Magnetization reversal in magnetic half-balls influenced by shape perturbations

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The magnetization reversal dynamics of three-dimensional (3D) ferromagnetic permalloy half-balls has been examined using micromagnetic simulations and finite element methods. The comparison between disturbed and nondisturbed sample shapes enabled observations of the nature of switching, types of oscillations, and times of reversal, triggered by an externally applied magnetic field. © *2010 American Institute of Physics*. [doi:10.1063/1.3524501]

I. INTRODUCTION

Understanding reversal mechanisms and dynamics of magnetic nanosystems is one of the leading topics in contemporary physics. Due to their potential applications, nanostructured ferromagnetic elements have been intensively studied over the past decade.[1,2] Such nanomagnets may improve efforts to continuative miniaturization of data storage media enabling higher data densities.[3,4] The dependence of magnetization reversal mechanisms on dimensions and shape of magnetic nanoparticles has been shown in several works for different shapes (e.g., ellipsoids and dots,[5] rectangles and triangles,[6] wires,[7] tubes,[8] and mixed geometries[9]). Especially, the analysis of the flux-closed vortex state is of high interest for applications of magnetic nanoparticles in storage devices due to minimization of stray fields.[10,11] The formation of a vortex state has been found to be strongly dependent on dimensions and shape of magnetic nanoparticles.[10,12,13] All these experiments and simulations are usually limited to two-dimensional (2D) nanomagnets. However, the results of first attempts to create thin films on nonmagnetic spheres with diameters between 20 and 1000 nm underline the importance of probing three-dimensional (3D) nanomagnets.[14,15]

The development of magnetic nano-objects for memory and sensing applications requires appropriate performance depending on switching time and magnetization evolution with characteristic oscillations. The observed magnetization dynamics is a response of a magnetic object to an externally applied magnetic field (or current) pulse, which drives magnetization reversal via subsequent states from one saturated state into the reversed one.

II. SIMULATIONS

In order to test simple, elementary 3D magnetic objects from permalloy (Py) (Fig. 1), we performed micromagnetic simulations testing the two directions of the externally applied field, namely, that applied along the direction of high symmetry (here, z-axis) and along the direction of lower symmetry, here applied in the sample x-y plane, along the x-axis of the Cartesian system.

When the simulations were carried out with the external magnetic field applied along the z-axis, the sequence of calculations was as follows: starting from a random state of magnetization (external field $H_{\text{ext}}=0$), the field was changed at a constant speed of 10 kA/(m$\times$ ns) up to 600 kA/m to saturate the sample. Next, starting from saturation, the field was swept at the same speed to -600 kA/m in order to obtain a reversed saturation. When the simulations were performed with the external magnetic field applied along the x-axis, the sequence of calculations was similar; however, the saturations were obtained for ± 450 kA/m. The chosen field sweeping speed is comparable to values normally used in MRAM applications.[16]

The simulations were carried out with the scalable parallel-processors micromagnetic solver (MAGPAR) (Ref. 17) using dynamic integration of the Landau–Lifshitz–Gilbert equation of motion and finite element meshing for sample visualization. Meshing was made from finite tetrahedral elements of dimensions no larger than 3.7 nm, while the Py exchange length equals 5.7 nm.[18] The meshing was denser near edges to include more strictly the influence of

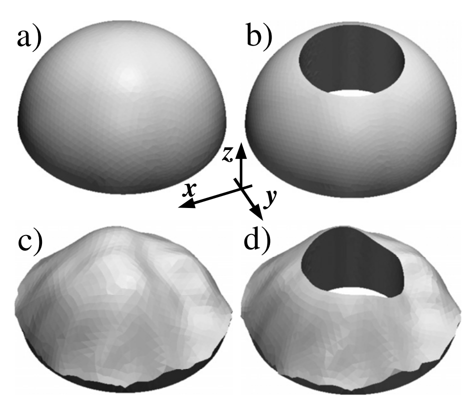

FIG. 1. The view of simulated Py half-balls: regular solid (a), regular with a hole (b), disturbed solid (c), and disturbed with a hole (d). The cylindrical hole diameter equals 50 nm. The diameter of a half-ball base, located at the x-y plane, equals 100 nm [(a) and (b)], while their height, measured along the z-axis, equals 50 nm.

