Research Article

Micromagnetic Simulations of Anisotropies in Coupled and Uncoupled Ferromagnetic Nanowire Systems

T. Blachowicz[1] and A. Ehrmann[2]

[1] *Institute of Physics, Center for Science and Education, Silesian University of Technology, Krzywoustego 2, 44100 Gliwice, Poland*
[2] *Faculty of Textile and Clothing Technology, Niederrhein University of Applied Sciences, 41065 Mönchengladbach, Germany*

Correspondence should be addressed to T. Blachowicz; tomasz.blachowicz@polsl.pl

The influence of a variation of spatial relative orientations onto the coupling dynamics and subsequent magnetic anisotropies was modeled in ferromagnetic nanowires. The wires were analyzed in the most elementary configurations, thus, arranged in pairs perpendicular to each other, leading to one-dimensional (linear) and zero-dimensional (point-like) coupling. Different distances within each elementary pair of wires and between the pairs give rise to varying interactions between parallel and perpendicular wires, respectively. Simulated coercivities show an exchange of easy and hard axes for systems with different couplings. Additionally, two of the systems exhibit a unique switching behavior which can be utilized for developing new functionalities.

1. Introduction

Innovative magnetic storage and sensing devices, magnetic logical circuits (MLC), magnetic quantum cellular automata (MQCA), and other novel magnetic systems are based on nanoscale ferromagnetic structures [1–7]. Magnetic states of reduced dimensionality appearing in patterned nanostructures enable achievement of much higher areal densities than in conventional media for data-storage applications [8]. Additionally, like in MLCs, they allow for pure magnetic signal processing without the use of an electron current flow and subsequently lowered energy consumption.

For patterned magnetic structures [9–13], it is important to enable a reliable coupling between neighboring magnetic units ordered in a set for consecutive dynamic operations. For coupled nanorings, for example, the overlap of neighboring rings has shown a strong influence on the signal transport properties in logical NOT gates, and so forth. [6], while in some systems a nonnegligible probability of unintentional signal inversions due to random effects was observed [14, 15]. Thus, the examination of cooperative processes in magnetic highly-ordered arrays of nanowires is of utmost importance for understanding steady-states and, even more important, for understanding basic functionalities and requirements

to realize magnetization dynamics in nanochains and nanowires.

Recent progresses in technology and measurement techniques of ferromagnetic nanowires give opportunities to analyze novel effects and applications [16–19]. While the behavior of single ferromagnetic wires is well understood, simply governed by the shape anisotropy, the interplay between spatially ordered nanowires of different orientations and coupling requires elementary studies [20, 21]. Since most commercial magnetic solutions nowadays are based on thin-layers technology, where the coupling between different materials can tailor these devices' functionalities via surface or bulk interactions (2D or 3D; surface or bulk), we analyze an approach which uses coupling between parallel wires (1D coupling) and/or perpendicularly oriented ones (0D coupling). The results of magnetization dynamics point out new functionalities of these novel wire sets. In this way, the results presented here broaden the knowledge about shape, size, and composition analysis of nanowire magnetism [22, 23].

