Domain configuration of permalloy ellipses in a rotating magnetic field

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Abstract. The domain configuration of micron-sized permalloy ellipses was studied under the influence of an in-plane rotating magnetic field using magnetic force microscopy. The field amplitude was chosen such that when the field is applied parallel to the long axis of the ellipses they are saturated, but when the field is perpendicular to the long axis they exhibit multi-domain states. The rotation angle for nucleation and annihilation of domains was determined for different magnitudes of the applied magnetic field and for two different lateral sizes of ellipses, 6 μm$\times$2 μm and 3 μm$\times$1 μm. It was found that both nucleation and annihilation occur over a range of angles for both lateral sizes of ellipses. Saturated states are stable for a wider range of angles for larger values of the applied field.

PACS numbers: 75.50.Bb; 75.70.Kw

Submitted to: *J. Phys. D: Appl. Phys.*

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1. Introduction

The separation of biomolecules from a heterogeneous suspension using magnetic particles is a well-established technique in life sciences. The surface of the magnetic particles is functionalized, so that they bind selectively to specific target molecules and can be separated from the suspension through the use of an external magnetic field. [1, 2] One limitation of this technique is that the particles and therefore the target molecules, are separated in large numbers. We have previously shown how it is possible to control the movement of single magnetic particles making use of lithographically defined arrays of magnetic ellipses.[3] Knowing how the domain structure changes in a rotating field is of great importance for the further development of this type of application. Furthermore, it is of fundamental interest for a better understanding of domain processes in small magnetic elements. Static measurements of the angular dependence of the switching field have been made by others. [4, 5] These studies infer the domain structure from a comparison of the experimentally obtained hysteretic behaviour with theory[4] or simulations[5]. However, no direct measurements of the domain structure is made by these authors.

In this article we report on a study of the domain structure of permalloy ellipses with aspect ratio 3:1 in a rotating in-plane applied magnetic field. For the particle transportation application [3] elements that can exhibit either multi-domain states or saturated states, depending on the magnitude and direction of the applied field, are required. Ellipses of two different lateral sizes have been studied, 6 μm$\times$2 μm and 3 μm$\times$1 μm. The larger size is that of the ellipses currently used in the transportation of single magnetic particles, because of the particle size used. An interesting question is if this programmable transportation is also possible for smaller element/particle combinations.

2. Experiments

Samples with elliptical permalloy, $Fe_{20}Ni_{80}$, elements of aspect ratio 3:1 were fabricated using e-beam lithography, thermal evaporation and a lift-off technique on silicon substrates. The studied ellipses were of two lateral dimensions 6 μm$\times$2 μm and 3 μm$\times$1 μm, both with a thickness of approximately 50 nm. The ellipses were arranged in two different patterns, one where adjoining ellipses have their long axes along perpendicular directions and one where all ellipses have parallel long axes, see figure 1. In the latter case, the inter-elemental distances are of a size where the elements can be assumed to be non-interacting. [6]

The magnetic domain structure of the ellipses was studied with a Nanoscope$^{\mathrm{TM}}$ Dimension 3100 magnetic force microscope (MFM) in tapping/lift mode, using standard commercial magnetic probes. Measurements were made at ambient temperature in air. Magnetic fields were applied in-situ using two perpendicular electromagnets. Two different types of MFM measurements in an applied magnetic field were made. Starting

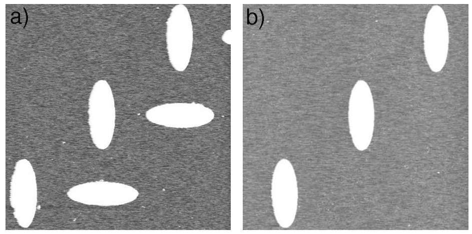

Figure 1. The two different studied arrangements of the ellipses. a) shows the so-called staircase pattern where adjoining ellipses have their long axes along perpendicular directions and b) shows the arrangement with no horizontal ellipses.

