

## Tailoring magnetic vortices in nanostructures

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Tailoring the properties of magnetic vortices through the preparation of structured multilayers is discussed. The dependence of the vortex core radius  $r$  on the effective anisotropy is derived within a simple model, which agrees with our simulations. As the perpendicular anisotropy increases,  $r$  also increases until a perpendicular magnetization appears in the disk rim. Co/Pt multilayer disks were studied; x-ray microscopy confirms qualitatively the predicted behavior. This is a favorable system for implementing vortex-based spin-transfer nano-oscillator devices, with enhanced rf power resulting both from the increase in the core size and synchronization afforded by the coupling of the Co layers. © 2010 American Institute of Physics. [doi:10.1063/1.3462305]

In nanomagnetic samples the magnetic domain configuration depends on several parameters of the system such as size, shape, anisotropy, magnetic exchange stiffness, interface roughness, etc. A magnetic vortex often represents the lowest energy configuration,<sup>1</sup> being characterized by the following features: polarity (up or down direction of the vortex core) and circulation (clockwise or counterclockwise curling direction). Vortices have drawn great interest among researchers dealing with nanostructured materials.<sup>2</sup> Their technological applications are numerous, encompassing from devices such as vortex random access memories<sup>3,4</sup> to bio-functionalized microdisks for cancer treatment.<sup>5</sup> They also represent a key system to understand magnetism in reduced dimensions; e.g., a vortex-antivortex square lattice was proposed as a laboratory system for the study as an analog to the Bose–Einstein condensation.<sup>6</sup>

Another application is vortex-based spin transfer nano-oscillators (VSTNOs), used as microwave generator devices and suitable for device integration.<sup>7–9</sup> Despite their great appeal, these devices generate low power and dissipate much heat. It was demonstrated experimentally,<sup>6</sup> that the microwave power can be increased through phase-locking of closely spaced nano-oscillators. Still lacking is optimizing the synchronization of these devices. To face these challenges, a fine engineering of the vortex features and optimizing device geometry is highly desirable. Many efforts have been made in order to modify the vortex properties,<sup>10</sup> however, properties such as vortex core size are hard to adjust and highly dependent on the magnetic anisotropies of the system.<sup>11</sup>

In Co/Pt multilayer systems the effective magnetic anisotropy ( $K_{\text{eff}}$ ) is sensitive to the interface contributions, and can be easily controlled from in-plane to out-of-plane by playing with the Co thickness [e.g., see Ref. 12]. Moreover, these systems have been shown to present TMR or GMR.<sup>9,13–15</sup> In this letter, we propose Co/Pt multilayer engi-

neering to tailor the Co vortex properties by means of the interface contribution to  $K_{\text{eff}}$ ; we show how the vortex core magnetization and radius ( $r$ ) can be tailored by controlling  $K_{\text{eff}}$ .

According to studies on single-layered structures, typically vortices cores have  $r \sim 5$  nm. In the limit of small thickness ( $t \rightarrow 0$ ),  $r$  can be expressed by<sup>16</sup>  $\sqrt{A/K_d}$ , where  $A$  is the exchange stiffness and  $K_d$  is the magnetostatic energy density ( $K_d = \mu_0 M_s^2 / 2$ ). The effective anisotropy  $K_{\text{eff}}$  in Co/Pt multilayers can be described by the following phenomenological expression:

$$K_{\text{eff}} = K_v - 2(K_s/t), \quad (1)$$

where  $t$  is the Co thickness,  $K_v$  and  $K_s$  are the volume and interface anisotropy, respectively. From Eq. (1), one sees that it is possible to vary  $K_{\text{eff}}$  of a multilayer, simply by varying  $t$ ; as  $K_{\text{eff}}$  crosses zero, there is a spin reorientation, from in-plane ( $K_{\text{eff}} > 0$ ) to out-of-plane ( $K_{\text{eff}} < 0$ ).<sup>12</sup>

