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Stability of magnetic nano-structures with respect to shape modifications

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Abstract. Magnetic nano-structures can be used for various applications. Examinations of nano-structured systems often aim at decreasing pattern sizes due to their possible utilization in data storage media, in order to enhance the possible information density in a given area. This scaling process, however, is limited by the resolution of the lithography process which is used to produce the nano-particles. Thus the influence of shape modifications on the magnetic properties is important to be examined, especially the correlation between small form changes and magnetization reversal processes or coercive fields. In a recent project, square nano-particles from permalloy were simulated using Magpar. Simulations were performed for the ideal geometric shape used in the lithography process, for the realistic shape of the produced nano-particles as obtained by SEM, and for intermediate steps between these extreme shapes. This study allows for estimation of the reliability of magnetic properties of nano-structures with respect to shape modifications in the lithography process.

1. Introduction

Magnetic nano-structures are currently being investigated intensively due to their possible utilization in magneto-electronic devices. In such nano-structured particles, the shape anisotropy often dominates over magneto-crystalline and magneto-elastic anisotropies. This allows for creating magnetic nano-particles with desired magnetic properties or even novel magnetic states.

Especially ring-shaped particles are often examined due to the strongly reduced stray fields, allowing for data storage applications [1,2]. In such ring-shaped nano-structures, so-called flux-closed vortex states occur in which the core regions of usual vortex states [3-5] are excluded.

Such open geometries may be formed as round or elliptical rings [6-8], square rings [9], triangles [10] etc. Among these, square rings have been shown to be of special importance since they can lead to stable intermediate states at remanence which turns them into useful candidates for quaternary memory cells, enabling storage of 2 bits per particle and thus doubling the usual amount of data per magnetic unit [11,12]. Former investigations have shown a severe dependence of the magnetic properties of such systems on the particle shapes [13,14].

This article thus depicts the dependence of a micromagnetic simulation on the shape of a square nano-ring. It focusses on comparing simulations for the ideal shape – as used for the lithographic process – and for the real particle's shape as well as shapes between these extrema.

2. Methods

The micromagnetic simulation program Magpar is used to model the round edges in the best possible way [15]. Being based on the finite element method, Magpar approximates spherical systems better than programs using finite differences, such as OOMMF [16].

In Magpar, simulations are performed by dynamically integrating the Landau-Lifshitz-Gilbert equation. Finite tetrahedral elements with dimensions of maximum 3 nm were modelled; demagnetizing fields were taken into account exactly by reducing the element sizes along the edges. For the simulation of the permalloy (Py) particles, the exchange constant was chosen as $A = 1.3 \cdot 10^{-11}$ J/m, the magnetic polarization at saturation $J = 1$ T, and the Gilbert damping constant $\alpha = 0.01$.

The simulation was carried out starting at zero external field, sweeping to + 200 kA/m (with the external field in the sample plane), reversed to -200 kA/m and back to + 200 kA/m again to close the hysteresis loop. The field sweeping speed was 10 kA/(m ns), comparable to typical values in MRAM applications [17].

Experimentally, samples were prepared using e-beam lithography on a silicon(100) wafer with a double layer resist and different exposure doses to create walls of different thickness. The samples were metalized by a 15 nm permalloy layer, followed by a 1-2 nm titan cap layer to avoid oxidation of the Py. Afterwards, the resist was stripped.

The experimental sample shape is depicted in Fig. 1. The sample width was set to 400 nm, the wall diameter to 100 nm and the height to 10 nm. The corners were cut diagonally.

The magnetic properties of the samples were examined using MOKE (magneto-optical Kerr effect) with a diode bridge. Due to the laser spot diameter of approximately 30 µm, each measurement result is superposed of the signals of several thousand nano-structures.

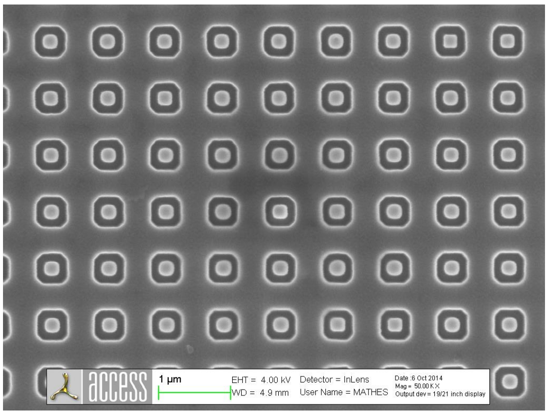

Figure 1. SEM picture of lithographically produced magnetic nano-particles.

