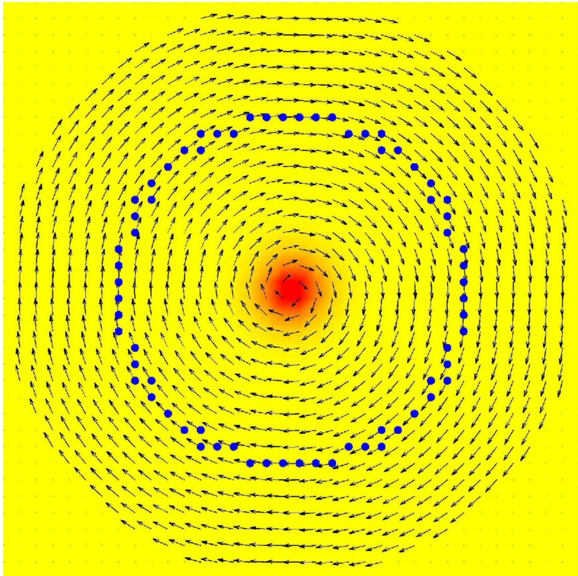

FIG. 1. Schematic of the modified nanodisks. The blue circles represent small clusters containing impurities; they define the ring of magnetic impurities.

where $\hat{m}_k \equiv (m_k^x, m_k^y, m_k^z)$ is a dimensionless vector with $|\hat{m}_k| = 1$ representing the magnetic moment located at the site k of the lattice. The first term in Eq. (1) represents the ferromagnetic coupling only for sites without impurities, whereas the second take into account the exchange interaction between sites with and without impurities. The exchange interactions between magnetic sites and that one containing the impurity were modelled by ferromagnetic coupling with the exchange constant strength J' differing of its value for sites without defects J. In this way, we describe two possible types of magnetic impurities, acting as pinning ($J' < J$) or scattering ($J' > J$) sites for the vortex core. The following terms are dimensionless versions of dipolar and Zeeman interactions, respectively. The Hamiltonian (1) can be rewritten as $H = J\mathcal{H}$, where $\mathcal{H}$ is the dimensionless term in curly brackets. The system energy is measured in unities of J.

The dynamics of the system is followed by solving numerically the discrete version of the Landau-Lifshitz-Gilbert equation given by

$$\frac{d\hat{m}_i}{d\tau} = -\frac{1}{1+\alpha^2}[\hat{m}_i \times \vec{b}_i + \alpha \hat{m}_i \times (\hat{m}_i \times \vec{b}_i)], \qquad (2)$$

where $\vec{b}_i = -\frac{\partial \mathcal{H}}{\partial \hat{m}_i}$ is the dimensionless effective field at site i, containing individual contributions from the exchange, dipolar, and Zeeman fields.

In the micromagnetics approach, the interaction constants depend on the material parameters and also the manner in which the system is partitioned into cells. As in Refs. 24 and 25, we have chosen to use cubic cells of edge length a. In this case, the interaction constants between the cells are given by $J = 2A\,a$ and $\frac{D}{J} = \frac{1}{4\pi}\left(\frac{a}{\lambda}\right)^2$. If there is an external applied magnetic field, the coefficient of Zeeman interaction is $\frac{Z}{J} = \left(\frac{a}{\lambda}\right)^2$. We have used the typical parameters for Permalloy-79: the saturation magnetization $M_S = 8.6 \times 10^5$ A/m, the exchange stiffness constant $A^{Py} = 1.3 \times 10^{-11}$ J/m, and the damping constant $\alpha = 0.01$. Using these parameters, we have estimated the exchange length as $\lambda = \sqrt{\frac{2A}{\mu_0 M_S^2}} \approx 5.3$ nm and the unit cell size was chosen as $5 \times 5 \times 5\,\text{nm}^3$. The time t is obtained by $t = \tau/\omega_0$, where τ is the dimensionless simulation time and $\omega_0 = \left(\frac{\lambda}{a}\right)^2 \mu_0 \gamma M_s$. For Permalloy-79, $\omega_0 \approx 2.13 \times 10^{11}\,\text{s}^{-1}$. The equation of motion (2) was integrated forward by using a fourth-order predictor-corrector scheme with time step $\Delta\tau = 0.01$. In our simulations, we have used the nanodisks with diameter $d = 170$ nm and thickness $L = 10$ nm, differing one to another only in the ring parameters: local variation of the exchange constant J'/J along the ring and ring diameter d'. The corresponding disk without ring was taken as a reference.

We have chosen as initial condition the disk with a vortex configuration with upward polarity and counter-clockwise chirality. The integration of the equations of motion (2) at external magnetic field $\vec{b}_i^{ext} = \vec{0}$ leads the system to a local energy minimum configuration and we assumed that the nanodisk remanent state was reached. The states obtained in this way were saved to be used as initial configurations in the studies of the gyrotropic mode and switching of vortex polarity.

