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Investigation of shape-dependent switching of coupled nanomagnets

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Abstract

This paper presents a magnetic force microscopy study of antiferromagnetic ordering along chains of dipole-coupled single-domain permalloy nanomagnets with a variety of shapes. Magnetization reversal processes occur due to antiferromagnetic coupling between the closely spaced dots when an appropriate external magnetic field is applied. The goal of this study was to investigate the switching properties and correlation lengths as a function of nanomagnet geometry. We have found that certain shapes (due to their stronger stray fields) clearly show stronger interaction than others when the chain is demagnetized. In addition we have seen that the performance of the nanomagnets also depends on the method of demagnetization, and this fact must be taken into account when shape engineering is used to design coupled nanomagnet systems for a given application.

Keywords: Nanomagnetics; Magnetic field coupling; Magnetic quantum-dot cellular automata

1. Introduction

Ferromagnetic and antiferromagnetic ordering in coupled nanostructures has recently received considerable attention. Magnetic logic devices have been proposed and realized [1–3] which are, in principle, capable of transmitting and processing binary information in an entirely magnetic way. These magnetic systems are adiabatically clocked by an external

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field that enables the structures to relax to their ground state from an initial metastable state. In order that certain arrangements of antiferromagnetically coupled dots be able to perform logical functionality (called magnetic quantum-dot cellular automata—MQCA operation), a reliable switching behavior of the dots is needed. Non-uniformities due to material and geometrical defects, however, lead to switching-field variations which limit the correlation length. Recent experiments have shown correlation lengths of 4–7 dots in chains of single-domain nanomagnets [4, 5].

In moving toward the proposed MQCA devices, we need to understand and to gain control over the switching properties of the particular nanomagnets that build up the device. It is well known that the switching behavior strongly depends on the physical shape of the dots [6]. According to our micromagnetic simulations, magnetization reversal in ferromagnets of 100 nm size occurs through domain-wall nucleation and propagation, and the exact site of domain-wall nucleation can be influenced by shape engineering of the magnet. In this study, we investigate the switching properties and correlation lengths in chains of coupled magnetic dots as a function of nanomagnet shape.

2. Experimental procedure

Arrays of chains of nanomagnets were fabricated on silicon dioxide by electron beam lithography on PMMA, e-beam evaporation of 30 nm permalloy, and lift-off. The dots were made in different sizes with 75, 95, and 125 nm short axes and three aspect ratios of 2, 2.5, and 3, giving altogether nine sizes. These elongated dots exhibit magnetic shape anisotropy with the easy axis along the length of the nanomagnet. We fabricated chains consisting 64 dots aligned parallel along their easy axis, with approximate spacing of 40 nm. For each particular dot shape we fabricated an array of nine chains, one chain for each size and aspect ratio.

We designed seven different shapes that can be divided into symmetric and asymmetric types with regard to the magnetic easy axis. Fig. 1 shows scanning electron microscope (SEM) images of the sample. In addition to the 64-dot chains, we also fabricated arrays of double and single dots in the same sizes and shapes in order to be able to study the effect of the applied magnetic field on such simpler structures.

Two types of demagnetization method were used and compared by evaluating magnetic force microscopy (MFM) images of the ordered magnetic dipoles.

One of the demagnetization procedures that we employed in this experiment is adiabatic field pumping, as suggested in [3]. Here, a homogeneous magnetic field is oriented perpendicular to the magnetic easy axis of the dots to “pump” energy into the system. This energy is used to appropriately modify the barriers of metastable states to allow the system to relax to the ground state [3]. The term “adiabatic” implies that the nanomagnet system is driven through lowest-energy states to avoid spin oscillations by changing the field sufficiently slowly.

In addition to the above method of field pumping, we also used a “rotating” magnetic field for demagnetization. During rotating field demagnetization, the sample is rotated in a decreasing external magnetic field parallel to the sample’s plane. This is similar to the widely used ac demagnetization technique (for example it was also used in [5]), but

