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The influence of magnetic impurities in the vortex core dynamics in magnetic nano-disks

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ABSTRACT

In this work we have used spin dynamics simulations to study the gyrotropic frequency behavior in nano-disks of Permalloy with magnetic impurities. We consider the effect of attractive impurity and repulsive impurity placed near the vortex core gyrotropic trajectory. We observed that the gyrotropic frequency is affected by the presence of impurity. The gyrotropic frequency shift depends on the relative position between the impurity and the vortex core gyrotropic trajectory and if impurity is attractive or repulsive. Our results agree with the analytical model and with experimental behavior for the gyrotropic frequency shown in the literature.

The magnetic devices can be used in many technological applications, for example in magnetic random access memories (MRAMs), digital reading heads, position sensors, devices for measurements of currents to applications in medicine in cancer treatment for example [1–6]. It was discovered recently that some magnetic nano-structures can present interesting properties that may lead to build efficient new storage devices [7–10]. Magnetic nano-device like a nano-disk shows a magnetic vortex configuration in ground state. The competition between magnetostatic energy and the exchange interaction is responsible for the formation of this magnetic vortex configuration in nano-disks [11]. The study of the dynamics of the vortex and a way to control the core magnetization is of paramount importance since the Z_2 symmetry of the vortex core [12,13] can be used as a bit in store devices. In numerical simulations it was observed that switching can be induced by vortex–hole interaction [14] or by the application of a time dependent external magnetic field which induces a vortex gyrotropic motion [15,16].

In the last few years the interaction of the vortex core with defects and impurities in magnetic materials has been the subject of intense investigation [17–19]. Even in pure samples, such as nano-disks made of Permalloy, structural defects are distributed randomly through the material. As example, the density of defects can be up to $\approx 2\times 10^{11}/\text{cm}^2$ for the pinning sites in Permaloy nanodisks that affect the vortex dynamics [20]. The pinning behavior of magnetic vortices was investigated by using Lorentz transmission electron microscopy [21]. Recently, the vortex core dynamics in individual magnetic disks was investigated using time-resolved Kerr microscopy [22]; it was observed fluctuations in the frequency of the gyrotropic mode in nano-disks of Permalloy. The authors argued that the fluctuations were due to a distribution of nanoscale defects pinning the vortex core. In a recent work [23] we showed the dynamical behavior of a magnetic nano-disk contaminated by pointlike impurities, using micromagnetic approach [24]. In this approach the nano-disk is partitioned into cubical working cells containing many atoms. Each working cell has dimensions $a\times a\times a$ and volume $v_{cell}=a^3$, where a is greater than unit cell parameter a_0. The spins in a working cell can be considered mostly aligned, hence the dipole moment in a cell has a fixed length μ_{cell} equal to the saturation magnetization times the cell volume, $\mu_{cell}=M_s v_{cell}$ [25]. In our model of nano-disk each site i will now represent the center of a working cell and an impurity is a set of spins located in a particular working cell. We define a unit vector $\hat{m}_i=\vec{\mu}_i/\mu_{cell}$ located in each site i, where $\vec{\mu}_i$ is the dipole moment of the working cell. The interaction between the magnetic cells in the nano-disk and the defects was considered depending only on the exchange energy. We observed that the magnetic impurities can behave both as apinning (attractive) and scattering (repulsive) cells. Using the known values of the parameters for Permalloy-79 we have calculated the interaction energy of the vortex core with a single defect and estimated the interaction range as approximately 10 nm. Both results agree quite well

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with experimental measurements of Ref. [22]. Our results [23] indicate that the possible origins of the pinning and scattering defects in thin films can be the local reduction or increase in the exchange constant respectively, caused by a local nanoscaled structural deformation during the nanofabrication process. We believe that not all structural defects produced in the samples are pinning defects, structural scattering defects can also be produced and certainly will affect the gyrotropic frequency as pointed out in Ref. [22]. From the experimental point of view, the magnetic impurities may also be lithographically inserted in magnetic nano-disks [21].

In this work we use the model proposed in Ref. [23] and spin dynamics simulations to study the influence of magnetic impurities in the frequency of the gyrotropic mode in nano-disks of Permalloy.