Over a wide range of the ring diameter d' and exchange constant ratio J'/J, we numerically calculated the dynamic response of the remanent state to a homogeneous in-plane magnetic field pulse

$$\vec{B}_i^{ext} = \hat{y}\, B \sin(2\pi\nu t). \qquad (3)$$

All simulations were done using $\nu = 0.5$ GHz. The relation between the applied magnetic field and its dimensionless corresponding is $\vec{B}_i^{ext} = \mu_0 M_S \vec{b}_i^{ext}$.

To excite the gyrotropic mode, we used a low excitation amplitude $B = 3$ mT. We observed that the vortex core describes a circular trajectory within the ring. The gyrotropic frequency dependence with the ring parameters is shown in Fig. 2. As a reference, we plot the gyrotropic frequency of the nanodisk without the ring ($J'/J = 1$), being shown as the dashed line. A local reduction of the exchange constant ($J'/J < 1$) always lowers the gyrotropic frequency of the nanodisk. On the other hand, if ($J'/J > 1$) the gyrotropic frequency increases. The variation in gyrotropic frequency is more pronounced for smaller ring diameters. That might be expected, since the interaction between the vortex core and the magnetic impurity is short-ranged. As expected, for

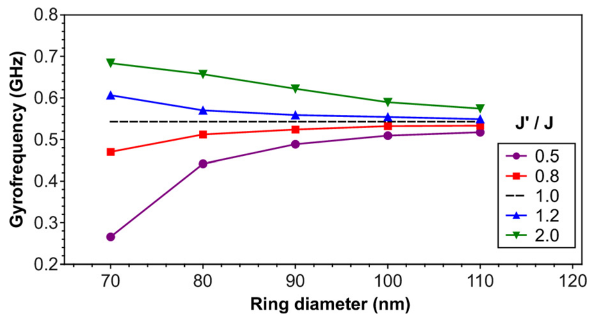

FIG. 2. Gyrotropic frequency depending on the local variation of the exchange constant J'/J and ring diameter d'. The dashed line, in black, corresponds to the gyrotropic frequency of the nanodisk without the ring of magnetic impurities, in this case 0.543 GHz. The effect of an attractive ring ($J'/J < 1$) is to lower the gyrofrequency, whereas the effect of a repulsive ring ($J'/J > 1$) is to increase gyrofrequency.

larger values of the ring diameter, the gyrotropic frequency tends to the frequency of the reference disk ($J'/J = 1$).

The reason why the magnetic impurities insertion modifies the gyrotropic frequency can be understood using a Thiele approach[26] and is discussed in Ref. 25.

The dynamics of the vortex core is substantially affected if the ring diameter approaches the gyrotropic trajectory diameter (30 nm for the disk without the ring). When ($J'/J > 1$), we observed the confinement of the vortex core, namely, the gyrotropic trajectory diameter is reduced. In extreme cases ($J'/J \gg 1$), due to the radial symmetric distribution of repulsive impurities, the vortex core can get stuck in its equilibrium position and the gyrotropic mode is not excited. Above a critical amplitude B, the vortex core escapes from inside the ring.

Augmenting the excitation amplitude, we have noticed a phenomenon not yet observed: the switching of polarity can be obtained from the interaction between the vortex core and magnetic impurity under peculiar conditions. The mechanism of switching involves necessarily a pinning site ($J'/J < 1$), the relative position of the attractive magnetic impurity in relation to the disk center and an external agent.

A set of 30 nanodisks with different ring of magnetic impurities was submitted to an in-plane magnetic field for varied excitation amplitudes B, see Fig. 3. The chosen values of B are not strong enough to reverse the vortex polarity in the nanodisk without the ring. For $B = 20$ mT, the vortex core expulsion was observed in our reference nanodisk but not if the ring is present. Thus, using the ring, we can expect an increase in the saturation field. For a strong excitation amplitude B, the dominant event is a random multiple switch, such that the polarity cannot be reversed in a controllably way. For moderate amplitudes, $B = 10$, 12, and 15 mT, the multiple switches region is mainly concentrated in the region of smaller ring diameters. Whenever the pinning effects are weak, ($J'/J \to 1$), no reversal is observed. In the case of strong pinning effects, ($J'/J \to 0$), the polarity cannot be controlled because the vortex core is pinned in some point of the ring. As shown in Fig. 3, the control of the polarity occurs in a very well defined range of parameters. In short, the polarity switching mechanism must involve a single interaction between the vortex core and the ring. The external field must be strong enough to provide the kinetic energy necessary, so that, the vortex core does not get stuck. Besides attracting the vortex core, a magnetic impurity of the pinning site reduces its out-of-plane component; as a result of the interaction, the vortex core magnetization can be reversed.