2. Materials and Methods

Systems of four iron (Fe) wires with diameter 10 nm and length 70 nm, ordered in four different configurations
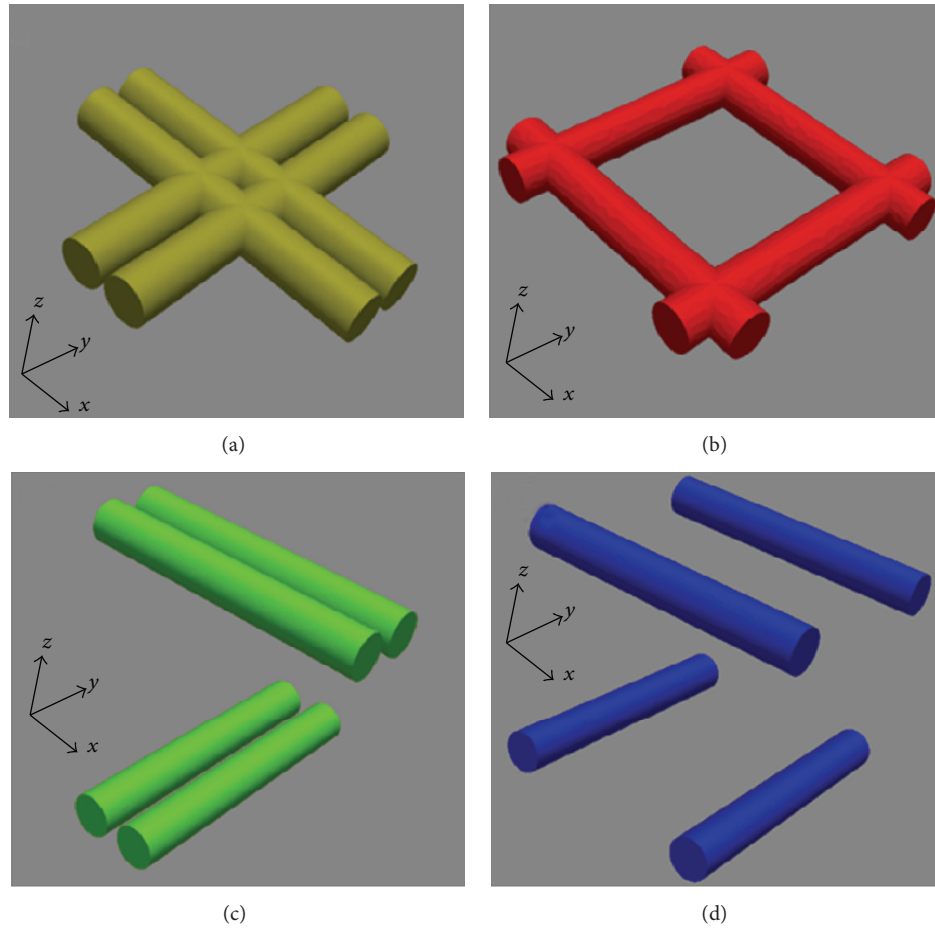
Figure 1: Magnetic systems composed of four nanowires, arranged in perpendicular pairs, with a different coupling within one pair/between the pairs: maximum coupling between the pairs and (a) coupling/(b) no coupling within each pair; no coupling between the pairs and (c) coupling/(d) no coupling within each pair.

(Figure 1), have been modeled using the finite element method. This order of magnitude is comparable with recent experimental results of patterns produced by interference lithography [24, 25]. The orientations of the wires in one plane or in two planes above each other have been chosen since such systems can be produced by photo-lithography, either in one step or in form of three layers with nonmagnetic materials between the magnetic wires. Additionally, the nontouching wires can serve as model systems for magnetic nanowires which are laid down on each other, either touching each other or with a certain distance due to a nonmagnetic cover over the magnetic core.

The "Parallel Finite Element Micromagnetics Package (MAGPAR)" [26] has been used for simulation, working with the Landau-Lifshitz-Gilbert (LLG) equation of motion $\partial \vec{M}/\partial t = -(\gamma/(1+\alpha^2))\vec{M} \times \vec{H}_{\text{eff}} - (\gamma\alpha/(1+\alpha^2)M_s)\vec{M} \times (\vec{M} \times \vec{H}_{\text{eff}})$ with the magnetization $\vec{M}$, the saturation magnetization M_s, the effective field $\vec{H}_{\text{eff}}$, the gyromagnetic ratio γ, and a dimensionless damping constant α.

For meshing, finite tetrahedral elements of dimensions of maximal 3 nm were used. This value is significantly smaller than the Fe exchange length which exceeds 20 nm [27]. The

other physical parameters were exchange constant $A = 2 \cdot 10^{-11}$ J/m, magnetic polarization at saturation $J_s = 2.1$ T, and the Gilbert damping constant $\alpha = 0.01$ [28]. These values are typically used for iron samples.

For the simulations, four different systems with the following coupling possibilities were taken into account (Figure 1): exchange dominated coupling between directly crossed pairs of wires (a), direct coupling at wire ends with other coupling mechanisms (dipolar, exchange) omitted (b), exchange dominated coupling within each pair and no magnetic coupling between the pairs (c), and a case of four wires with all magnetic coupling contributions excluded, while the wires are placed at infinite distance to each other (d).

