JOURNAL OF APPLIED PHYSICS 110, 073911 (2011)

Fourfold nanosystems for quaternary storage devices

T. Blachowicz[1,a)] and A. Ehrmann[2]
[1]Institute of Physics, Silesian University of Technology, 44-100 Gliwice, Poland
[2]Faculty of Textile and Clothing Technology, Niederrhein University of Applied Sciences, 41065 Mönchengladbach, Germany

(Received 6 June 2011; accepted 22 August 2011; published online 12 October 2011)

In nano-magnetic coupled systems of wires, pronounced magnetization steps in the hysteresis loops have been found by micromagnetic simulations. The steps can be attributed to stable intermediate states, similar to flux-closed vortex states in ferromagnetic nano-rings. Due to the fourfold anisotropy of the system of four crossed nanowires, these states can be distinguished even by measuring the magnetization of the whole system, giving rise to four separated states without application of external magnetic field. Opposite to actual trials with nano-rings or layered structures, no additional method of symmetry breaking is necessary. Such an easily created system can be utilized, e.g., in quaternary (four states, i.e., two bits per magnetic nano-object) magnetic storage applications. © 2011 American Institute of Physics. [doi:10.1063/1.3646490]

I. INTRODUCTION

Ferromagnetic nanowires as part of patterned structures play a role of the next candidate, after thin-layered structures, for denser data storage devices.[1] High areal densities, exceeding conventional solution limits, can be obtained by the use of nanoporous template technology.[2,3] A single bit in such structures can be represented by a specific domain states of a single ferromagnetic object (particle).[4] Magnetic states in nano-scale ferromagnetic systems are investigated for use in magnetorestrictive random access memory (MRAM) devices, magnetic logical circuits, or magnetic quantum cellular automata, etc.[5–9] Especially, nano-patterned rings are of special interest due to minimization of stray fields and occurrence of flux closed vortex states.[10–14] With these solutions, different magnetic states can be represented, for example, by the chiralities (left or right) of the vortices enabling storage of digital (zero/one) information.

However, magnetic particles with more than two different magnetic states are even more challenging for information storage devices, to enhance significantly the possible data density per unit area. A quaternary storage medium, e.g., with four distinguishable states (zero/one/two/three) would double the amount of storable information by regarding these four states as two binary bits, even without the necessity to change the usual digital logics. Several recent publications have reported on magnetic systems with three, four or even eight magnetization states in a variety of nanostructures.[13,15–18] However, distinguishing between these different states is normally not so easy, since the magnetization cannot be measured for the complete structure but has to be detected at several distinct spatial positions, what strongly enhances the experimental demands. One possibility to overcome this problem is breaking the symmetry of, e.g., a system of coupled rings, by coating some parts of them.[9] This, however, complicates technology and finally increases production costs.

Efforts to invent patterned nano-objects by implementing appropriate technology without the necessity of using additional steps, like coatings mentioned above, which result in more than two stable, easily detectable magnetic states, are of great interest for magnetic storage devices and related applications.

II. MODELING

To address the mentioned postulates, we propose in the present report a system of four iron (Fe) wires with diameter 10 nm and length 70 nm in a square configuration, the wires immersing near the ends (see inset in Fig. 1). Lateral dimensions between 50 and 300 nm are typical in recent theoretical investigations of magnetic nano-particles.[14,16,18–23] Additionally, the system has been scaled down to smaller dimensions which are comparable to actual grain or dot sizes. Although today's hard disks are based on perpendicular recording, the system described here is ordered in-plane, as usual for nano-patterned rings,[10–14] etc., to support comparison between both kinds of magnetic nano-structures. The system, creating an elementary magnetic particle, possesses two spatial features: wires with a given length-to-diameter aspect ratio, and four local crossing regions. These features are responsible for subsequent demagnetizing fields driving the particle.

For the first tests of this system, a single magnetic particle has been simulated to verify the existence of four stable magnetic states in principle, as often practiced in actual publications about magnetic nanosystems.[13,14,16,17,19,20] In a second step, further simulations will examine the influence of magnetic stray fields of neighboring particles, depending on distance and respective orientation, to optimize the system for application in magnetic storage media.