In summary, we have shown how the dynamics of the vortex core in a nanodisk can be managed introducing a distribution of impurities in the system; with this we can control the gyrotropic mode and the vortex core magnetization. A fine tuning of the gyrotropic frequency can be obtained through the control of the exchange constant strength and the impurity distribution. When the gyrotropic trajectory is described inside the ring, the effect of an attractive ring ($J'/J < 1$) is to reduce the gyrotropic frequency, whereas the

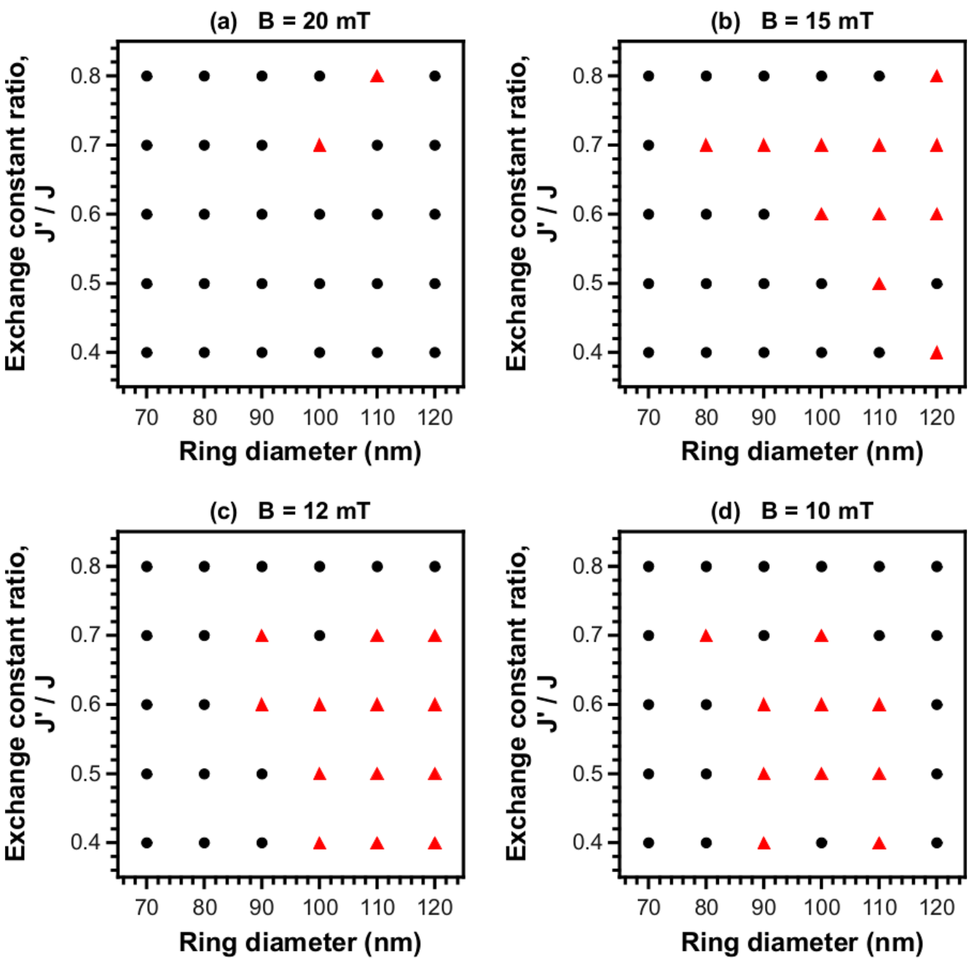

FIG. 3. Polarity controllability diagram for the magnetic impurities ring parameters in Py nanodisks with diameter $d = 170$ nm and thickness $L = 10$ nm. Red triangles correspond to a combination of parameters when a single switching occurs and black circles include the following events: dynamics of vortex core without switching, multiple switches, pinning, or expulsion of the vortex core.

effect of a repulsive ring ($J'/J > 1$) is to increase the gyrotropic frequency. Moreover, we showed an alternative mechanism to switch the vortex polarity, mediated by the interaction between the vortex core and attractive magnetic impurities. The control of the polarity occurs in a very well defined range of parameters. In our simulations, the polarity switching can be obtained for an amplitude of $\sim$10 mT with the switching time about 1.5 ns. The great differential of this polarity switching process is that it does not require a high excitation amplitude. A nonmagnetic defect, such as a cavity, has already been intentionally incorporated in Permalloy disks by using an image reversal electron beam lithography process.[13,14] We believe that a magnetic impurity can be lithographically inserted in nanodisks by depositing a ferromagnetic material into a cavity previously created. In order to verify our predictions, a ring of cluster of Ni or Fe ($A^{Ni} = 0.86 \times 10^{-11}$ J/m, $A^{Fe} = 1.98 \times 10^{-11}$ J/m),[27] for example, could be inserted in Permalloy nanodisks to act as attractive or repulsive ring for the vortex core, respectively. As $A^{Ni} < A^{Py}$, we expect that $J^{Ni} < J' < J^{Py}$ for attracting, and as $A^{Fe} > A^{Py}$, we expect that $J^{Py} < J' < J^{Fe}$ for scattering the vortex core. We consider here only one possible realization of the vortex core dynamics controllability with a very single ring. We believe that the usage of others magnetic impurity distributions lithographically inserted will be promising for different applications of nanomagnets.

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