Tailoring magnetic vortices in nanostructures

F. Garcia,[1,a)] H. Westfahl,[1] J. Schoenmaker,[1] E. J. Carvalho,[1] A. D. Santos,[2] M. Pojar,[3] A. C. Seabra,[3] R. Belkhou,[4,5] A. Bendounan,[4] E. R. P. Novais,[6] and A. P. Guimarães[6]
[1]*Laboratório Nacional de Luz Síncrotron, Campinas, 13083-970 São Paulo, Brazil*
[2]*LMM, IFUSP, São Paulo, 05508-900 São Paulo, Brazil*
[3]*LSI-PSI, Poli-USP, São Paulo, 05508-900 São Paulo, Brazil*
[4]*Synchrotron SOLEIL, F-91192 Gif-sur-Yvette Cedex, France*
[5]*Elettra Synchrotron, 34149 Trieste, Italy*
[6]*CBPF, Rio de Janeiro, 22290-180 Rio de Janeiro, Brazil*

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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,[1] 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.[2] Their technological applications are numerous, encompassing from devices such as vortex random access memories[3,4] to biofunctionalized microdisks for cancer treatment.[5] 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.[6]

Another application is vortex-based spin transfer nano-oscillators (VSTNOs), used as microwave generator devices and suitable for device integration.[7–9] Despite their great appeal, these devices generate low power and dissipate much heat. It was demonstrated experimentally,[6] 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,[10] however, properties such as vortex core size are hard to adjust and highly dependent on the magnetic anisotropies of the system.[11]

In Co/Pt multilayer systems the effective magnetic anisotropy (K_{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.[9,13–15] In this letter, we propose Co/Pt multilayer engineering to tailor the Co vortex properties by means of the interface contribution to K_{eff}; we show how the vortex core magnetization and radius (r) can be tailored by controlling K_{eff}.

According to studies on single-layered structures, typically vortices cores have $r \sim 5$ nm. In the limit of small thickness ($t \to 0$), r can be expressed by[16] $\sqrt{A/K_d}$, 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_{eff} in Co/Pt multilayers can be described by the following phenomenological expression:

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

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_{eff} of a multilayer, simply by varying t; as K_{eff} crosses zero, there is a spin reorientation, from in-plane ($K_{\text{eff}} > 0$) to out-of-plane ($K_{\text{eff}} < 0$).[12]

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 β 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:

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

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:

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

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.

a)Electronic mail: fgarcia@lnls.br.

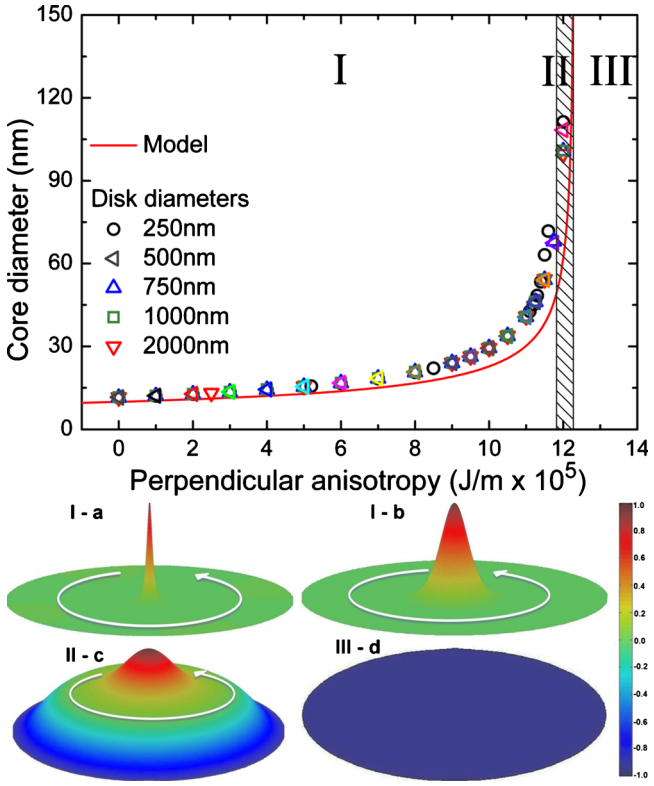

FIG. 1. (Color online) Simulated phase diagram of spin configuration of the Co/Pt multilayer disks as a function of perpendicular anisotropy and disk diameter. [a(i)] narrow core diameter (K_z=0). [b(i)] wide core diameter (K_z=1.18×10^5 J/m^3). [c(II)] annular spin structure (K_z=1.2×10^5 J/m^3). [d(III)]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

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_{eff}. Micromagnetic simulations (OOMMF code[17]) were performed to verify the model validity. We obtained the ground state configuration for 0.25, 0.5, 0.75, 1, and 2 μm diameter disks of a single Co layer as a function of the perpendicular anisotropy constant (K_z). The cell size was taken as 2×2×2 nm^3; A=30×10^{-12} J/m and M_s=1400×10^3 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 (~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 configuration 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_{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.

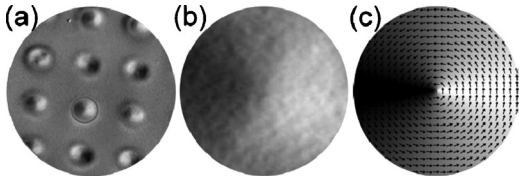

FIG. 2. (a) Image obtained by XMCD-PEEM of the [Co_2/Pt_2]×6 1 μm disk array. (b) Detail of the disk highlighted by the red circle, presenting a typical vortex pattern. (c) OOMMF simulation of a disk with the same characteristic, showing a good agreement with (a).

Four samples, consisting of lithographed arrays of Co/Pt multilayered disks [D=1 and 2 μm] deposited by sputtering on SiO_2/Si(100) wafers, were produced. Their structure was ([Co_t/Pt_2]$_6$/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°), 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 [Co_2/Pt_2]×6 multilayered disks, which presented the highest K_{eff}. For the 1 and 2 μm 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 [Co_t/Pt_2] ×6 (t=0.6 and 0.8 nm), i.e., for K_{eff}~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

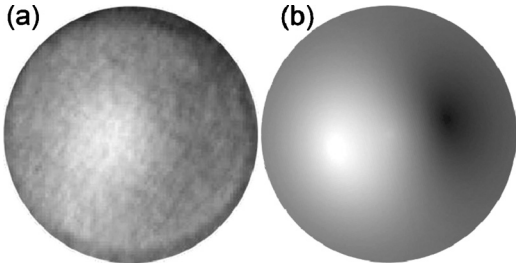

FIG. 3. (a) XMCD-PEEM image of 1 μm $[Co_{0.6}/Pt_2]\times 6$ disk. (b) simulated spin configuration of a disk of the same size (region II in the phase diagram of Fig. 1), showing a good agreement with (a).

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° 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.[6] 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[6] 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,[18] 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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