We consider the magnetic nano-disks modeled by magnetic moments with dipole–dipole and exchange interactions [26] and we follow Ref. [27] to build the simulated nano-disks. As in Ref. [23], using a pseudospin language, we can write a model Hamiltonian for the nano-disk with magnetic impurities and under the action of an external magnetic field as

$$H = J\left\{ -\frac{1}{2}\sum_{\langle i\neq i',j\rangle}\vec{S}_i\cdot\vec{S}_j - \frac{J'}{2J}\sum_{\langle i',j\rangle}\vec{S}_{i'}\cdot\vec{S}_j + \frac{D}{2J}\sum_{i\neq j}\left[\frac{\vec{S}_i\cdot\vec{S}_j - 3(\vec{S}_i\cdot\hat{r}_{ij})\times(\vec{S}_j\cdot\hat{r}_{ij})}{(r_{ij}/a)^3}\right] - \sum_i \vec{S}_i\cdot\vec{b}_i \right\}. \tag{1}$$

The sites i and j are sites without impurities in the sample. The impurities are located in the sites i' of the sample. Here $r_{i,j}$, measured in units of length, is the distance between sites i and j, $\hat{r}_{ij} = \vec{r}_{ij}/r_{ij}$ and the parameter a is the lattice parameter defined as the distance between the first neighbors sites in lattice. The vectors $\vec{S}_i$, $\vec{S}_j$ and $\vec{S}_{i'}$ located in the sites i, j and i' satisfying the condition $|\vec{S}| = 1$. These vectors are dimensionless, analogous to vectors $\hat{m}_i$, $\hat{m}_j$ and $\hat{m}_{i'}$ respectively, and represent classical spins. The exchange coupling constant between $\vec{S}_i$ and $\vec{S}_j$ is given by J (in units of energy) and the exchange coupling constant between $\vec{S}_{i'}$ (impurities) and $\vec{S}_j$ is given by J'. The dipole strength is given by D (in units of energy). The sums in thefirst and second terms are over first neighbors and in the third term the sum runs over the entire lattice. The sum in the last term is the contribution of the Zeeman energy. The $\vec{b}_i$ is the dimensionless simulation magnetic field and the external applied field, measured in Tesla (T), is given by $\overrightarrow{B_i^{ext}} = \mu_0 M_s \vec{b}_i$ [25] where M_s is the saturation magnetization of the material. The Hamiltonian (1) can be rewritten as $H = J\mathcal{H}$, where $\mathcal{H}$ is the dimensionless term in curly brackets. The dynamics of the system is followed by solving numerically the discrete version of the Landau–Lifshitz–Gilbert (LLG) equation [28,29] given by

$$\frac{d\vec{S}_i}{d\tau} = -\left[\vec{S}_i \times \frac{\partial\mathcal{H}}{\partial\vec{S}_i}\right] + \alpha\left[\vec{S}_i \times \vec{S}_i \times \frac{\partial\mathcal{H}}{\partial\vec{S}_i}\right], \tag{2}$$

where τ is the dimensionless simulation time. The Hamiltonian time t, measured in seconds, is obtained by [30] $t = \tau/\omega_0$ ($\omega_0 = 2.13\times10^{11}\ \mathrm{s}^{-1}$ for Permalloy-79 [27]). We used the fourth-order predictor–corrector method and time step $d\tau = 0.01$ to integrate the equations of motion (this leads to a $dt = 4.7\times10^{-14}$ s for Permalloy-79). As the damping affects only the amplitude of the gyrotropic mode and does not affect the frequency gyrotropic, we use $\alpha = 0.0$. In our simulations we consider no cut-off in the dipolar interaction and used $(D/J) = 0.0708$ for Permalloy-79 [27].

In our simulations to study the influence of magnetic impurities in the frequency of the gyrotropic mode in nano-disks, we consider a magnetic impurity near the vortex core gyrotropic trajectory (of radius r_{mode} shown schematically in Fig. 1). We studied the effect of attractive impurity ($J' < J$) and repulsive impurity ($J' > J$) [23] placed at a distance r_{imp} from the center of the nano-disk. We consider the possibilities where $r_{imp} < r_{mode}$ and $r_{imp} > r_{mode}$ (see Fig. 1). To excite the gyrotropic mode around the center of the nano-disk we consider the application of a pulse of in-plane magnetic field $\overrightarrow{B_i^{ext}}$ of magnitude 5 mT [15,16]. This value ensures that the gyrotropic mode is excited without destroying the vortex state. We use micromagnetic approach with the values of the parameters of Permaloy-79, as described in Refs. [23,27]. All simulations were done considering nano-disks with thickness l = 10 nm and diameter d = 125 nm, 145 nm, 175 nm, 195 nm, 225 nm and 275 nm. For $d < 125$ nm the nano-disks does not shows the magnetic vortex configuration in the ground state [27].