The system is modeled using the finite element method and the Landau-Lifshitz-Gilbert (LLG) equation of motion. In a former simulation,[24] this structure has been found to be promising for new types of anisotropy symmetries, arranged

a)Author to whom correspondence should be addressed. Electronic mail: tomasz.blachowicz@polsl.pl.

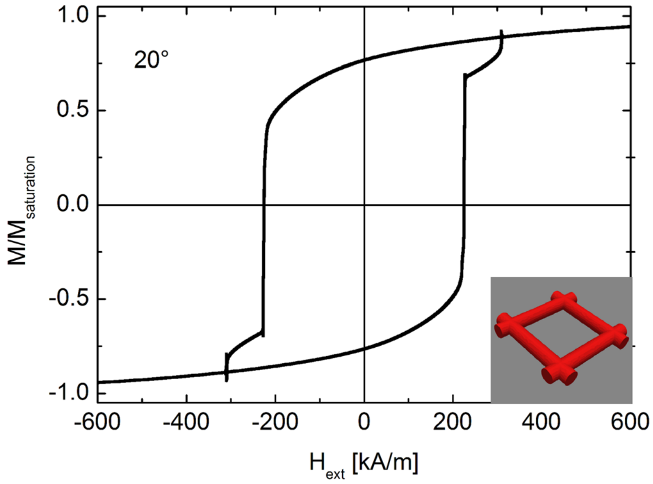

FIG. 1. (Color online) Hysteresis loop, simulated for the nano-wire system shown in the inset, for an angle of 20° between one pair of wires and the direction of the externally applied magnetic field.

for different spatial orientations of wires, giving also a hint for possible quaternary magnetic storage devices. The simulation has been performed with the "parallel finite element micromagnetics package (MAGPAR)".[25] This program allows precise exploration of the influence of the fiber shapes on the magnetization reversal mechanisms.[26] Finite tetrahedral elements of dimensions no larger than 3 nm were used for meshing, which is smaller than the Fe exchange length that can exceed 20 nm.[27] The other physical parameters were chosen as follows: exchange constant $A = 2\cdot10^{-11}$ J/m, magnetic polarization at saturation $J_s = 2.1$ T, and the Gilbert damping constant $\alpha = 0.1$.[28]

In the simulations, the external magnetic field was applied in the sample plane, for different sample orientations starting from that parallel to the *x*-axis (0°) which is parallel to one pair of wires. The field vector was always kept at the 0° position. In order to test magnetization performance of that system, simulations begun from a random magnetization state (i.e., external field $H_{ext} = 0$), while the field was changed at a constant speed of 10 kA/(m·ns) up to 800 kA/m to saturate the sample. Next, for simulation of the hysteresis loop, the field was swept at the same speed from positive saturation to − 800 kA/m in order to obtain negative saturation and afterwards back to positive saturation again. The field sweeping speed is comparable to typical values used in MRAM applications.[29]

III. RESULTS AND DISCUSSION

Figure 1 shows a typical hysteresis loop, obtained for the sample oriented at an angle of 20°. It is clearly seen, that both sides of the loop exhibit steps, implying a two-step magnetization reversal process as it is known from other magnetic objects, like e.g., nano-rings,[9,13] but also from some exchange-biased systems.[30]

To test if these steps are correlated with *stable* intermediate states, which could be used in magnetic storage media, the next simulations were arranged using the following sequence of the externally applied magnetic field: Starting from positive saturation, the external field was swept to the region of the first intermediate step, afterwards was swept back to zero field, next, the first half of the hysteresis loop was finished by completing the sweep to negative saturation. Afterwards, the second half of the loop has been simulated in the same way, via the second intermediate step region and zero-valued field, with reversed sign of the external field. The whole procedure is depicted in Fig. 2(a). The resulting curves are shown in Fig. 2(b)–(f), for various sample orientations. While the intermediate step is relatively flat and broad

