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Controlling the vortex core of thin Permalloy nano-cylinders dipolar coupled to Co polarizers

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We report a theoretical study of the vortex profile of in-plane magnetized Py^{TM} nano-cylinders subjected to the stray field of perpendicular anisotropy Co nano-cylinders. We consider 6 nm thick Py^{TM} cylinders dipolar coupled to 60 nm thick Co cylinders, at distances from 1.5 nm to 30 nm, with diameters (D) ranging from 45 nm to 105 nm. We find considerable reduction of critical diameter for stable Py^{TM} magnetic vortices and spiral-vortex phases, as well as vortex core diameters twice as large as the bulk value.
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The pioneering proposal[1,2] of a new mechanism to locally manipulate the magnetic order of nano-sized magnetic systems, triggered an ever increasing interest in the small-scale architecture of the magnetic order of nanoelements.

The magnetic profile of the vortex core in submicron sized nanoelements is relevant for a number of phenomena of current interest.[3]

From the viewpoint of applications, tailoring the vortex core is a primary issue for devices based on vortex core dynamics,[4] such as spin-transfer torque nano-oscillators.[5,6]

The recent development of high efficacy[7,8] and external field-free spin-transfer nano-oscillators is based on magnetic tunnel junctions (MTJ) which contains a perpendicular spin current polarizer combined with an in-plane magnetized free layer.

This MTJ cell brings the free layer and the polarizer within the reach of the dipolar field of each other. Thus the vortex core profile at the free layer is affected by the dipolar field of the polarizer.

Also, the magnetic order of the polarizer is affected by the dipolar field of the free layer. Therefore the phase diagram of perpendicular anisotropy ferromagnetic cylinders[9] may change.

In this paper, we report a theoretical study of the vortex structure of thin Py^{TM} nano-cylinders dipolar coupled to perpendicular anisotropy Co nano-cylinders, separated by distances ranging from 1.5 nm to 30 nm, with diameters (D) ranging from 45 nm to 105 nm

We have found that the dipolar interaction may lead to relevant changes in the Co magnetic order as well as in the Py^{TM} vortex profile.

We have found that a single Co nano-cylinder with diameter ranging from 75 nm to 105 nm requires a height of at least 60 nm in order to magnetize in a quasiuniform single domain small angle flower state[9] along the axis. For this reason we have fixed the Co cylinder height in 60 nm for all examples discussed. There are variations in the angle with the axis according to the distance of the Py^{TM} nano-cylinder to the Co surface.

Also, we have found that a minimum diameter of 93 nm is required to fit a vortex in a 6 nm single Py^{TM} nano-cylinder. The dipolar interaction with the Co polarizer shifts this threshold to much smaller diameter values.

There is a considerable reduction of the critical dimensions for the nucleation of a stable magnetic vortex-like state on the Py^{TM} cylinder.

At a distance of 15 nm from the polarizer surface, a 6 nm thick small diameter (75 nm) Py^{TM} cylinder displays a vortex-like (spiral-vortex) state at remanence. At the same distance from the polarizer surface, a vortex state is formed in a 6 nm thick, 81 nm diameter, Py^{TM} cylinder.

There are also considerable changes in the vortex core diameter. The vortex core diameter of a 60 nm diameter Py^{TM} cylinder covers from 50% to 100% of nano-element area for distances in the 15 nm–1.5 nm range from the surface of the Co polarizer.

For a 105 nm diameter Py^{TM} nano-cylinder the corresponding values are 25% to 30%. For both diameter values the vortex at small Py^{TM}—Co separation has a spiral shape, while the uniform Co state along the z-axis turns into a flower state with small angle with the z-axis.

In Fig. 1 we show details of the magnetic structure and stray field of a 75 nm diameter, 60 m thick, Co nano-cylinder coupled to a 6 nm thick Py^{TM} nano-cylinder located at a 15 nm distance from the Co surface.

Along the Co cylinder axis, the strength of the Co stray field varies from 5.5 kOe at the Co surface, down to 2 kOe at a distance of 33 nm.

Within the Py^{TM} nano-cylinder the Co stray field is of the same order of magnitude as the self-dipolar field of the Py^{TM} nano-cylinder.

The magnetic phase of a single 75 nm diameter, 6 mn thick Py^{TM} nano-cylinder is an in-plane quasiuniform state.