Simulations were carried out with the external magnetic field applied in the sample plane, for a sample orientation of $0°$ along the x-axis which is always parallel to one pair of wires. Beginning at a random magnetization state (i.e., external field $H_{\text{ext}} = 0$), the field was changed at a constant speed of 10 kA/(m·ns) up to 800 kA/m to saturate the sample. Afterwards, the field was swept at the same speed to −800 kA/m to obtain negative saturation, and afterwards
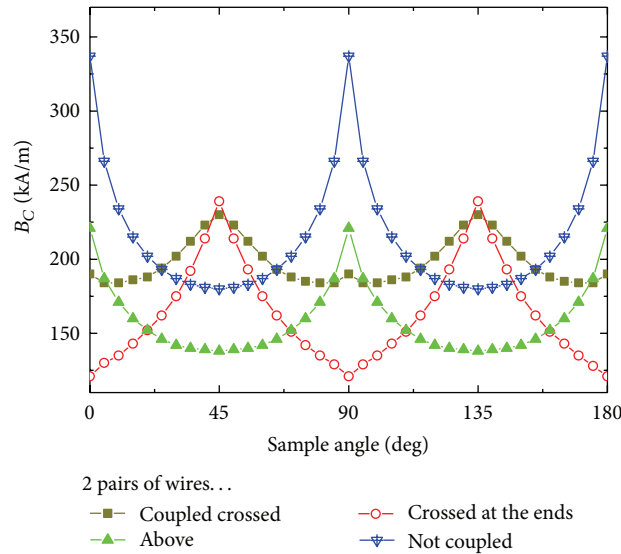
FIGURE 2: Simulated coercivities of the magnetic systems depicted in Figure 1.

3. Results and Discussion

The coercivities B_C of these four magnetic nanosystems have been derived from the simulated hysteresis loops. Figure 2 shows the calculated values of B_C for the angular region of $0° \cdots 180°$. As expected in systems with fourfold geometry, a fourfold anisotropy can be detected in all four situations. From former simulations [30] it is known that a "typical" fourfold anisotropy leads to sharp maxima of B_C along the easy axes and broad minima around the hard axes, as can be seen here for situations (c) and (d), that is, no coupling between the two pairs. However, both the other situations with coupling between the two pairs show deviations from this behavior. Assuming that the identification of easy axes by maxima in the coercivity is universal and can thus be used for all cases under examination, even an exchange of easy and hard axes of the systems, resulting from different couplings between the pairs of nanowires, can be recognized. Apparently this finding can be attributed to the direct ferromagnetic exchange coupling, which is dominant in cases (a) and (b), opposite to systems (c) and (d) where this coupling does not play a role.

For a deeper understanding of this finding, the simulated hysteresis loops are depicted in Figure 3 for orientations relative to the external magnetic field of $0°$ (i.e., parallel to one pair of wires), $20°$, and $45°$. In all four cases, the simulated loops show deviations from "typical" hysteresis curves. Mostly, the shapes can be regarded as composed of two hysteresis loops, one with typical attributes of an easy axis (i.e., broad loop with abrupt magnetization changes) and one with typical signs of a hard direction (i.e., narrow loop with broad transition regions from one saturated state to the other).

Apparently, easy and hard axes cannot easily be defined in the wire systems under examination. Case (d), where no coupling between the wires exists, corresponds to a pure superposition of the individual wires, while the coupled cases (a) and (b) show completely different hysteresis loops.

Comparing Figure 2 with absolute maxima in the coercivity around $0°$ for cases (c) and (d) and Figure 3 with abrupt magnetization changes at $0°$ for cases (a) and (c), it is obvious that the identification of an easy fourfold axis by a maximum in the coercivity is no longer valid in the systems under examination. Instead, the coercivities are related to the magnetization reversal processes which may differ in dependence of the coupling configuration and the angle.

A detailed study of magnetization reversal processes in fourfold nanowire systems similar to sample (b) of different dimensions has revealed the existence of six different reversal mechanisms, depending on wire length and diameter as well as on the orientation of the system to the external magnetic field (to be published). Additionally, for sample (b) even a step in the hysteresis loop can be found, which has been previously reported as a typical feature of some exchange bias systems [31, 32]. This finding supports the idea of exploring differently spaced magnetic nanowires to examine the influence of variable dipole coupling fields on the magnetic properties of such systems—not only to understand the mechanisms better but also to find systems with novel interesting and unexpected properties (e.g., [33]).

