Magnetization reversal modes in fourfold Co nano-wire systems

T Blachowicz\textsuperscript{1,3} and A Ehrmann\textsuperscript{2,3}
\textsuperscript{1} Institute of Physics – Center for Science and Education, Silesian University of Technology, 44-100 Gliwice, Poland
\textsuperscript{2} Faculty of Engineering Sciences and Mathematics, Bielefeld University of Applied Sciences, 33609 Bielefeld, Germany
\textsuperscript{3} VIARAM – Virtual Institute for Applied Research on Advanced Materials

E-mail: tomasz.blachowicz@polsl.pol

Abstract. Magnetic nano-wire systems are, as well as other patterned magnetic structures, of special interest for novel applications, such as magnetic storage media. In these systems, the coupling between neighbouring magnetic units is most important for the magnetization reversal process of the complete system, leading to a variety of magnetization reversal mechanisms. This article examines the influence of the magnetic material on hysteresis loop shape, coercive field, and magnetization reversal modes. While iron nano-wire systems exhibit flat or one-step hysteresis loops, systems consisting of cobalt nano-wires show hysteresis loops with several longitudinal steps and transverse peaks, correlated to a rich spectrum of magnetization reversal mechanisms. We show that changing the material parameters while the system geometry stays identical can lead to completely different hysteresis loops and reversal modes. Thus, especially for finding magnetic nano-systems which can be used as quaternary or even higher-order storage devices, it is rational to test several materials for the planned systems. Apparently, new materials may lead to novel and unexpected behaviour – and can thus result in novel functionalities.

1. Introduction

Magnetic nano-structures are possible candidates for research aiming at increasing the data density of magnetic storage devices. Especially magnetic particles exhibiting more than two magnetization states at vanishing external magnetic field are of great interest for this purpose. A quaternary storage medium, showing four distinguishable states (zero, one, two, three) at zero magnetic field, would allow for storing two binary bits, thus increasing the storage density by a factor of two without changing the storage position dimension.

This idea has stimulated research by several groups, leading to reports about magnetic systems with three, four, or even eight different magnetization states in diverse nano-structures\cite{1-5}. The detection of these states, however, is normally not easy, since magnetization has to be measured at different spatial positions to differentiate between similar states, a procedure which is not compatible with contemporary hard disk drive technology.

Thus, our previous work has concentrated on fourfold magnetic nano-wire systems produced from iron (Fe), showing four stable intermediate states at remanence which can easily be detected by an overall magnetization measurement, as it is used in hard disk write/read heads\cite{6-8}. However, Fe wire...
systems seem to be limited to the aforementioned four states in square nano-structures. In Fe particles of higher symmetry, such as six-fold wire systems, more intermediates states can be found; however, these states are not stable enough to be used as reliable storage possibilities [9]. Thus, other materials have been chosen to be tested. While permalloy (Py) or FeCu show smaller anisotropies and mostly flat hysteresis loops without any additional steps indicating possible stable intermediate states, simulations of cobalt (Co) nano-wire systems exhibit a rich spectrum of different magnetization reversal mechanisms, resulting in several steps in the hysteresis loops for some angular orientations. This article gives an overview of the different reversal mechanisms and hysteresis loop forms found in fourfold Co nano-wire systems.

2. Mathematical Model

To allow for modelling the round wire shapes in the best possible way, the micromagnetic simulation program Magpar is used [10]. Since it is based on the finite element method, Magpar approximates spherical systems better than programs using finite differences, such as OOMMF [11]. Magpar is based on dynamically integrating the Landau-Lifshitz-Gilbert equation of motion. Finite elements are meshed as tetrahedral elements with dimensions of max. 3 nm; the element sizes were significantly decreased along the edges to include the influence of demagnetizing fields more exactly. The exchange constant was chosen as $A = 1.3 \times 10^{-11}$ J/m, the magnetic polarization at saturation $J = 1.76$ T, and the Gilbert damping constant $\alpha = 0.1$. Both values $A$ and $J$ are smaller than in Fe, but larger than in Py [12]. The simulation was carried out starting at zero external field, sweeping to +600 kA/m (with the external field in the sample plane), reverse the magnetic field to $-600$ kA/m and close the hysteresis loop by sweeping to +600 kA/m again. The field sweeping speed was 10 kA/(m ns), comparable to typical values in MRAM applications [13].

3. Results

The simulated coercive fields of a Co particle consisting of four wires with length 70 nm and diameter 10 nm are depicted in Fig. 1; the inset shows the meshed particle used for modelling. The angular orientation of 0° is defined by one of the wires being oriented parallel to the external magnetic field. For comparison, the angle-dependent coercive fields of the same particle modelled for Fe are added. While the coercivities of Co show values quantitatively similar (about 50 % higher) to those simulated for Fe, the angle-dependence has a different form, with broader maxima and sharper minima in the Co nano-particle.

![Figure 1](https://example.com/figure1.png)  
**Figure 1.** Coercive field and reversal fields simulated for a fourfold Co nano-structure (see inset). Coercivities of Fe are added for better comparability. From [14], modified.
Figure 2. Simulated hysteresis curves for the Co sample depicted in Fig. 1 (Inset), exemplarily shown for orientations relative to the external magnetic field of 0° (i.e. parallel to one pair of wires), 5°, 10°, and 20°. From [14], modified.