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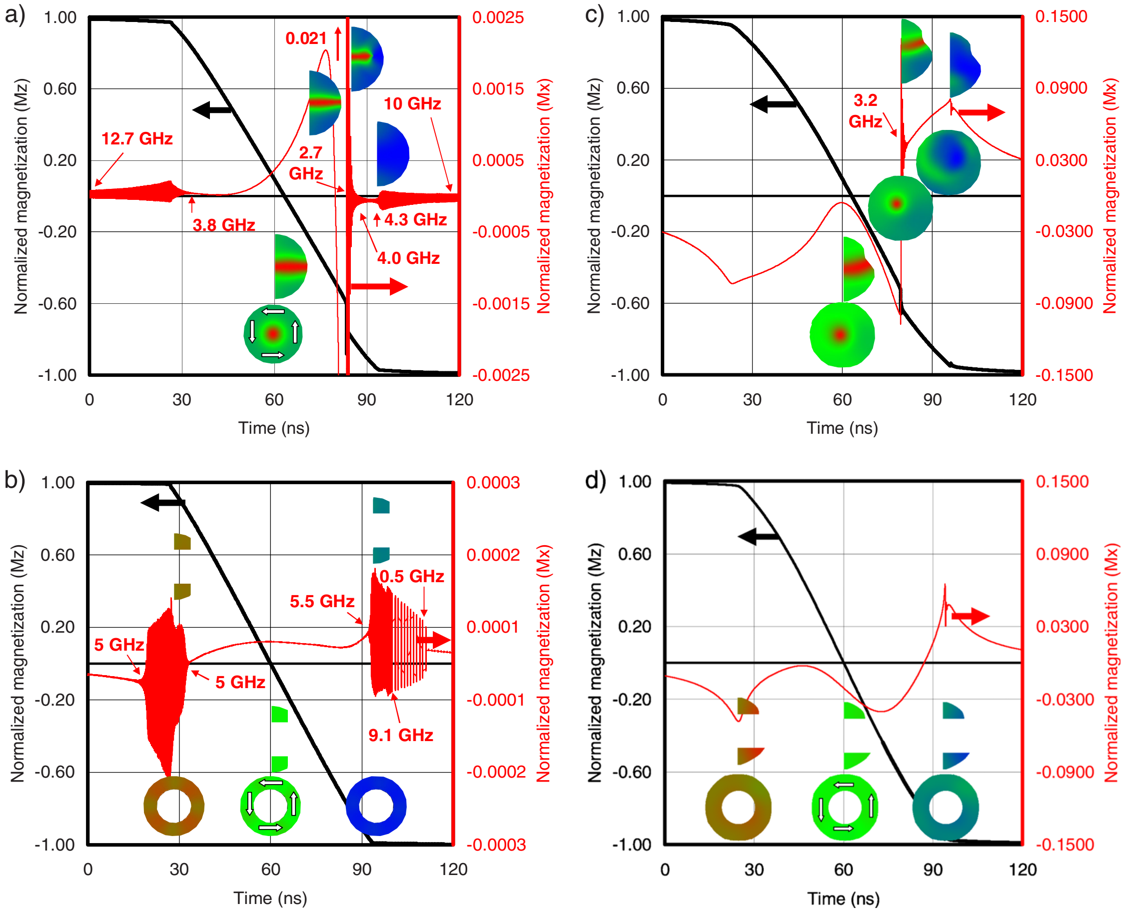

FIG. 2. (Color online) The time-evolution of the M_z (left ordinate) and M_x (right ordinate) magnetization components for the magnetic field applied along the z-axis direction, for the following cases: regular solid half-ball (a), regular half-ball with a hole (b), disturbed solid half-ball (c), and disturbed half-ball with a hole (d). The values of characteristic frequencies are shown. The external field changes sign at 60 ns. Graphical insets show M_z distribution at transient moments and for $H_{ext}=0$. The meaning of colors is as follows: M_z parallel with z-axis (red), M_z antiparallel to z-axis (blue), M_z perpendicular to z-axis (green).

demagnetizing fields. The other physical parameters were as follows: exchange constant $A=1.05\times10^{-11}$ J/m, magnetic polarization at saturation $J_s=1$ T, and the Gilbert damping constant $\alpha=0.1$.[18] Simulations also provided information about time-evolution of demagnetizing and exchange energies of samples.