4. Conclusion

In conclusion, our micromagnetic simulations of systems consisting of two perpendicular pairs of parallel wires—as an alternative to exchange and/or dipolar coupled layered systems—have shown the strong dependence of the magnetic properties on the kind of coupling between them. Additionally, some systems exhibit unexpected features which are promising for the development of new functionalities.
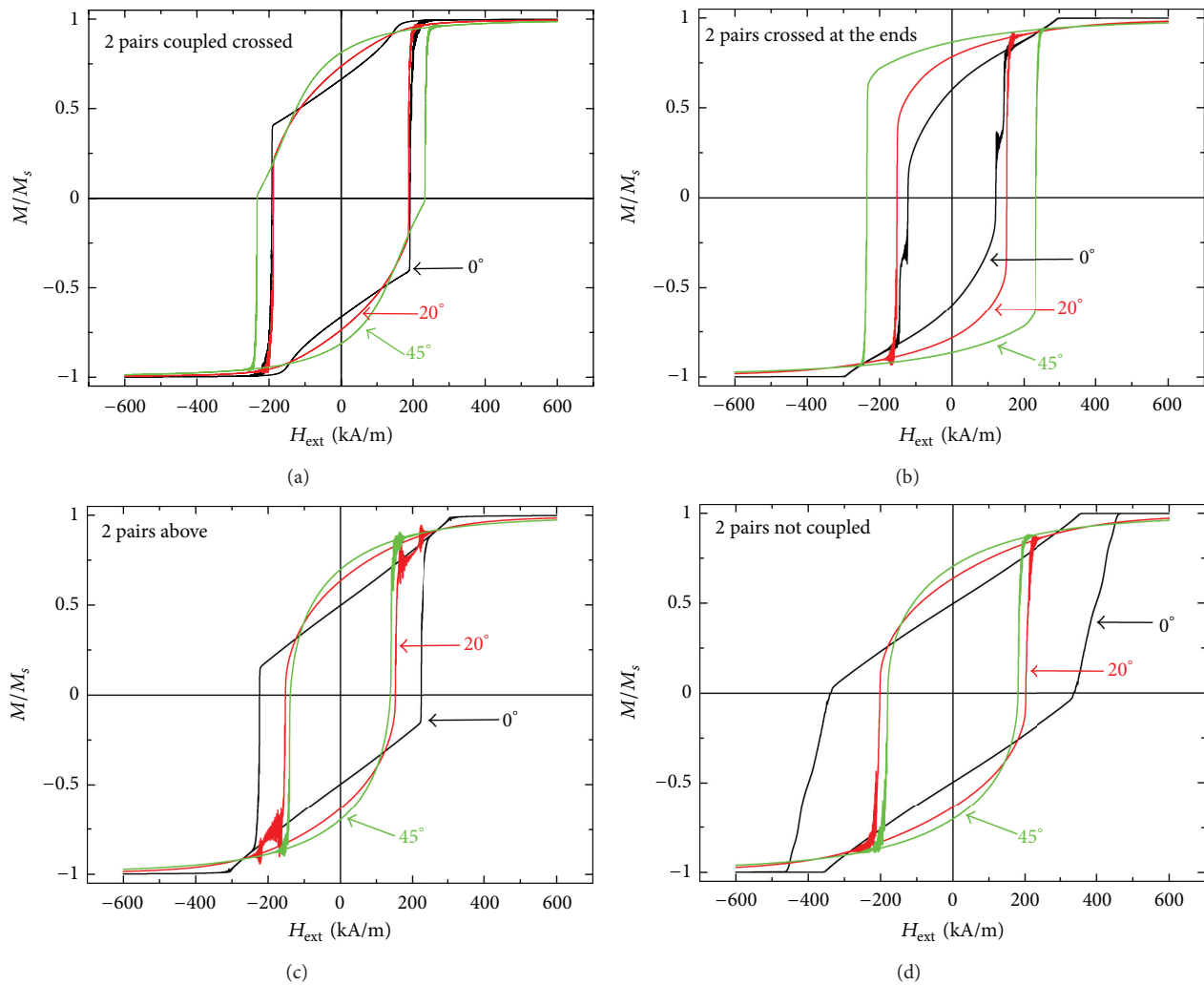
(a)

(b)

(c)

(d)