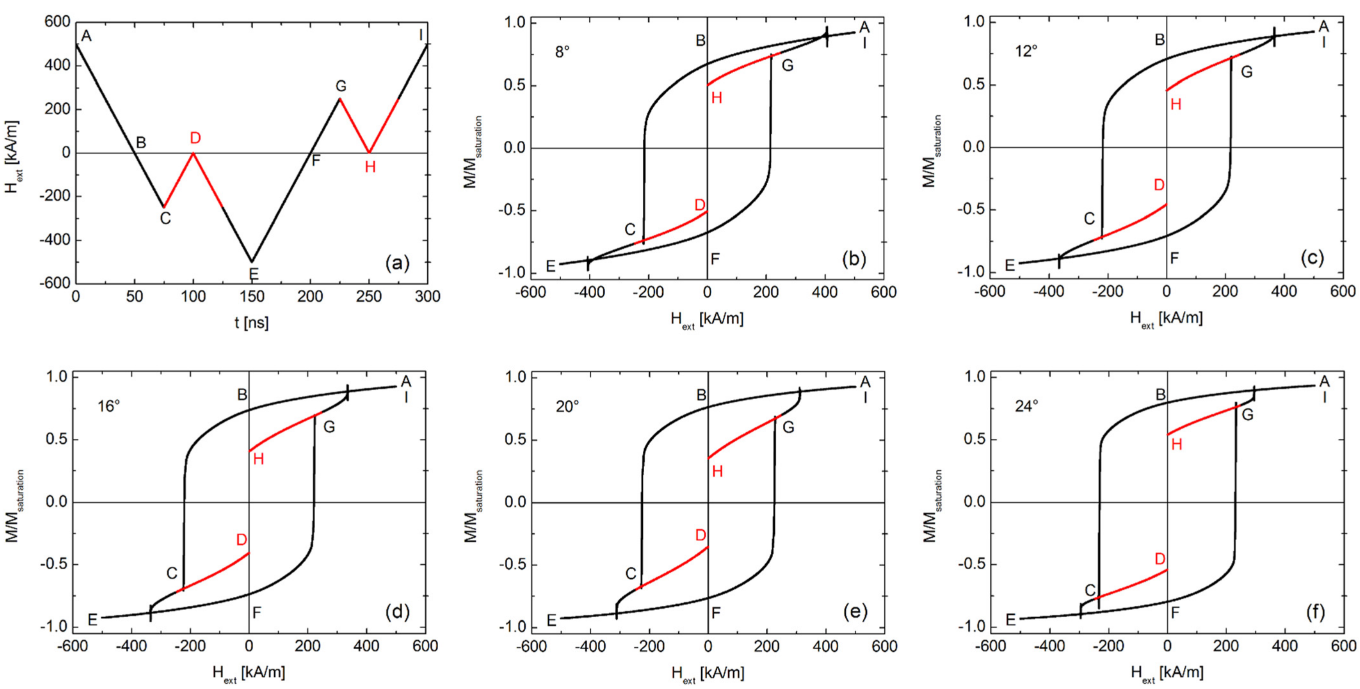

FIG. 2. (a) (Color online) Field sweeping scheme for the hysteresis loops shown in panels (b)–(f) for different sample angular orientations: (b) 8°, (c) 12°, (d) 16°, (e) 20°, and (f) 24°.

for smaller angles, it becomes higher and narrower for larger angles. The ideally tailored angle is equal to about 20°, in a sense that the four magnetic states are optimally separated for zero-valued external field. Obviously, for this angular orientation all four states could be detected unambiguously by sensing the net magnetizations. This advantage of the proposed solution stays in opposition to vortex states in symmetric nano-rings — measuring on one or more exact spatial positions within the rings is not necessary here.[9]

To compare the nano-wire system with the other systems with the step-like behavior in the hysteresis loop, i.e., nano-rings and exchange-biased bilayers like Fe/MnF_2,[30] snapshots of the spatial distribution of the magnetization in the system are depicted in Fig. 3 for prominent positions [see Fig. 2(a) for definition of the steps A-I].

Starting at positive saturation (A) with a magnetic state similar to the onion state, the "step" position C shows a partial magnetization reversal, starting from the crossing points of the wires, which introduces domain walls. In the intermediate stable state (D), the magnetization of the wires which are oriented 16° to the external field is already reversed, while magnetization reversal occurs only after the step region for the other two wires. Opposite to nano-rings, no vortex-state can be found here. Instead, the system behaves similarly to the exchange-biased system Fe/MnF_2 with twinned antiferromagnet,[30] in which the magnetization shows coherent magnetization rotation to a stable intermediate state oriented at about 90° to the saturation magnetization orientations. The negative saturation (E) shows an onion-like state again. In states (F) to (I), the magnetization reverses from negative to positive saturation via the additional zero-field state in the same way as described above.

