Micromagnetic simulation of vortex core polarity in bi-component magnetic nanodisks

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Abstract

The nucleation and management of the vortex state in magnetic nanostructures has received a lot of interest in recent decades, with potential applications in logic networks and non-volatile magnetic random-access memory. Because of their potential use in magnetic memory, magnetic vortex structures are of considerable technical importance. Investigation of bi-component magnetic nanodisks as prospective storage systems, in both single and coupled configurations, has been performed, where the information unit is represented by vortex core polarity. The work mainly engages in magnetic nanodisks of permalloy and iron having a diameter of 200 nm and a thickness of 40 nm. The potential of adjusting the polarity of the vortex core by the application of a magnetic field using micromagnetic simulations has been illustrated. Micromagnetic simulation studies show that bi-material structures are important not just for fundamental research but also for data storage.

Keywords: *Magnetic vortex, Micromagnetic simulation, Iron, Permalloy, Dipolar coupling*

1. Introduction

The scientific community has been exploring new approaches to structuring and designing materials at the nanoscale in order to build downsized and energy-efficient electronics in the near future [1]. Owing to its potential use in data storage and, notably, nonvolatile magnetic random-access memory, the control of the vortex state in magnetic nanodisks is a focus of intense investigation in this context. Using either vortex polarity (up/down alignment of magnetization in the vortex core) or chirality (clockwise/counterclockwise rotational direction of magnetization), two bits of information may be stored on a single nanodisk [2, 3]. Despite magnetic vortices' technological possibilities, manipulating their topological features is still a challenging task [4]. To tune vortex chirality and perhaps polarity, many methods have been suggested, such as the use of asymmetric dots with a flattened edge or regular polygonal nanomagnets having an odd number of sides [5, 6]. Using resonant stimulation with a rf current, static and dynamic control of both polarity and chirality for a vortex contained in a magnetic tunnel junction was demonstrated [7, 8]. Vortex chirality and polarity can also be manipulated using broken rotational symmetry [9]. In this context, bi-component disks (consist of two different magnetic materials) may be used to produce broken symmetry [10].

In this paper, bi-component magnetic nanodisks comprised of iron and permalloy with a configuration of crescent-shaped iron and lens-shaped permalloy have been reported to investigate the feasibility of adjusting the vortex's core polarity and stability using local shape anisotropies at the two different material interfaces. The simulation results show such bi-component magnetic structures might open up new opportunities in fundamental research and practical applications.

2. Theory and Simulation details

The micromagnetic simulator OOMMF (Object Oriented MicroMagnetic Framework) is used to run the simulations. The Landau-Lifshitz-Gilbert (LLG) equation of motion is solved dynamically, which uses finite differences for meshing [11, 12]. Using the eXtensible Solver, OOMMF allows to construct bi-component maps in a variety of ways. The study concentrates on magnetic nanodisks with a diameter of 200 nm and thickness of 40 nm and comprising of two magnetic materials, namely a permalloy (Py) lens and an iron (Fe) crescent [Figure 1(a)]. The material parameters used in the simulations for Fe (Py) are: saturation magnetization $M_{s,Fe} = 1700 \times 10^3 A/m$ ($M_{s,Py} = 800 \times 10^3 A/m$), magneto-crystalline anisotropy constant $K_{1,Fe} = 48 \times 10^3 J/m^3$ ($K_{1,Py} = 0$), and exchange constant $A_{Fe} = 21 \times 10^{-12} J/m$ ($A_{Py} = 13 \times 10^{-12} J/m$). These values are averaged along the boundaries between the separate materials' values. The simulations are carried out using a cell size of $1 \times 1 \times 40\ nm^3$ for a time duration of 20 ns.