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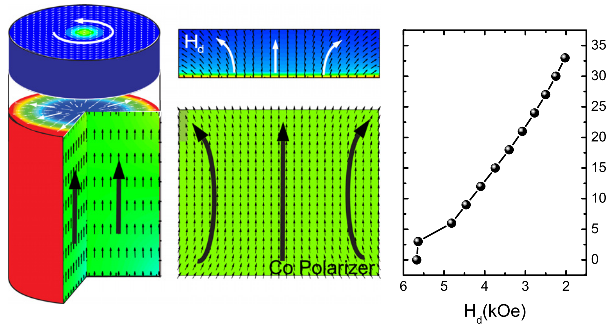

FIG. 1. Py^{TM} (6 nm)/15 nm/Co(60 nm). The panel in the center shows the magnetization profile of the polarizer and, on the top, the stray field from the polarizer on the nano-disk region. The curve shows how the strength of the Co stray field varies with the distance along the axis, starting at the surface of the Co polarizer.

TABLE I. Py^{TM} vortex and vortex-like states.

	$Py^{TM} = 6$ nm			
D (nm)	Py^{TM} isolated	d = 6 nm	d = 15 nm	d = 30 nm
45	Uniform	45 nm[a]	Uniform	Uniform
63	Uniform	Flower	42 nm[a]	Uniform
75	Uniform	Flower	60 nm[a]	45 nm[b]
81	Uniform	Flower	66 nm[a]	60 nm[b]
93	36 nm[b]	72 nm[a]	66 nm[a]	66 nm[b]
105	36 nm[b]	78 nm[a]	78 nm[a]	78 nm[b]

[a]Spiral vortex core diameter.
[b]Vortex core diameter.

The Co stray field breaks the balance between the intrinsic exchange and self-dipolar field of the Py^{TM} nano-cylinder, leading to the formation of a vortex (or vortex-like) state.

In the theoretical model we use cubic cells of edge $d = 3$ nm. For each value of the external field strength, the equilibrium configuration is found by seeking a set of directions of the moments in all cells ($\hat{m}_i,\ i = 1, \ldots, N$) which makes the torque in each one of them smaller than 10^{-14} Am^2/s.[10–12]

The z-axis is chosen perpendicular to the surface of the nanoelement and the uniaxial anisotropy easy axis of the Co polarizer is out of plane and along the z-axis. The effective field is given by $\vec{H}_{eff} = -(\partial E/\partial \vec{M})$ and the energy density is given by

$$
\begin{aligned}
E = &\frac{A}{d^2}\sum_j\sum_k(1 - \hat{m}_j.\hat{m}_k) \\
&-M_S\vec{H}.\sum_j \hat{m}_j - K\sum_j (m_j^z)^2 \\
&+\frac{M_S^2}{2}\sum_j\sum_k\left(\frac{\hat{m}_j.\hat{m}_k}{n_{jk}^3} - \frac{3(\hat{m}_j.\hat{n}_{jk})(\hat{m}_k.\hat{n}_{jk})}{n_{jk}^5}\right),
\end{aligned}
\tag{1}
$$

where the first term is the intrinsic exchange energy, coupling magnetic moments of nearest-neighbor cells and A is the ferromagnetic exchange stiffness. The second and third terms are the Zeeman and anisotropy energies. The last term is the magnetostatic energy. It involves an unrestricted sum of the dipolar energy, coupling all pairs of cells, either in the same material, or in different materials. $\hat{m}_i$ is the direction of the magnetic moment of the $i-th$ cell, and n_{ij} is the distance between the cells i and j in units of cell size d.

We obtain the equilibrium pattern at remanence by starting from saturation at large external field values (H) along the z-axis direction (10 kOe was enough to achieve saturation for all examples in this study).

Then we followed the sequence of equilibrium states using a fine grid of values of H, all the way down to $H = 0$. The equilibrium profile for each value of the external field strength was used as the initialization pattern for the next value of the external field strength.

In all cases discussed in this study, as shown in Table I and in Fig. 2(a), the phase of the Co cylinder is a quasiuniform single-domain flower state[9] with the magnetization aligned at small angles with the z-axis.

As shown in Fig. 2(a), in the near axis region the magnetization is nearly aligned with the z-axis. The misalignment angle is larger near the lateral surfaces, reaching values around $\pi/6$, as for example in the case of the 75 nm diameter Co(60 nm)/15 nm/Py^{TM} (6 nm) system.

The phases of the Py^{TM} nano-cylinder include: (i) a flower state with large misalignment angles. For a distance of 1.5 nm, and all diameters in this case, the flower angle reaches a value near $\pi/3$. The absence of uniaxial anisotropy turns the misalignment angle of the Py^{TM} nano-cylinder larger than the corresponding value in the Co nano-cylinder; (ii) the vortex state, which consists in an in-plane curling magnetization pattern around the core at the center, where there is a perpendicular component of the magnetization;[13]