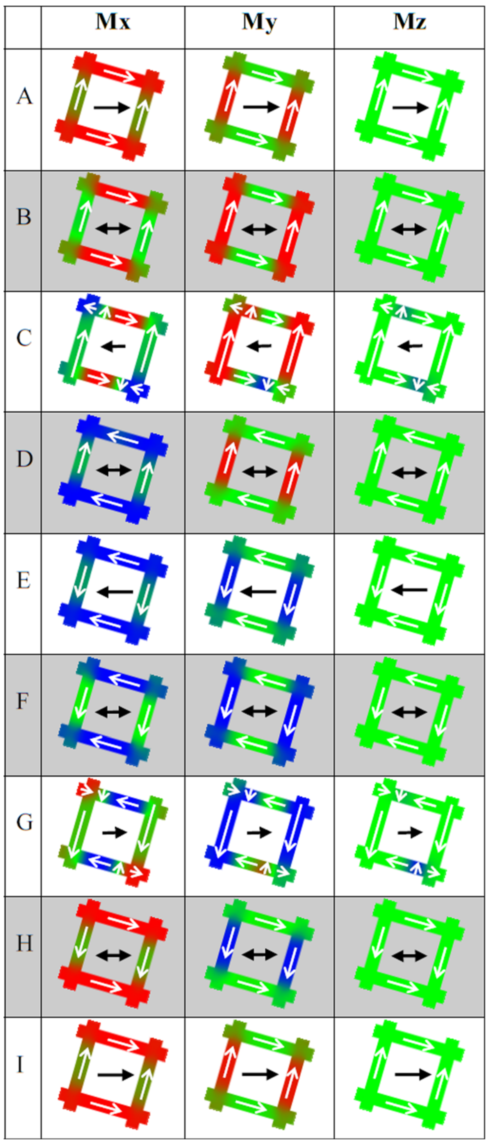

FIG. 3. (Color online) Magnetization reversal mechanism in nano-wire system for prominent positions along the hysteresis curve with additional zero-valued field sweeps, as depicted in Fig. 2(a). States with zero external field have a light-gray background. The sample is tilted at an angle of 16° in respect to direction of externally applied magnetic field. Arrows inside squares inform about actual external field sequence.

To understand scaling effects in the system under investigation, simulations have also been performed with systems of smaller dimensions. These sizes are closer to typical actual grain sizes of about 10 nm or to dot sizes of about 20 nm which are necessary to reach areal densities of 1 Tbit/inch^2 if conventional binary storage is used.[18]

Figure 4 shows four different combinations of wire lengths and diameters for a sample orientation of 20°, which was found to be ideal in the original system. For a wire length of 60 nm, the steps with the correlated stable intermediate states are still visible; however, the steps are narrower and less broad. For a wire length of 35 nm (half the original length), the whole systems reverses magnetization as one single domain; the hysteresis loop is much narrower. Decreasing also the wire diameter leads to a less uniform magnetization reversal with a broader hysteresis again; however, the step is no longer visible.

As this short outlook has shown, downscaling the system leads to qualitatively different magnetization reversal mechanisms, which may necessitate changing the material (e.g., to get a smaller exchange length, etc.) in order to gain systems with four stable magnetic states at remanence again.

IV. CONCLUSIONS

In conclusion, investigations of a fourfold nano-wire system have proven the possibility to create a patterned magnetic system with four unambiguously distinguishable states in vanishing external field, which can thus be utilized for quaternary storage devices (four states/two bits per particle). Opposite to nano-rings, no vortices are used during magnetic-based data processing; instead, the intermediate states show global net magnetizations. Further micromagnetic simulations will show whether even more than four stable states can be achieved by respectively constructed patterned nano-wire systems, and which influences can be expected due to stray fields from neighboring particles.

Downscaling the system for utilization in magnetic storage applications leads to qualitative changes in the magnetization reversal, which have to be taken into account by changing the material or adjusting the design. However, the possibility of creating a nano-system with four stable states at remanence has principally been proven by the system presented in this article.