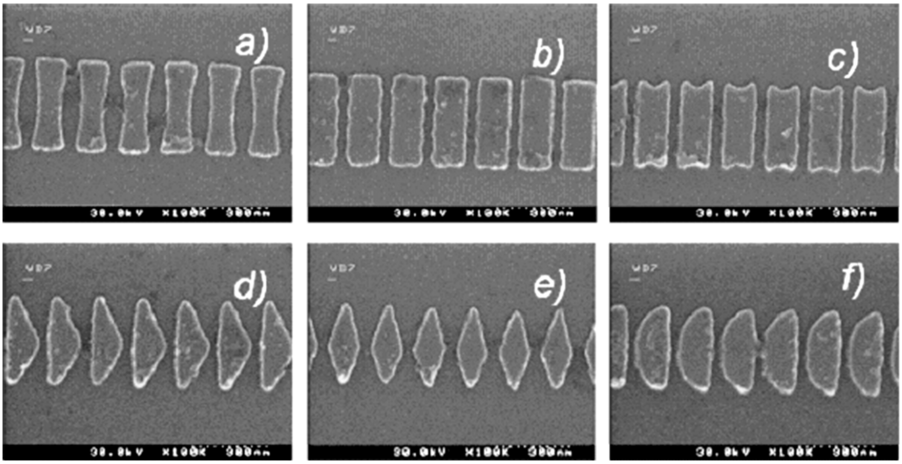

Fig. 1. SEM micrographs of chains of dots with various shapes studied in this paper.

has some additional advantages. First, having no fixed direction relative to the chains eliminates the effect of field misalignment with respect to the magnetic axis. Second, since the external field is swept without changing polarity, i.e. ramping down to zero, it is a fast process with relatively small field changes per cycle (in our experiments this rate was approximately 3 G/rotation).[1]

We used conventional MFM to obtain magnetic images of our samples. Single-domain states (dipoles) appear as bright and dark spots, corresponding to magnetic north and south poles, whereas multi-domain dots have low contrast in the MFM image.

We studied the degree of ordering due to magnetic coupling by inspecting the MFM images, and by counting the number of errors. Perfectly ordered chains have all poles alternating, as can be seen in the first chain in Fig. 2. An error occurs where two neighboring dots have moments pointing in the same direction, such as in the middle of the third chain in Fig. 2. Another type of error occurs if a dot splits into multiple domains under the influence of its neighbors. In this case, the dot appears as a low-contrast magnetic image due to vortex-type domain formation and simply due to the lack of spatial resolution (some dots in the middle chain in Fig. 2).

3. Results and discussion

The differences in shape, size, and demagnetizing process had a strong effect on the quality of the antiferromagnetic ordering. Fig. 3 summarizes our results for rotating field demagnetization by giving an average ordering length for every shape based on the number of parallel-aligned dipole pairs (errors) which we observed in the chains. The average ordering length is an estimate of the size of a device that can be built using the given type

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[1] The rotation speed was 1800 RPM, and the applied maximum field was 4000 G.

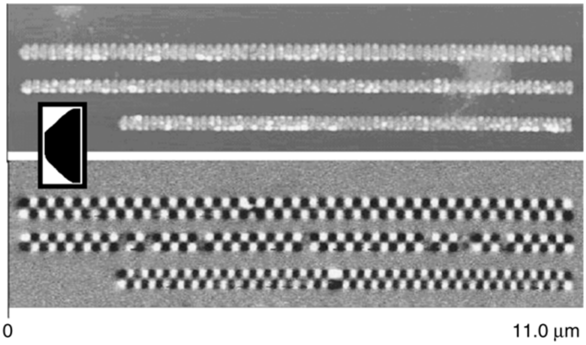

Fig. 2. AFM topography and MFM images of three trapezoid-shape chains after rotating field demagnetization. The top chain with the largest dot size shows perfect ordering along 64 dots. The middle chain, having dots with smaller aspect ratios, develops multi-domain states (in this way avoiding higher-energy aligned moments at critical places). The chain at the bottom has only single-domain states, and a frustration error is shown in the middle.

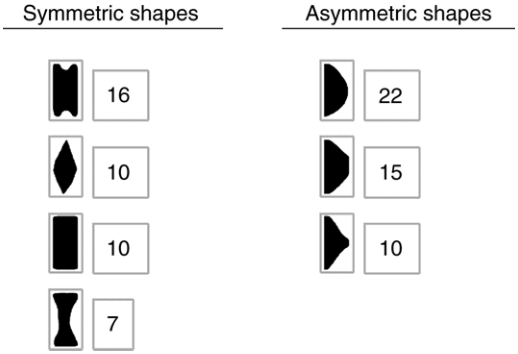

Fig. 3. Average correlation lengths for the different shapes as determined from averages of three independent demagnetization processes for the arrays.

of nanomagnet. In previous work, we have found this number to be between 7 and 8 for the cobalt dots that we fabricated [4]. For permalloy dots a correlation length of 4 or 5 was observed earlier by Cowburn [5]. In the present study, we demonstrate average ordering lengths from 7 (in the case of 14% errors) to 22 (in the case of 4.5% errors).