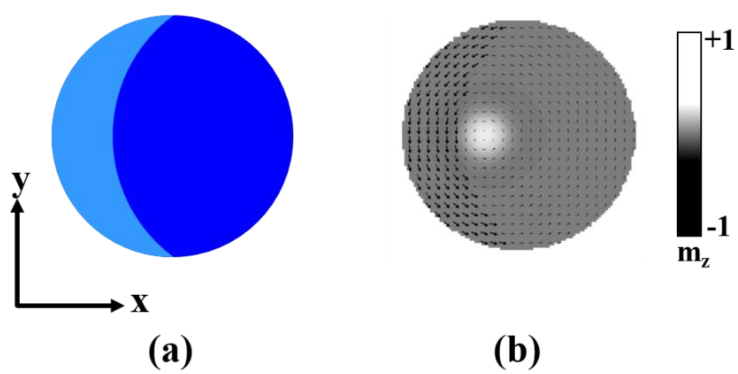

FIG 1. (a) Schematic sketch of the bi-component magnetic nanodisk configuration under study consisting of an iron crescent (sky) and a lens permalloy (blue); one-third portion of the disk is iron while two-third is permalloy (b) Ground state spin considered configuration. The color bar indicates m_z (the out-of-plane magnetization component).

3. Results and Discussions

An isolated magnetic bi-component nanodisk of iron and permalloy having a diameter of 200 nm and a thickness of 40 nm has been considered, and the stable and equilibrium ground state has been established. The technique for determining the magnetic vortex's ground equilibrium state may be found elsewhere [13]. A magnetic vortex, after forming initially at the centre of the magnetic nanodisk, moves along the negative x-axis and finally stabilizes in the permaslloy region at the boundary of the iron-permalloy as shown in Figure 1(b). To find out the gyration frequency of the isolated bi-component nanodisk, we applied a broadband sinc excitation along the x-direction containing power up to 45 GHz. The details of the excitation can be found in the reference [13]. The Fast Fourier Transform (FFT) of the time variable magnetization is used to determine the frequency of vortex core gyration. The gyrotropic frequency of an isolated bi-component magnetic disk is found to be 1.835 GHz [Figure 2(a)]. To investigate the possibility of tuning of vortex core polarity, another magnetic nanodisk having an identical dimension has been considered, which is placed at a separation of s = 10 nm [Figure 2(b)].

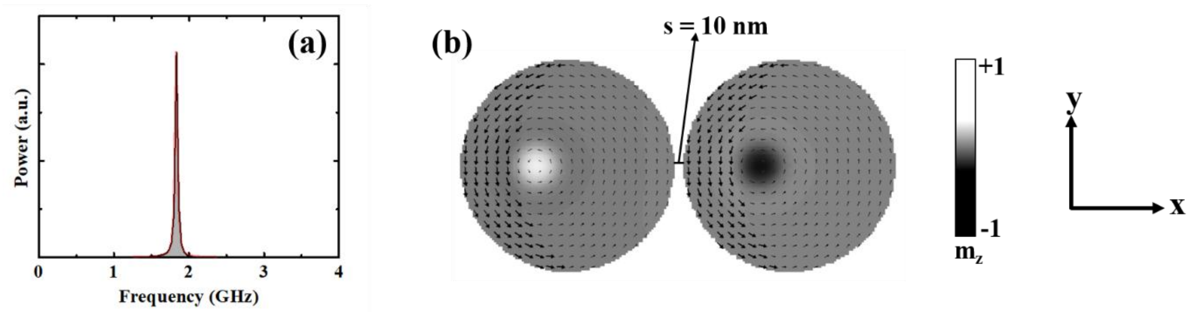

FIG 2. (a) Gyrotropic frequency of an isolated bi-component magnetic nanodisk configuration under study (b) Coupled bi-component magnetic vortices each of diameter = 200 nm and thickness = 40 nm. In the case of coupled vortices, the center-to-centre spacing is a = 210 nm.

Simulations are performed considering two identical bi-component magnetic nanodisks with four different possibilities of vortex core polarity. The detailed configuration and the possibility of manipulating the core polarities have been presented in Table 1.

Table 1: Combination of vortex core polarities with the possibility of controlling them; the two disks being with configuration: (a) Fe-Py, Fe-Py (b) Fe-Py, Py-Fe and (c) Py-Fe, Fe-Py.