The most intriguing feature, however, are the additional reversal fields which can be attributed to steps in the respective hysteresis loops and are found in Fe only for small angular regions [6,8]. In the fourfold Co wire particle, however, there seem to be additional reversal fields for all angles – 3 relatively small fields around 0°, 90° etc., and 2 significantly larger reversal fields around 45°, 135° etc.

To examine these reversal fields further, Fig. 2 shows hysteresis loops taken at different angles between the wire system and the external magnetic field. For 0° sample orientation, starting at positive saturation, the magnetization reverses into a horseshoe state before the external magnetic field vanishes. This behaviour has not been recognized in fourfold Fe wire samples, but is well-known from magnetic nano-dots [15,16]. Magnetization reversal is continued via a vortex state and a second horseshoe state to negative saturation.

Rotating the sample to 5° changes this magnetization reversal mechanism. Here, magnetization reversal from positive to negative saturation occurs via 3 different onion states. Rotating the sample further to 15°, the second onion state vanishes.

For 20° and larger angles around 45°, saturation is not reached. However, since there are no energy barriers between positive saturation and the first onion state, this finding does not influence the magnetization reversal processes in the simulation.
Figure 3. Magnetization reversal of the Co wire system from positive to negative saturation for sample angles of 0° (top row), 5° (2nd row), 10° (3rd row), and 45° (bottom row). The colors depict a magnetization orientation in positive (red) or negative (blue) x-direction; the external field direction is marked in each row. From [14], modified.

Fig. 3 shows snapshots of the magnetization reversal process for four different angular orientations of the magnetic wire system. The different magnetization states are defined as follows: In saturation, the magnetization is aligned along the external magnetic field in all four wires. In a vortex state, magnetization orientation follows the wires steadily clockwise or counter-clockwise (e.g. 1st row, 3rd panel). In an onion state, magnetization “splits” into two different ways to be aligned from one position of the system to an opposite position (e.g. 2nd row, 2nd panel). A horseshoe state, finally, is defined by the magnetization following a horseshoe-like form, which means that magnetization is aligned parallel in one pair of wires and antiparallel in the other pair (e.g. 1st row, 2nd panel).

For 0° (upper row), positive saturation is followed by a first horseshoe state, a vortex state and the second horseshoe state, before negative saturation is reached (now shown here).

At a sample orientation of 5° (second row), three different onion states are visible after positive saturation, finally leading to negative saturation.

For a sample orientation of 10° (third row), the second onion state is no longer visible in the hysteresis loop; however, as the snapshots of magnetization reversal show, a new non-diagonal onion state
occurs. This new state is not correlated with additional steps in the hysteresis loops, which is typical for domain wall processes.

Finally, the last row shows magnetization reversal for 45° (identical to 20° and the angles between). It is clearly visible that saturation is not completely reached for the maximum external fields used in the simulation. The first onion state is transformed into an “extreme onion state” (2nd panel), as it is already known from fourfold Fe wire samples [8]. Magnetization reversal into the opposite onion state (4th panel) happens via an asymmetric domain wall state (3rd panel), before negative saturation is approached.

4. Conclusion
Concluding, we have shown that different materials used to model identical nano-structure geometries can lead to completely different hysteresis loops and reversal modes. Especially for finding magnetic nano-systems which can be used as higher-order storage devices to enhance data density limits, testing diverse materials by simulations is necessary, before the most promising systems can be realized using lithographically produced samples, to allow for experimental examination. As depicted for the example of Co, in comparison with recently tested Fe systems, new materials may lead to novel and unexpected behavior – and can thus result in new functionalities.

References
[1] Wang R-H, Jiang J-S, Hu M 2009 Mater. Res. Bull. 44 1468
[2] Huang L, Schofield M A and Zhu Y 2010 Adv. Mater. 22 492
[3] Thevenard L, Zeng H T, Petit D and Cowburn D 2010 J. Magn. Magn. Mater. 322 2152
[4] Zhang W and Haas S 2010 Phys. Rev. B 81 064433
[5] Moritz J, Vinai G, Auffret S and Dieny B 2011 J. Appl. Phys. 109 083902
[6] Blachowicz T, Ehrmann A 2011 J. Appl. Phys. 110 073911
[7] Blachowicz T, Ehrmann A, Steblinski P, Palka J 2013 J. Appl. Phys. 113 013901
[8] Blachowicz T and Ehrmann A 2013 Sci World J 2013 472597
[9] Blachowicz T, Ehrmann A 2013 J. Magn. Magn. Mat. 331 21-23
[10] Scholz W, Fidler J, Schrefl T, Suess D, Dittrich R, Forster H and Tsiantos V 2003 Comp. Mat. Sci. 28 366
[11] Donahue M J, Porter D G 1999 OOMMF User’s Guide, Version 1.0. Interagency Report NISTIR 6376, National Institute of Standards and Technology, Gaithersburg, MD
[12] Smith N, Markham D and la Tourette D 1989 J. Appl. Phys. 65 4362
[13] Tehrani S, Engel B, Slaughter J M, Chen E, DeHerrera M, Durlam M, Naji P, Whig R, Janesky J and Calder J. 2000 IEEE Trans. Magn. 36 2752
[14] Ehrmann A, Examination and simulation of new magnetic materials for the possible application in memory cells, Logos Verlag, Berlin / Germany 2014, ISBN 978-3-8325-3772-2
[15] He K, Smith D J and McCartney M R 2010 J. Appl. Phys. 107 09D307
[16] Blachowicz T, Ehrmann A 2015 Journal of Physics: Conference Series accepted