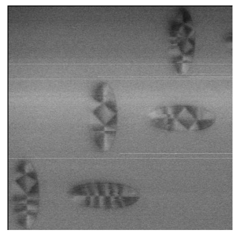

Figure 2. A zero-field MFM image of the 6 μm$\times$2 μm ellipses with perpendicular neighbours showing three different multi-domain states. The ellipse in the upper right-hand corner is in a double diamond state and the lowest horizontal ellipse is in a cross-tie state. The other three ellipses exhibit the diamond state, with one or two cross-ties.

out with demagnetized elements, the field was applied parallel with the long axis of the ellipses to determine the switching field from multi-domain states to saturated states. The so determined switching field was then applied and rotated one full revolution taking MFM-images every 5°. This was repeated for a field equal to $\sqrt{2}$ times the switching field. The rotation angles at which multi-domain states were nucleated and annihilated, respectively, were determined for both field magnitudes and for both ellipse sizes.

Micromagnetic simulations for 3 μm$\times$1 μm$\times$50 nm ellipses were performed using the Object Oriented Micromagnetic Framework, OOMMF. [7] The parameters used were the default settings for permalloy, i.e. M_s=860 kA/m, A=13 pJ/m and K_1=0 J/m^3. The system was regarded as two dimensional and the discretization cell size was set to 5 nm$\times$5 nm$\times$50 nm. The first step was to compute a zero field ground-state, by relaxing the system in zero-field from an initially random spin configuration. Two different ground-states were found and the applied magnetic fields required to saturate these different states were determined using the zero-field ground-states as the initial configurations. Simulations where an in-plane rotated magnetic field has been applied to 3 μm$\times$1 μm$\times$50 nm ellipses have been reported on elsewhere. [8]

3. Results

Several different experimental zero-field domain structures were found in the MFM measurements. In figure 2 five 6 μm$\times$2 μm ellipses can be seen, three showing diamond

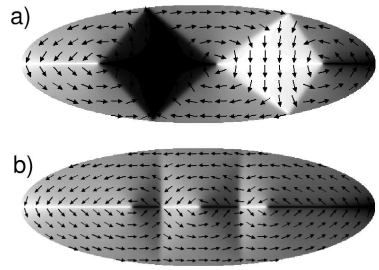

Figure 3. Two different ground-states for a 3 μm$\times$1 μm ellipse from the OOMMF simulations, both with three vortices. a) shows a double diamond structure and b) shows a double cross-tie structure.

structures with one or two cross-ties, one showing a multiple cross-tie structure and one showing a double-diamond structure. These domain structures are also observed in the 3 μm$\times$1 μm ellipses. The occurrence of different domain states is not due to imperfections in the elements. The same element can exhibit different multi-domain states, in different field cycles, which has been observed previously for 2 μm$\times$1 μm ellipses [9] as well as 1.47 μm$\times$0.64 μm and 1.47 μm$\times$0.75 μm ellipses [10]. Thus the edge roughness of a particular element seems to be of minor importance for the zero field multi-domain state attained. Rather the local field landscape and history seem to be the deciding factors.

The ellipses of lateral dimension 6 μm$\times$2 μm become saturated, or nearly saturated, at a field B=5 mT applied along their long axes. In the 3 μm$\times$1 μm ellipses this occurs at B=9 mT. However, some cross-tie structures remain to higher fields in both lateral sizes of ellipses. The ellipses with diamond structures are saturated at lower applied fields than those with pure cross-tie structures. The fact that a larger field is required to saturate smaller ellipses is expected from simulations. [11]

The simulation results for the 3 μm$\times$1 μm ellipses show two different ground-states. Both have three vortices, but the sense of rotation around them differs yielding a double diamond state and a double cross-tie state, see figure 3. This is in good agreement with the MFM-measurements, which show several different zero-field states among others a double diamond state and a multiple cross-tie state. The simulations yield E_{tot} = 3.6 kJ/m^3 for the double cross-tie state and E_{tot} = 3.1 kJ/m^3 for the double diamond state, making the double diamond state the more favourable. The double diamond state is (nearly) saturated at a field of 10 mT applied parallel to the long axis of the element, while the double cross-tie state becomes (nearly) saturated at a field of 16 mT, which agrees with the MFM-measurements where the cross-tie states are stable in higher fields than the diamond states.