Polarity of vortex core (p)	**Possible to control and stable the vortex core polarity**
+1, +1	Yes
+1, -1	Yes
-1, +1	Yes
-1, -1	Yes

(a)

Polarity of vortex core (p)	**Possible to control and stable the vortex core polarity**
+1, +1	Yes
+1, -1	Yes
-1, +1	Yes
-1, -1	Yes

(b)

Polarity of vortex core (p)	**Possible to control and stable the vortex core polarity**
+1, +1	Yes
+1, -1	No
-1, +1	No
-1, -1	No

(c)

From the above table, it is seen that when the two considered disks are Fe-Py, Fe-Py and Fe-Py, Py-Fe the vortex core polarity is stable and can be manipulated in all the four possible combinations, while when the considered disks are Py-Fe, Fe-Py, it is not possible to control the core of the vortex when any one or both of the polarities are p = -1. This is due to the strong dipolar coupling between the interacting nanodisks, which can be attributed to the high exchange coupling constant of iron. The strength of dipolar coupling dominates, and hence the polarity of the vortex cores cannot be controlled. In all these cases, the vortex is formed in the permalloy region at the interface of the iron-permalloy boundary. Thus, we can control the polarity of vortex core in the bi-component magnetic nanodisk when the interacting faces are iron-permalloy and permalloy-permalloy.

4. Conclusion

To conclude, control of magnetic vortex core polarity in bi-component magnetic nanostructures made of iron and permalloy was investigated using micromagnetic simulations. In such a magnetic nanostructure, a magnetic vortex is always formed in the permalloy region at the boundary of iron and permalloy. Also, the vortex core polarity can be controlled when the interacting faces of the nanodisks are either iron-permalloy or only permalloy in a coupled magnetic nanodisk. However, when the interacting face is iron, the core polarity of the magnetic vortex cannot be controlled due to the high exchange coupling constant of iron. Finally, the results of these simulations so obtained are needed to assess the possibility of influencing the vortices exclusively, allowing for the storage of one bit of information in such a magnetic nanoparticle.

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REFERENCES

[1] J. M. De Teresa, A. Fernández-Pacheco, R. Córdoba, L. Serrano-Ramón, S. Sangiao, and M. R. Ibarra, J. Phys. D: Appl. Phys. 49, 243003 (2016).
[2] J. W. Lau and J. M. Shaw, J. Phys. D: Appl. Phys. 44, 303001 (2011).
[3] R. Hertel, Nat. Nanotechnol. 8, 318–320 (2013).
[4] Y. Zheng and W. J. Chen, Rep. Prog. Phys. 80, 086501 (2017).
[5] M. Schneider, H. Hoffmann, and J. Zweck, Appl. Phys. Lett. 79, 3113–3115 (2001).
[6] T. Kimura, Y. Otani, H. Masaki, T. Ishida, R. Antos, and J. Shibata, Appl. Phys. Lett. 90, 132501 (2007).
[7] M. Jaafar, R. Yanes, D. Perez de Lara, O. Chubykalo-Fesenko, A. Asenjo, E. M. Gonzalez, J. V. Anguita, M. Vazquez, and J. L. Vicent, Phys. Rev. B 81, 054439 (2010).
[8] S. Yakata, M. Miyata, S. Nonoguchi, H. Wada, and T. Kimura, Appl. Phys. Lett. 97, 222503 (2010).
[9] R. K. Dumas, D. A. Gilbert, N. Eibagi, and K. Liu, Phys. Rev. B 83, 060415(R) (2011).
[10] G. Shimon, A. O. Adeyeye, and C. A. Ross, Appl. Phys. Lett. 101, 083112 (2012).
[11] M. J. Donahue, Porter, D.G. OOMMF User's Guide, Version 1.0; Interagency Report NISTIR 6376; National Institute of Standards and Technology: Gaithersburg, MD, USA, 1999.
[12] T. L. Gilbert, IEEE Trans. Magn. 40, 3443 (2004).
[13] S. Barman, S. Saha, S. Mondal, D. Kumar, A. Barman, *Sci. Rep.* 6 (1), 33360 (2016).