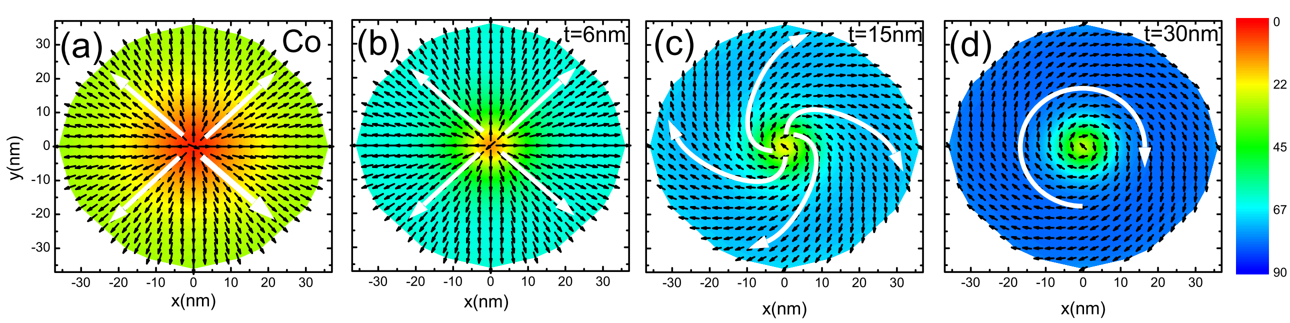

FIG. 2. The panels show the (a) the magnetic structure of the flower state of a 60 nm thick, 75 nm diameter Co cylinder, and the magnetic phases of 6 nm thick Py^{TM} nanoelements with diameter of 75 nm at a distance from the Co surface of (b) $d = 6$ nm, *flower state*; (c) $d = 15$ nm, vortex-like state (*spiral-vortex state*); and (d) $d = 30$ nm, vortex state. The color bar code shows the angle with z-axis (normal to the surface).

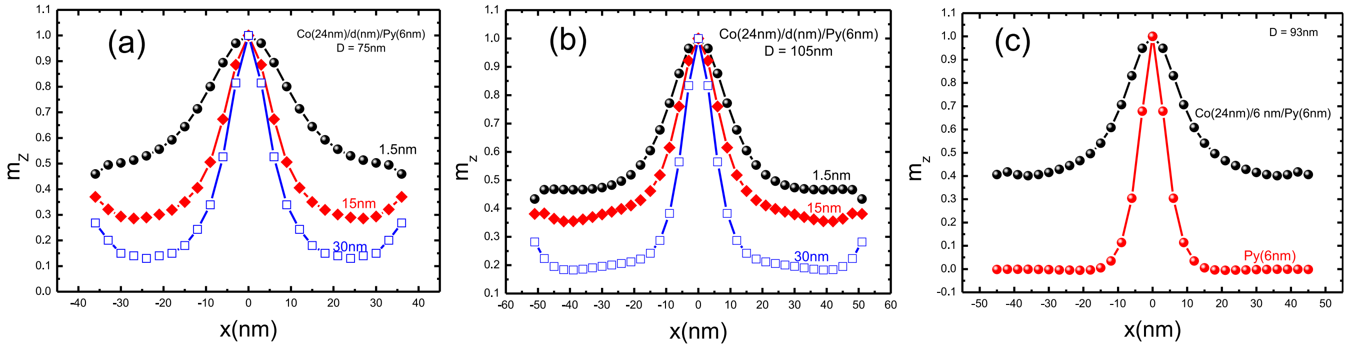

FIG. 3. The panels show (a) the magnetic structure of the flower state of a 60 nm thick, 75 nm diameter Co cylinder, and the magnetic phases of 6 nm thick Py^{TM} nanoelements with diameter of 75 nm at a distance from the Co surface of (b) $d = 6$ nm, *flower state*; (c) $d = 15$ nm, vortex-like state (*spiral-vortex state*); and (d) $d = 30$ nm, vortex state. The color bar code shows the angle with z-axis (normal to the surface).

and (iii) and a spiral-vortex phase in which outside the core the magnetization is not in-plane.

We have found that for distances to the Co polarizer surface smaller than 6 nm, and diameter ranging from 45 nm to 105 nm, the Py^{TM} nano-cylinder display a flower state pattern, or a spiral-vortex phase with large angle ($\pi/3$) outside the core.

As shown in Table I and in Fig. 3, vortex states are formed at a distance of $d = 30$ nm. For $d = 15$ nm we have found spiral-vortex phases with core diameters larger than the bulk Py^{TM} core size. Even a large diameter ($D = 93$ nm) Py^{TM} nano-cylinder, which displays a vortex phase if isolated, has a strongly modified phase (spiral-vortex) in the presence of the Co stray field at short distances ($d = 6$ nm).

We have shown that the Co–Py^{TM} interaction affects the vortex profile and leads to new phases. These phases emerge from the dipolar interaction and may be of interest for the safe design of magnetic tunnel junction devices.

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