III. DISCUSSION OF RESULTS

The results were analyzed in the following way. If the field was applied along the z-axis, then the z-component and x-component of magnetization, as functions of time, were examined. In this case, the z-component (the field direction component) evolving from positive to negative saturation indicates the switching time—defined by the moment when the component definitely changes its algebraic sign—while the x-component of magnetization vector tests a sample's susceptibility to oscillatory behavior. Similarly, if the field was applied along the x-axis, then the x-component and the z-component of magnetization, as functions of time, provided the respective physical information.

The response of tested samples, depending on specific details of their shapes due to demagnetization fields and eventual existence of vortex states, however displays some repeatable effects. First, for the external field applied along the z-axis, each "jump" in the magnetization along the z-direction is accompanied by an oscillation in M_x. However, there is no oscillation visible in M_z. For the external field applied along the x-axis, in each sample a two-stage magnetization reversal with oscillations in both magnetization components can be observed. Second, oscillation frequencies of magnetization components perpendicular to the externally applied magnetic field direction follow the effective field intensity. Third, the observed GHz oscillations can be subdivided into two types as follows: those close to saturation, and those correlated with the switching moment (between saturations), when a magnetization component changes its sign from positive to negative values, sometimes revealing a rapid, transient character. Additionally, we should mention that oscillations can possess one or two dominating frequencies. Fourthly, intentional perturbations of the sample shape, influencing demagnetization fields, may strongly suppress magnetization oscillations for H_{ext} applied along the z-axis. Lastly, the holes seem to significantly influence the character (amplitude, duration and frequencies) of oscillations for the external field applied along the z-axis. Thus, the perturbation of a shape can change oscillations resulting from demagnetizing fields, similarly to holes excluding vortex oscillations.

All the above observations—for the descending magnetic field intensity—can be seen in Figs. 2(a)–2(d), for the external field applied along the z-axis, and in Figs. 3(a)–3(d),

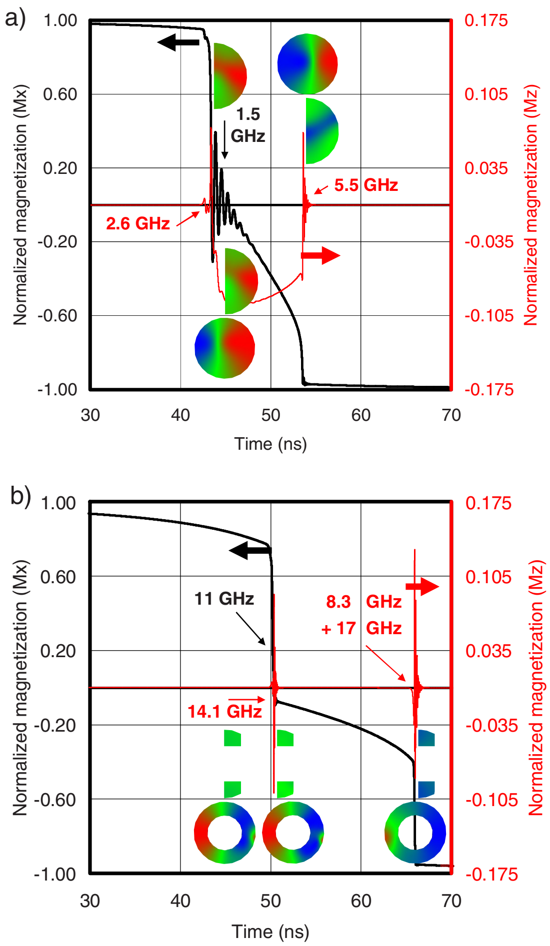

FIG. 3. (Color online) The time-evolution of the M_x (left ordinate) and M_z (right ordinate) magnetization component for the magnetic field applied along the x-axis direction, for the following cases: regular solid half-ball (a), regular half-ball with a hole (b), disturbed solid half-ball (c), and disturbed half-ball with a hole (d). The values of characteristic frequencies are shown. The external field changes sign at 45 ns. Graphical insets show M_x distribution at transient moments and for $H_{\mathrm{ext}}=0$. The meaning of colors is as follows: M_x parallel with x-axis (red), M_x antiparallel to x-axis (blue), and M_x perpendicular to x-axis (green).

for the field applied along the x-axis, respectively. In the figures, characteristic frequency values were marked in regions of their occurrence.