3. Results

Fig. 2 depicts the shapes simulated for this examination.

Figure 2. Simulated shapes under examination, with average lateral dimensions of 400 nm x 400 nm x 10 nm.

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Starting from an ideal square ring (a), the corners were flattened (b), the inner corner rounded (c), and finally the shape of a real particle obtained by SEM (scanning electron microscopy) was modelled.

In Fig. 3, simulations of the coercive fields of samples (a)-(d) are shown. Obviously, the symmetry of the particle shape is reflected in the symmetry of the angle-dependent coercive fields. While the fourfold symmetry of sample (a) results in a fourfold symmetry of the simulated coercive field, no such symmetry is observed in the simulated coercive field of particle (d). The other two samples with rounded corners and – in case of sample (c) – slightly reduced symmetry show differences to both extremal particles and also have some features in common with them. Particle (b) still shows a fourfold symmetry and quantitatively similar coercive fields as sample (a), with significant differences around hard and soft axes (45° and 0°). Sample (c) resembles the coercive fields of particle (a), with clear symmetry breaking areas. Finally, sample (d) shows strong deviations from the original symmetry.

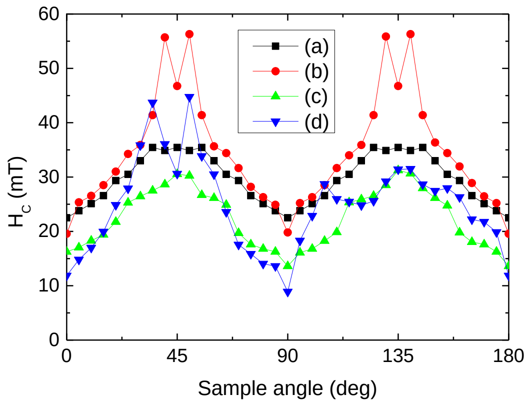

Figure 3. Simulations of the coercive fields of the samples depicted in Fig. 2.

These simulations show the strong influence of shape modifications on the angle-dependent coercive fields – and thus the modifications which can be expected due to undesired deviations from the ideal shape in the lithography process. To test the effect of such shape deviations experimentally, lithographically produced samples (c*) and (d*) – which were used as real bases for the particle models (c) and (d) – were investigated using MOKE. Fig. 4 shows the angle-dependent results of these measurements.

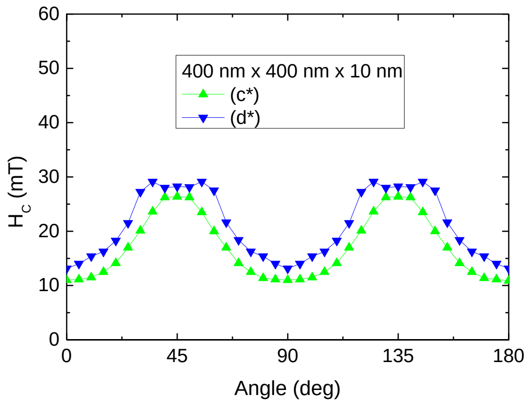

Figure 4. Measurements of real samples with different shapes.

Experimental and theoretical results are similar, with the experimental values being more symmetric and even than the simulated ones. This finding can easily be explained by the averaging processes over several particles which take place in the experiment.

The peaks arising in the simulation of sample (d) near 45° are strongly reduced in the measurement which can also be attributed to an averaging effect in the experiment.

Quantitatively, theoretical and experimental results are also similar.

These results show that micromagnetic simulations can support the identification of shape influences on the magnetic properties of nano-particles, especially since no averaging effects blur the results, opposite to the experiment. On the other hand, averaging over a large number of nano-particles in the experiment helps understanding principle dependencies of the particle shape on the coercive fields, since small deviations from the desired shape are averaged out.

4. Conclusion

To conclude, we have shown the significant influence of nano-particle shapes on their magnetic properties which can be modelled using micromagnetic simulations.

These principal findings are reflected in the experimental results, however, in a less pronounced way due to averaging over several single nano-particles in MOKE measurements. In this way, both approaches – experimentally and theoretically – can support and complement each other.

Acknowledgements

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