FIGURE 3: Simulated hysteresis curves for the samples depicted in **Figure 1**, exemplarily shown for orientations relative to the external magnetic field of 0° (i.e., parallel to one pair of wires), 20°, and 45°.
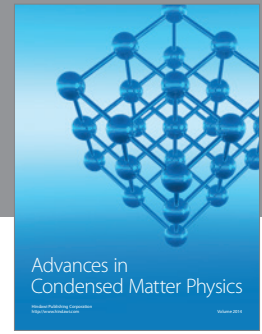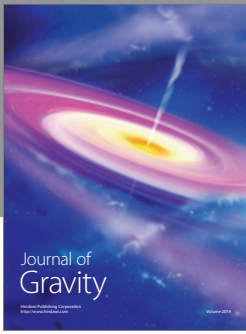
References

[1] B. D. Terris and T. Thomson, "Nanofabricated and self-assembled magnetic structures as data storage media," *Journal of Physics D*, vol. 38, article R199, 2005.

[2] J. Åkerman, "Toward a universal memory," *Science*, vol. 308, no. 5721, pp. 508–510, 2005.

[3] S. D. Bader, "*Colloquium*: opportunities in nanomagnetism," *Reviews of Modern Physics*, vol. 78, pp. 1–15, 2006.

[4] Y. Li, T. X. Wang, and Y. X. Li, "The influence of dipolar interaction on magnetic properties in nanomagnets with different shapes," *Physica Status Solidi B*, vol. 247, p. 1237, 2010.

[5] R. P. Cowburn and M. E. Welland, "Room temperature magnetic quantum cellular automata," *Science*, vol. 287, no. 5457, pp. 1466–1468, 2000.

[6] S. R. Bowden and U. J. Gibson, "Optical characterization of all-magnetic not gate operation in vortex rings," *IEEE Transactions on Magnetics*, vol. 45, no. 12, pp. 5326–5332, 2009.

[7] J. F. Pulecio and S. Bhanja, "Magnetic cellular automata coplanar cross wire systems," *Journal of Applied Physics*, vol. 107, no. 3, Article ID 034308, 2010.

[8] K. Nielsh, R. B. Wehrspohn, J. Barthel, J. Kirschner, and U. Gösele, "Hexagonally ordered 100 nm period nickel nanowire arrays," *Applied Physics Letters*, vol. 79, article 1360, 2001.

[9] Y. Henry, K. Ounadjela, L. Piraux, S. Dubois, J.-M. George, and J.-L. Duvail, "Magnetic anisotropy and domain patterns in electrodeposited cobalt nanowires," *European Physical Journal B*, vol. 20, no. 1, pp. 35–54, 2001.

[10] M. Vazquez, M. Hernandez-Velez, and K. Priota, "Arrays of Ni nanowires in alumina membranes: magnetic properties and spatial ordering," *European Physical Journal B*, vol. 40, pp. 489–497, 2004.

[11] E. L. Silva, W. C. Nunes, M. Knobel et al., "Transverse magnetic anisotropy of magnetoelastic origin induced in Co nanowires," *Physica B*, vol. 384, no. 1-2, pp. 22–24, 2006.

[12] L. Vila, M. Darques, A. Encinas et al., "Magnetic vortices in nanowires with transverse easy axis," *Physical Review B*, vol. 79, no. 17, Article ID 172410, 2009.

[13] G. Kartopu, O. Yaḻn, K.-L. Choy, R. Topkaya, S. Kazan, and B. Akta, "Size effects and origin of easy-axis in nickel nanowire arrays," *Journal of Applied Physics*, vol. 109, no. 3, Article ID 033909, 2011.

[14] U. Welp, V. K. Vlasko-Vlasov, G. W. Crabtree et al., "Magnetization reversal in arrays of individual and coupled co-rings," *Journal of Applied Physics*, vol. 93, no. 10, pp. 7056–7058, 2003.

[15] U. Welp, V. K. Vlasko-Vlasov, J. M. Hiller, N. J. Zaluzec, V. Metlushko, and B. Ilic, "Magnetization reversal in arrays of co rings," *Physical Review B*, vol. 68, no. 5, Article ID 054408, 2003.

[16] H. García-Miquel, S. M. Bhagat, S. E. Lofland, G. V. Kurlyandskaya, and A. V. Svalov, "Ferromagnetic resonance in FeCoNi electroplated wires," *Journal of Applied Physics*, vol. 94, no. 3, pp. 1868–1872, 2003.