Following Ref. 16, we used the ansatz for the core magnetization of a vortex, in cylindrical coordinates;  $m_z = m_z(\rho) = \exp(-2\beta^2\rho^2)$ , where  $\beta$  is the variation parameter, corresponding to  $1/2r$ . We have considered no in-plane anisotropy, only perpendicular anisotropy energy, proportional to the perpendicular anisotropy constant  $K_z$  as follows:

$$E_z = -2\pi K_z t \int \rho d\rho m_z^2 = \pi K_z t \frac{[\exp(-4D^2\beta^2) - 1]}{4\beta^2}. \quad (2)$$

Minimizing the total energy, i.e., exchange, magnetostatic [Eqs. (5) and (8) of Refs. 16, respectively] and perpendicular anisotropy energy, we arrive at the following:

$$\frac{1}{\beta} = 2r = 2\sqrt{\frac{A}{K_d - K_z}}, \quad (3)$$

valid up to the limit  $r$  much smaller than the disk diameter  $D$ , i.e.,  $\beta D \gg 1$ . Note that in this approximation  $r$  diverges for a sufficiently large anisotropy, and for  $K_d < K_z$ , there is no real solution.

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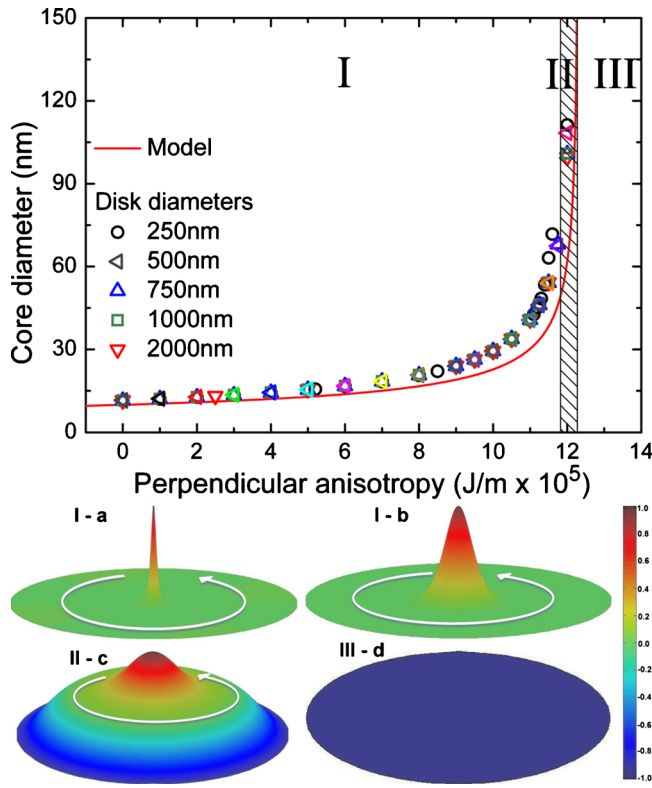


FIG. 1. (Color online) Simulated phase diagram of spin configuration of the Co/Pt multilayer disks as a function of perpendicular anisotropy and disk diameter. [a(i)] narrow core diameter ( $K_z=0$ ). [b(i)] wide core diameter ( $K_z=1.18 \times 10^5$  J/m<sup>3</sup>). [c(II)] annular spin structure ( $K_z=1.2 \times 10^5$  J/m<sup>3</sup>). [d(III)] perpendicular single domain ( $K_z > 1.2 \times 10^5$  J/m<sup>3</sup>).

Considering that  $K_d$  and  $K_z$  are, respectively, equivalent to the volume anisotropy  $K_v$  and the interface term  $2K_s/t$  in Eq. (1), in our model  $r$  is a function of  $K_{\text{eff}}$ . Micromagnetic simulations (OOMMF code<sup>17</sup>) were performed to verify the model validity. We obtained the ground state configuration for 0.25, 0.5, 0.75, 1, and 2  $\mu\text{m}$  diameter disks of a single Co layer as a function of the perpendicular anisotropy constant ( $K_z$ ). The cell size was taken as  $2 \times 2 \times 2$  nm<sup>3</sup>;  $A=30 \times 10^{-12}$  J/m and  $M_s=1400 \times 10^3$  A/m (the values used for bulk Co). Again, we have considered only the perpendicular term in the simulations;  $r$  was determined from a pseudo-Voigt function fit to  $m_z(\rho)$  obtained from the simulation.