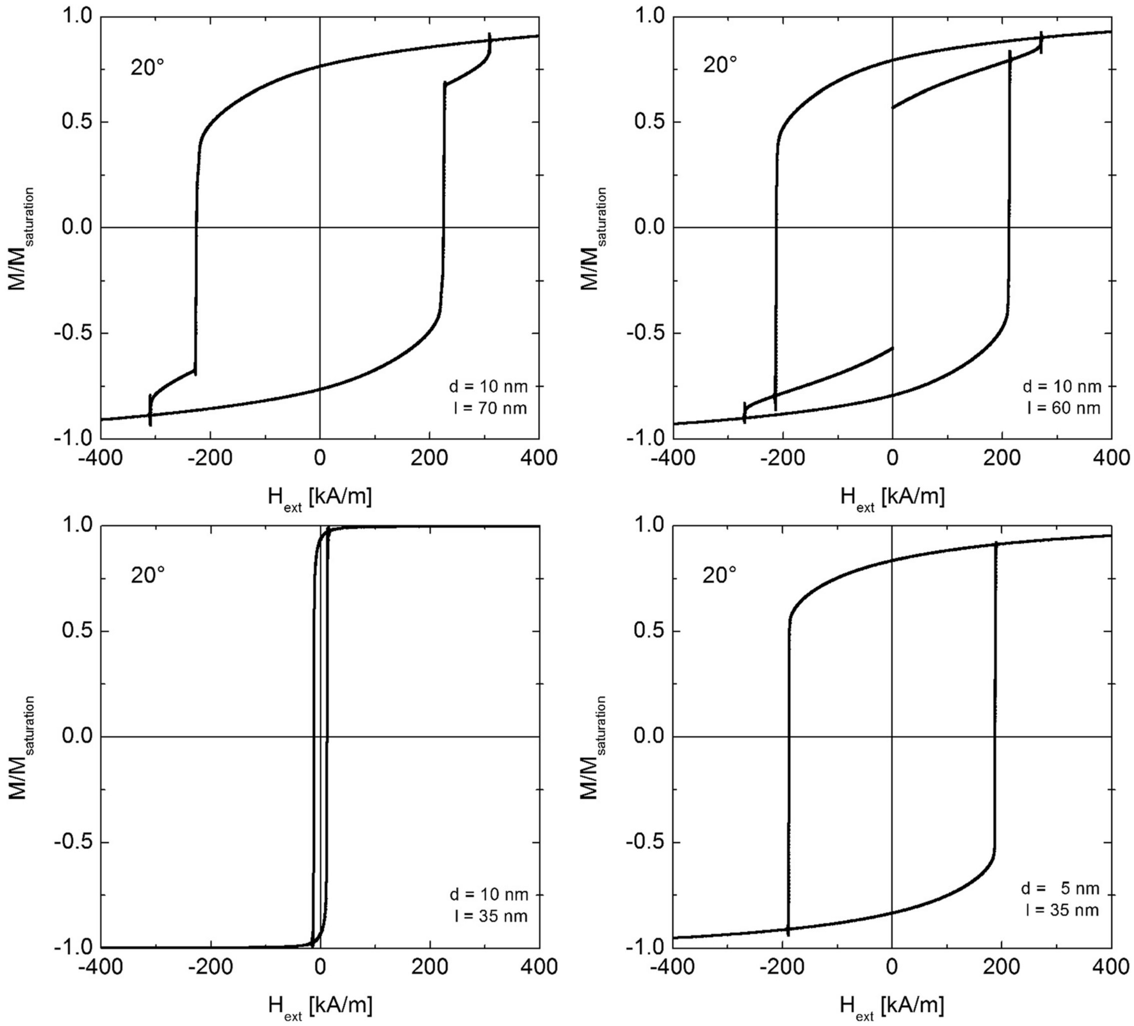

FIG. 4. Simulations of the system shown in Fig. 1 (inset) with different dimensions.

ACKNOWLEDGMENTS

The authors acknowledge project funding by Niederrhein University of Applied Sciences.