We studied four situations: (1) $r_{imp} < r_{mode}$ and $J' < J$, (2) $r_{imp} < r_{mode}$ and $J' > J$, (3) $r_{imp} > r_{mode}$ and $J' < J$ and (4) $r_{imp} > r_{mode}$ and $J' > J$. We follow the procedure used in Ref. [14] for analysis of the gyrotropic frequency. In all situations we observed that the gyrotropic frequency is affected by the presence of impurity. The gyrotropic frequency shift is defined as $\Delta f = f_{imp} - f_{pure}$, where

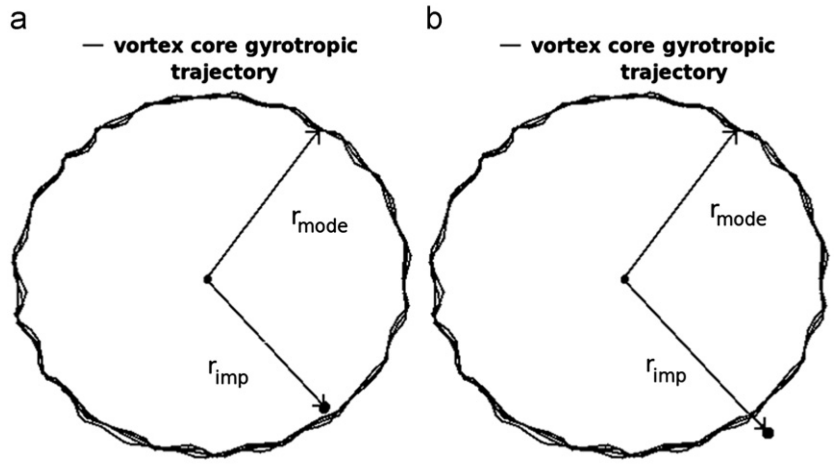

Fig. 1. Vortex core gyrotropic trajectory in a nano-disk with diameter $d = 225$ nm and thickness $l = 10$ nm. The radius of the trajectory is $r_{mode} = 35$ nm. (a) Schematic view of the relative position of the impurity in the nano-disk in the situation where $r_{imp} < r_{mode}$. (b) Schematic view of the relative position of the impurity in the nano-disk in the situation where $r_{imp} > r_{mode}$. The black circle represents a magnetic impurity located near the gyrotropic trajectory, satisfying the condition $|r_{imp} - r_{mode}| \approx 10$ nm [23].

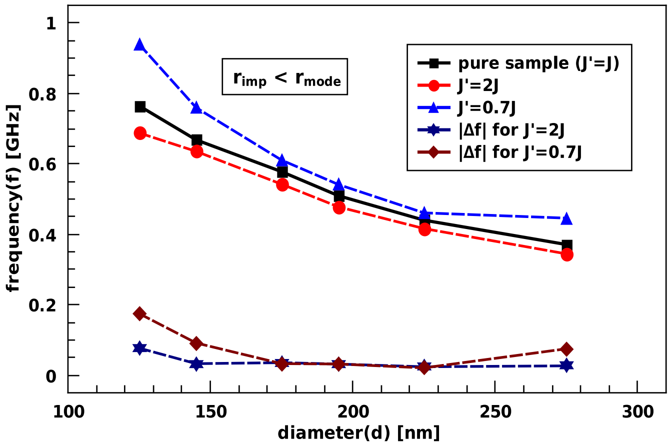

Fig. 2. Behavior of gyrotropic frequency as a function of the diameter of the nano-disks to the possibility $r_{imp} < r_{mode}$. Behavior is shown to nano-disks without impurity (square, $J' = J$, pure sample), to nano-disks with an attractive impurity (triangle, $J' = 0.7J$) and to nano-disks with a repulsive impurity (circle, $J' = 2J$). The modulus of the gyrotropic frequency shift $|\Delta f|$ is also shown (diamond for $J' = 0.7J$ and star for $J' = 2J$).