Treating oscillations as an unwanted effect, we can conclude that the optimum performance for switching applications represents the (d) case from Fig. 1. It results from the fact that in this ferromagnetic object the advantages resultant from exclusion of vortex cores and perturbation of demagnetizing fields are combined. From Figs. 2 and 3, we can also read out characteristic times of reversal.

To complete the above analysis, it is worth mentioning transient and rapid changes in magnetization, for example, that of M_x reaching an approximate value of 0.021 for $t=82$ ns, shown in Fig. 2(a). This situation is associated with maximized exchange energy of the system resulting from the existence of a vortex state. For $t>82$ ns, the vortex core began to vanish, while in the solid half-ball with distortion [Fig. 2(c)], the vortex core started moving along a direction favored by the uneven shape. This is why the effect was significantly reduced for the (b) and the (d) cases of the simulated objects with 50 nm holes where a flux-closed vortex appeared which is favorable for applications in magnetic storage devices. On the other hand, similar transient effects were observed for those simulations when the external field probed the x-direction, exhibiting the nucleation and propagation of domain walls, and spikes were observed for all four samples; (a) through (d). In these cases the transient effects were associated with maximized demagnetization energy which accumulated at the edges independently of the sample shapes.

In summary, micromagnetic simulations, not for the first time, have proven to be a very effective research tool. Results obtained for switching times and oscillatory behavior suggest that moderate nonperfectness of nanoelements can be seen as an advantage. All the above can give practical hints for designers of switching magnetoelectronic elements.

[1]S. D. Bader, Rev. Mod. Phys. **78**, 1 (2006).
[2]Y. Li, T. X. Wang, and Y. X. Li, Phys. Status Solidi B **247**, 1237 (2010).
[3]B. D. Terris and T. Thomson, J. Phys. D: Appl. Phys. **38**, R199 (2005).
[4]J. Akerman, Science **308**, 508 (2005).
[5]W. K. Hiebert, A. Stankiewicz, and M. R. Freeman, Phys. Rev. Lett. **79**, 1134 (1997).
[6]L. Thevenard, H. T. Zeng, D. Petit, and R. P. Cowburn, J. Magn. Magn. Mater. **322**, 2152 (2010).
[7]R. P. Cowburn, D. A. Allwood, G. Xiong, and M. D. Cooke, J. Appl. Phys. **91**, 6949 (2002).
[8]N. A. Usov, A. Zhukov, and J. Gonzalez, J. Magn. Magn. Mater. **316**, 255

(2007).
[9] L. Huang, M. A. Schofield, and Y. Zhu, Adv. Mater. **22**, 492 (2010).
[10] W. Zhang and S. Haas, Phys. Rev. B **81**, 064433 (2010).
[11] F. Q. Zhu, D. L. Fan, X. C. Zhu, J. G. Zhu, R. C. Cammarata, and C. L. Chien, Adv. Mater. **16**, 2155 (2004).
[12] R. P. Cowburn, D. K. Koltsov, A. O. Adeqeqe, M. E. Welland, and D. M. Tricker, Phys. Rev. Lett. **83**, 1042 (1999).
[13] K. He, D. J. Smith, and M. R. McCartney, J. Appl. Phys. **107**, 09D307 (2010).
[14] M. M. Soares, E. de Biasi, L. N. Coelho, M. C. dos Santos, F. S. de Menezes, M. Knobel, L. C. Sampaio, and F. Garcia, Phys. Rev. B **77**, 224405 (2008).
[15] E. Amaladass, B. Ludescher, G. Schütz, T. Tyliszczak, M.-S. Lee, and T. Eimüller, J. Appl. Phys. **107**, 053911 (2010).
[16] S. Tehrani, B. Engel, J. M. Slaughter, E. Chen, M. DeHerrera, M. Durlam, P. Naji, R. Whig, J. Janesky, and J. Calder, IEEE Trans. Magn. **36**, 2752 (2000).
[17] W. Scholz, J. Fidler, T. Schrefl, D. Suess, R. Dittrich, H. Forster, and V. Tsiantos, Comput. Mater. Sci. **28**, 366 (2003).
[18] N. Smith, D. Markham, and J. LaTourette, J. Appl. Phys. **65**, 4362 (1989).