Our simulations (Fig. 1) show vortices when  $K_z$  is included, pointing to the possibility of obtaining vortices in Co/Pt multilayer disks. A more relevant conclusion is that  $r$  varies as a function of  $K_z$ , following the behavior predicted by our model [Eq. (3)]. A phase diagram (Fig. 1) displays core size versus  $K_z$  (and therefore Co thickness) for  $D=250, 500, 750, 1000,$  and  $2000$  nm [Eq. (3) is also plotted]. A good agreement between the core diameters is obtained for the simulation and our model [Eq. (3)] for all disk diameters investigated. From this phase diagram, we can distinguish three regimes. For low values of  $K_z$  (region I, Fig. 1), we find an ordinary vortex structure with nearly the expected vortex core diameter ( $\sim 10$  nm) for a soft magnetic micrometric disk, i.e., for  $K_z=0$  [I-a in Fig. 1]. In region I, we observe a monotonic increase in the diameter as a function of  $K_z$ , as predicted by the model. The increase in  $2r$  is extended up to the limit of validity given by Eq. (3) [I-b of Fig. 1], followed by region II in the graph of Fig. 1. In region II, we observe that by augmenting the interface contribution, the spin con-

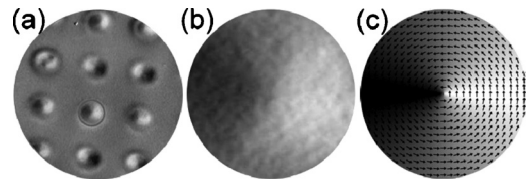


FIG. 2. (a) Image obtained by XMCD-PEEM of the  $[\text{Co}_2/\text{Pt}_2] \times 6$  1  $\mu\text{m}$  disk array. (b) Detail of the disk highlighted by the red circle, presenting a typical vortex pattern. (c) OOMMF simulation of a disk with the same characteristic, showing a good agreement with (a).

figuration may present increasingly out-of-plane components. Besides the perpendicular magnetization of the vortex core, a perpendicular magnetization also appears at the rim of the disks [II-c in Fig. 1], forming a domain configuration of out-of-plane concentric rings. Although  $K_v$  is still larger than  $2K_s/t$ , the boundary conditions impose an out-of-plane  $K_{\text{eff}}$ . Region III: for  $2K_s/t > K_v$ , it gives rise to an out-of-plane single domain [region III and III-d of Fig. 1], and therefore the vortex is no longer observed.

Four samples, consisting of lithographed arrays of Co/Pt multilayered disks [ $D=1$  and  $2$   $\mu\text{m}$ ] deposited by sputtering on  $\text{SiO}_2/\text{Si}(100)$  wafers, were produced. Their structure was  $([\text{Co}_t/\text{Pt}_2]_6/\text{Pt}_6)$  with Co layer thickness  $t=2.0, 1.6, 0.8,$  and  $0.6$  nm. Continuous films were also produced in the same sputtering runs. The magnetic properties and morphology of the samples were characterized by magnetometry, x-ray magnetic circular dichroism (XMCD) photoelectron emission microscopy (PEEM) and magnetic force microscopy.

The XMCD-PEEM measurements were performed at the Nanospectroscopy beamline at Elettra Synchrotron, Italy. The final pictures were obtained by averaging up to 250 images (taken at Co  $L_3$  edge) originated from subtracting two images acquired with opposite (left/right) circular polarizations. This imaging technique contrasts the magnetization alignment relative to the x-ray beam direction. The experiment was carried out in grazing incidence setup ( $16^\circ$ ), therefore the images distinguish mostly the in-plane magnetization distribution, the black/white contrast referring to parallel/antiparallel relation between the magnetization components and the beam direction. However, the measurements are still sensitive to the perpendicular magnetization, due to the angle between the perpendicular magnetization and the x-ray beam.