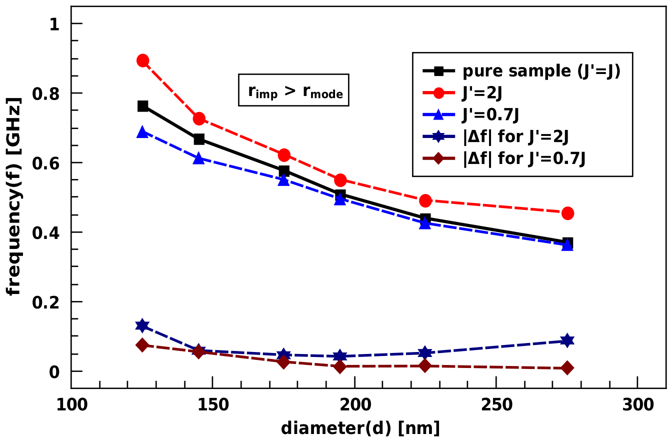

Fig. 3. Behavior of gyrotropic frequency as a function of the diameter of the nano-disks to the possibility $r_{imp} > r_{mode}$. Behavior is shown to nano-disks without impurity (square, $J' = J$, pure sample), to nano-disks with an attractive impurity (triangle, $J' = 0.7J$) and to nano-disks with a repulsive impurity (circle, $J' = 2J$). The modulus of the gyrotropic frequency shift $|\Delta f|$ is also shown (diamond for $J' = 0.7J$ and star for $J' = 2J$).

f_{imp} is the gyrotropic frequency in nano-disks in the presence of impurity and f_{pure} is the gyrotropic frequency in nano-disks without impurities (pure sample). Fig. 2 shows the behavior of the gyrotropicfrequency as a function of the diameter of the nano-disks for situations (1) and (2), compared to the behavior of the gyrotropic frequency in nano-disks without impurities (pure sample). We observed that for $r_{imp} < r_{mode}$, if $J' < J$ the gyrotropic frequency increases and if $J' > J$ the gyrotropic frequency decreases. Our results for the situation (1) are in qualitative agreement with the experimental behavior of the gyrotropic frequency shown in Ref. [22]. Fig. 3 shows the behavior of the gyrotropic frequency as a function of the diameter of the nano-disks for situations (3) and (4). We observed that for $r_{imp} > r_{mode}$, if $J' < J$ the gyrotropic frequency decreases and if $J' > J$ the gyrotropic frequency increases. From Figs. 2 and 3 we see that the gyrotropic frequency shift $|\Delta f|$ in all situations can be considered independent of the diameter of the nano-disks,which also is in agreement with the experimental observation from Ref. [22]. In our model for magnetic impurities the $|\Delta f|$ depends on the ratio J'/J.

The vortex core dynamics are governed by the Thiele force equation [15,31,32]:

$$\vec{F}_k + \vec{F}_G + \vec{F}_D = \vec{F}(t) \quad (3)$$

where $\vec{F}_k$ is the restoring force that arises when the vortex core is displaced from the center of the nano-disks, $\vec{F}_G$ is the gyrotropic force that arises due to the speed of the vortex core, $\vec{F}_D$ is the damping force and $\vec{F}(t)$ is the time-dependent driving force. As explained in Ref. [22] the restoring force can be given by $\vec{F}_k = -k\vec{R}$, where $\vec{R}$ is the vortex core displacement from the center of the nano-disks and the effective spring constant $k = k_M + \Delta k_{imp}$. The k_M is the contribution due to the magneto-static properties of the entire vortex and the Δk_{imp} refers to a contribution due to vortex core interaction with the impurity. Also, it was shown in Ref. [22] that $\Delta f \propto \Delta k_{imp}$. Based on this model, our results indicate that the presence of impurity in situations (1) and (4) makes $\Delta k_{imp} > 0$ increasing the gyrotropic frequency ($\Delta f > 0$) and the presence of impurity in situations (2) and (3) makes $\Delta k_{imp} < 0$ decreasing the gyrotropic frequency ($\Delta f < 0$).

In summary, we have used spin dynamics simulations to study the influence of magnetic impurities in the gyrotropic frequency in nano-disks of Permalloy. We studied the effect of attractive and repulsive impurity placed near the vortex core gyrotropic trajectory. We observed that in the four situations considered the frequency is affected by the presence of impurity. The gyrotropic frequency shift Δf depends on the relative position between the impurity and the vortex core gyrotropic trajectory and if impurity is attractive or repulsive. Our results agree with the analytical model and with experimental behavior for the gyrotropic frequency shown in Ref. [22]. A potential technological application can be the use of rings of magnetic impurities lithographically inserted in magnetic nano-disks to control the gyrotropic frequency and the core magnetization.

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