Some shapes (such as the asymmetric “circle segment”, Fig. 1(f), and “triangle”, Fig. 1(d)) show large differences in the quality of ordering, while “the rhombus” and “the rectangle” performed very similarly.

An important comparison of two symmetric shapes can be seen in Fig. 4. The top row shows MFM images for the shape of Fig. 1(a), and the bottom row shows data for the shape of Fig. 1(c). The three images in each row are for three independent demagnetization processes. The data for the two repeated rotating field demagnetization processes (left and middle images) demonstrate that the errors are distributed more or less homogeneously and are approximately the same for each array. Moreover, many times they appear at exactly

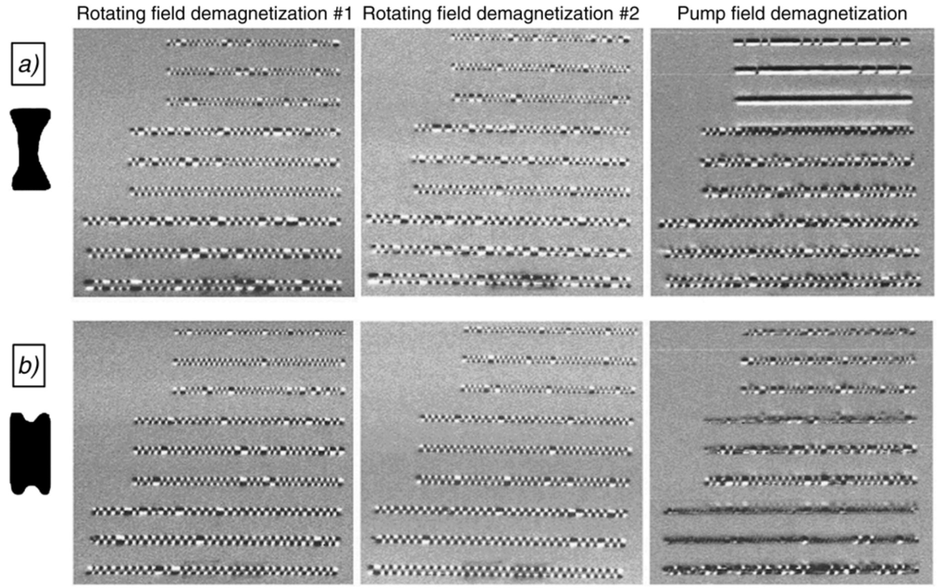

Fig. 4. MFM images comparing ordering along chains of two symmetric shapes when different demagnetization fields were applied.

the same location in the chains, which suggests that the average number of errors and the average ordering length are determined by fabrication defects in some dots, but can be affected by the shape.

The dots in the bottom row (shape of Fig. 1(c)) show longer-range ordering, which indicates a better fault tolerance of this shape (left and middle image). This effect can be attributed to the sharpened corners, which generate strong local stray (and coupling) fields. However, these dots exhibit poorer coupling behavior (right image) when the adiabatic pump field is applied,[2] since the sharp corners lead to strong, non-uniform demagnetizing fields that promote the formation of domain structures during switching and cause these dots to relax into a metastable state at the end of the pumping cycle.

We find that the shapes of Fig. 1(f) consistently show the best ordering for the rotating field demagnetization, and the dots of Fig. 1(a) perform best for the adiabatic pumping field. These results will be useful in our future studies to determine optimal shapes for implementing MQCA structures.

4. Conclusion and summary

In summary, we investigated antiferromagnetic ordering in arrays of dipole-coupled permalloy nanomagnets with various shapes. Statistical results were extracted from

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[2] The applied field points horizontally (along the chains) and was slowly increased to 1700 G, and then reduced to zero.

magnetic force microscopy images, and the nature of the demagnetization method was considered when we evaluated the results. We have found shape-dependent long-range ordering effects in chains of magnetic dots. To our knowledge, our study is the first to address in detail the geometry and applied field dependence of antiferromagnetic ordering phenomena.

As a general rule, we find that shapes with well-defined nucleation sites for poles during demagnetization, i.e. designed magnetic domain formation during magnetization reversal, make the switching process more predictable and result in greater correlation lengths in arrays of coupled nanomagnets. In addition to the shape dependence, we also find a dependence on the demagnetization process. Therefore, both the shape and the process have to be considered together for specific applications.

Our results are encouraging as regards the proposed magnetic logic devices. We have shown that ordering persists over chain lengths of some 20 dots, and this length is attractive for logic applications. While the realization of more complex geometries and the perfection of our fabrication technology remains challenging, our results do *not* indicate any inherent fault intolerance of the antiferromagnetic ordering.

Acknowledgements

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