[1]G. Kartopu, O. Yalçın, K. L. Choy, R. Topkaya, S. Kazan, and B. Aktaş, J. Appl. Phys. **109**, 033909 (2011).
[2]K. Nielsch, R. B. Wehrspohn, J. Barthel, J. Kirschner, and U. Gösele, Appl. Phys. Lett. **79**, 1360 (2001).
[3]A. Fert and L. Piraux, J. Magn. Magn. Mater. **200**, 338 (1999).
[4]L. Vila, M. Darques, A. Encinas, U. Ebels, J. M. George, G. Faini, A. Thiaville, and L. Piraux, Phys. Rev. B **79**, 172410 (2009).
[5]R. P. Cowburn and M. E. Welland, Science **287**, 1466 (2000).
[6]B. D. Terris and T. Thomson, J. Phys. D: Appl. Phys. **38**, R199 (2005).
[7]J. Akerman, Science **308**, 508 (2005).
[8]S. D. Bader, Rev. Mod. Phys. **78**, 1 (2006).
[9]S. R. Bowden and U. J. Gibson, IEEE Trans. Magn. **45**, 5326 (2009).
[10]R. P. Cowburn, D. K. Koltsov, A. O. Adeqeqe, M. E. Welland, and D. M. Tricker, Phys. Rev. Lett. **83**, 1042 (1999).
[11]J. G. Zhu, Y. F. Zheng, and G. A. Prinz, J. Appl. Phys. **87**, 6668 (2000).
[12]F. Q. Zhu, D. L. Fan, X. C. Zhu, J. G. Zhu, R. C. Cammarata, and C. L. Chien, Adv. Mater. **16**, 2155 (2004).
[13]W. Zhang and S. Haas, Phys. Rev. B **81**, 064433 (2010).
[14]K. He, D. J. Smith, and M. R. McCartney, J. Appl. Phys. **107**, 09D307 (2010).
[15]R.-H. Wang, J.-S. Jiang, M. Hu, Mater. Res. Bull. **44**, 1468 (2009).
[16]L. Thevenard, H. T. Zeng, D. Petit, R. P. Cowburn, J. Magn. Magn. Mater. **322**, 2152 (2010).
[17]L. Huang, M. A. Schofield, and Y. Zhu, Adv. Mater. **22**, 492 (2010).
[18]J. Moritz, G. Vinai, S. Auffret, and B. Dieny, J. Appl. Phys. **109**, 083902 (2011).
[19]A. L. Dantas, G. O. G. Rebouças, and A. S. Carriço, IEEE Trans. Magn. **46**, 2311 (2010).
[20]Y. Li, T. X. Wang, and Y. X. Li, Phys. Status Solidi B **247**, 1237 (2010).
[21]B. Zhang, W. Wang, C. Mu, Q. Liu, J. Wang, J. Magn. Magn. Mater. **322**, 2480 (2010).
[22]J. Mejía-López, D. Altbir, P. Landeros, J. Escrig, A. H. Romero, Igor V. Roshchin, C.-P. Li, M. R. Fitzsimmons, X. Batlle, and I. K. Schuller, Phys. Rev. B **81**, 184417 (2010).
[23]I. Tudosa, J. A. Katine, S. Mangin, and E. E. Fullerton, Appl. Phys. Lett. **96**, 212504 (2010).
[24]T. Blachowicz and A. Ehrmann, "Micromagnetic simulations of anisotropies in coupled and uncoupled ferromagnetic nanowires," Phys. Status Solidi. (submitted).
[25]W. Scholz, J. Fidler, T. Schrefl, D. Suess, R. Dittrich, H. Forster, V. Tsiantos, Comput. Mater. Sci. **28**, 366 (2003).
[26]A. Tillmanns, M. O. Weber, T. Blachowicz, L. Pawela, T. Kammermeier, Proceedings of ECCM 2010, Paris, France, May 16–21, 2010.
[27]R. W. Gao, W. C. Feng, H. Q. Liu, B. Wang, W. Chen, G. B. Han, P. Zhang, H. Li, W. Li, Y. Q. Guo, W. Pan, X. M. Li, M. G. Zhu, and X. Li, J. Appl. Phys. **94**, 664 (2003).
[28]E. F. Kneller and R. Hawig, IEEE Trans. Magn. **27**, 3588 (1991).
[29]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).
[30]A. Tillmanns, S. Oertker, B. Beschoten, G. Güntherodt, C. Leighton, I. K. Schuller, J. Nogués, Appl. Phys. Lett. **89**, 202512 (2006).