[17] S. Katoa, H. Shinagawaa, H. Okadaa, G. Kidoa, and K. Mitsuhashi, "Application of ferromagnetic nano-wires in porous alumina arrays for magnetic force generator," *Science and Technology of Advanced Materials*, vol. 6, article 341, 2005.

[18] R. B. Morgunov, A. I. Dmitriev, Y. Tanimoto, J. S. Kulkarni, J. D. Holmes, and O. L. Kazakova, "Spin dynamics in oriented ferromagnetic nanowires $Ge_{0.99}Co_{0.01}$," *Physics of the Solid State*, vol. 50, no. 6, pp. 1103–1109, 2008.

[19] R. El Kammouni, G. Infante, and J. Torrejo, "Microwave behavior in CoFe-based single- and two-phase magnetic microwires," *Physica Status Solidi A*, vol. 208, pp. 520–525, 2011.

[20] R. Hertel, "Micromagnetic simulations of magnetostatically coupled Nickel nanowires," *Journal of Applied Physics*, vol. 90, no. 11, pp. 5752–5758, 2001.

[21] K. Pitzschel, J. Bachmann, S. Martens et al., "Magnetic reversal of cylindrical nickel nanowires with modulated diameters," *Journal of Applied Physics*, vol. 109, no. 3, Article ID 033907, 2011.

[22] E. P. Hernández, A. Azevedo, and S. M. Rezende, "Structure and magnetic properties of hexagonal arrays of ferromagnetic nanowires," *Journal of Applied Physics*, vol. 105, Article ID 07B525, 2009.

[23] M. Fonin, C. Hartung, and U. Rüdiger, "Formation of magnetic domains and domain walls in epitaxial Fe_3O_4(100) elements (invited)," *Journal of Applied Physics*, vol. 109, Article ID 07D315, 2011.

[24] H. H. Solak, C. David, J. Gobrecht et al., "Sub-50 nm period patterns with EUV interference lithography," *Microelectronic Engineering*, vol. 67-68, pp. 56–62, 2003.

[25] Y. Fukushima, Y. Yamaguchi, T. Iguchi et al., "Development of interference lithography for 22 nm node and below," *Microelectronic Engineering*, vol. 88, no. 8, pp. 1944–1947, 2011.

[26] W. Scholz, J. Fidler, T. Schrefl et al., "Scalable parallel micromagnetic solvers for magnetic nanostructures," *Computational Materials Science*, vol. 28, no. 2, pp. 366–383, 2003.

[27] R. W. Gao, W. C. Feng, H. Q. Liu et al., "Exchange-coupling interaction, effective anisotropy and coercivity in nanocomposite permanent materials," *Journal of Applied Physics*, vol. 94, no. 1, pp. 664–668, 2003.

[28] E. F. Kneller and R. Hawig, "The exchange-spring magnet: a new material principle for permanent magnets," *IEEE Transactions on Magnetics*, vol. 27, no. 4, pp. 3588–3600, 1991.

[29] S. Tehrani, B. Engel, J. M. Slaughter et al., "Recent developments in magnetic tunnel junction MRAM," *IEEE Transactions on Magnetics*, vol. 36, no. 5 I, pp. 2752–2757, 2000.

[30] A. Tillmanns, T. Błachowicz, M. Fraune, G. Güntherodt, and I. K. Schuller, "Anomalous magnetization reversal mechanism in unbiased Fe/FeF_2 investigated by means of the magneto-optic Kerr effect," *Journal of Magnetism and Magnetic Materials*, vol. 321, pp. 2932–2935, 2009.

[31] C. Leighton, M. R. Fitzsimmons, P. Yashar et al., "Two-stage magnetization reversal in exchange biased bilayers," *Physical Review Letters*, vol. 86, no. 19, pp. 4394–4397, 2001.

[32] A. Tillmanns, S. Oertker, B. Beschoten et al., "Magneto-optical study of magnetization reversal asymmetry in exchange bias," *Applied Physics Letters*, vol. 89, Article ID 202512, 2006.

[33] T. Blachowicz and A. Ehrmann, "Fourfold nanosystems for quaternary storage devices," *Journal of Applied Physics*, vol. 110, Article ID 073911, 2011.