Figure 2 shows images of the  $[\text{Co}_2/\text{Pt}_2] \times 6$  multilayered disks, which presented the highest  $K_{\text{eff}}$ . For the 1 and 2  $\mu\text{m}$  array, almost all disks have a single vortex structure. This is confirmed if we compare the experimental result of a particular disk size with the equivalent simulated one (Fig. 2). The realization of magnetic vortices in a multilayer system represents a great step toward better controlling the magnetic vortex properties and characteristics.

For the arrays with a smaller Co thickness  $[\text{Co}_t/\text{Pt}_2] \times 6$  ( $t=0.6$  and  $0.8$  nm), i.e., for  $K_{\text{eff}} \sim 0$ , the magnetic configurations do not seem to correspond to an usual vortex [XMCD-PEEM image in Fig. 3(a)]. In this case, it is observed a smaller bright/dark contrast close to the center. Our interpretation is that we have the same spin configuration of region II of the phase diagram [see II-c in Fig. 1], i.e., at the center M is pointing upwards, at the rim downwards and in-between there is a planar vortex. For comparison, Fig. 3(b) also presents the spin configuration of c(II) (Fig. 1), but

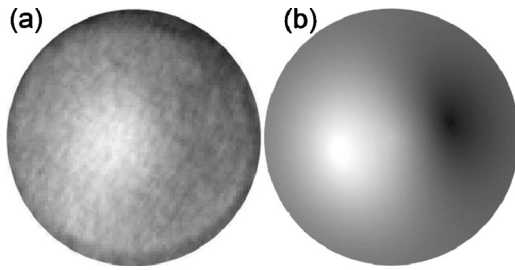


FIG. 3. (a) XMCD-PEEM image of  $1 \mu\text{m}$   $[\text{Co}_{0.6}/\text{Pt}_2] \times 6$  disk. (b) simulated spin configuration of a disk of the same size (region II in the phase diagram of Fig. 1), showing a good agreement with (a).

in a pattern that mimics the PEEM contrast, showing a good agreement between the measurement and the simulation. In this case, the faint contrast is due to the  $16^\circ$  tilt angle between the plane of the sample and the x-rays direction.

Although the XMCD-PEEM technique is not well suited for assessing  $r$ , we could observe a behavior that corroborates our proposition. For the thicker Co layers, where it is expected a larger in-plane anisotropy, we obtained a vortex structure (Fig. 2). As we get closer to the spin reorientation transition condition, i.e., for thinner Co layers, we observed out-of-plane magnetization in concentric annular regions (Fig. 3). This agrees with the simulations, i.e., vortex structure and annular arrangement, corresponding to regions I and II (Fig. 1).

These results open up opportunities for optimizing VSTNOs devices.<sup>6</sup> The magnetic dipole moment of the vortex core is proportional to its square radius ( $r$ );  $\mu = \pi r^2 t M_s$ . The synchronization of the gyrotropic motion of the cores in an array of vortices<sup>6</sup> is dependent on the coupling between vortices through the antivortices, and therefore dependent on the dipolar and long-range exchange interactions between vortices and antivortices counter balanced by the restoring forces (Oersted field). Since both interactions depend on  $r$ , tailoring  $r$  is relevant for increasing the microwave power and for achieving phase locking in VSTNOs.

Maybe the most significant contribution of multilayer-based vortex systems would be the establishment of an alternative architecture for the VSTNOs, i.e., a vertical vortices stacking, possibly solving the problems of synchronization and power. This vortices stacking device is naturally phase-locked, since it is well-known that the Co layers are coupled,<sup>18</sup> and therefore the power generated will be amplified relative to an individual vortex. Hence, we would have a

synchronized set of vortices in a very compact device.

In conclusion, tailoring magnetic vortex core diameters as well as other properties of magnetic disks is proposed by adjusting the interface energy contribution in Co/Pt multilayered structured system. The proposal is supported by a model and by micromagnetic simulations which present consistent results. Theory and simulation are also presented in the form of a phase diagram defining three regions with distinct domain structure. We demonstrated experimentally vortex formation on Co/Pt multilayered disks. We also verified that vortex nucleation is affected by the interface contribution, consistently with the model. Finally, we proposed and demonstrated a strategy to engineer magnetic vortex properties to suit technological application demands.

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