The MFM-measurement in a rotated in-plane applied magnetic field showed the same qualitative behaviour for both sizes of ellipses. For the pattern with perpendicular ellipses the field was initially applied along the long axes of the horizontal ellipses. (This direction was defined as 0°.) The horizontal ellipses were saturated while the vertical ellipses exhibited multi-domain states, see figures 4a and 5a. Upon rotation of the field,

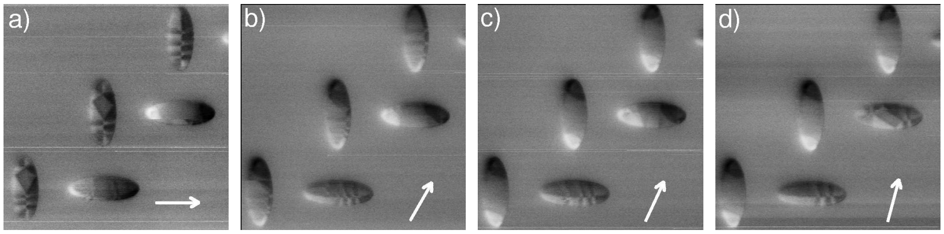

Figure 4. MFM images of the 6 μm$\times$2 μm ellipses in an applied magnetic field of 5 mT of different angles. The arrows indicate the applied field direction. 0° is defined as the direction parallel with the long axes of the horizontal ellipses. In a) the field is applied at 0° and the horizontal ellipses are saturated, while the vertical ellipses exhibit multi-domain states. The field is rotated and in b) at 60° the vertical ellipses show distorted multi-domain states. One of the horizontal ellipses has been switched to a multi-domain state, but the other one is still nearly saturated. In c) the field is applied at 65° and the vertical ellipses have all switched to nearly saturated states. On further rotation of the field to 75° in d) the horizontal ellipses exhibit multi-domain states, while the vertical ellipses are (nearly) saturated.

the multi-domain states in the vertical ellipses were distorted, see figures 4b and 5b, and were eventually annihilated, see figures 4c and 5c. Table 1 gives the mean value for the annihilation angle for the different magnitudes of the applied field and the different sizes of ellipses. Further rotation leads to nucleation of multi-domain states in the horizontal ellipses, see figures 4d and 5d. The mean value of the nucleation angles are listed in table 1. Previous micromagnetic simulations for a 3 μm$\times$1 μm ellipse show a similar behaviour: the element switches from a nearly saturated state to a multi-domain state as the applied field is rotated 90°, starting parallel with the long axis of the ellipse. [8]

The behaviour of the domain configuration on rotating the field depends, not surprisingly, on the magnitude of the field. For the larger field the (nearly) saturated states exist in a broader interval of angles than for the smaller field, see figures 4 and 5 as well as table 1. The annihilation occurs at a smaller angle for the higher field and the nucleation occurs at a larger angle, for both sizes of ellipses. For the smaller field some of the cross-tie structures remain, even with the field applied parallel with the long axis of the ellipse. This is not the case for the larger field, where all of the ellipses become saturated when the field direction is parallel with the long axes.

Annihilation and nucleation occur over a range of angles for both lateral sizes of ellipses, in large as well as small applied fields. The mean values and its distribution can be seen in table 1 and figure 6. As mentioned above, different multi-domain states become saturated at different field magnitudes, so a range of switching angles is to be expected. It is also possible that the edge roughness influences the switching field so that each type of multi-domain state switches over a range of angles. [12]

The pattern with only parallel ellipses shows the same behaviour with (nearly) saturated and multi-domain states as the pattern with perpendicular ellipses in a rotated in-plane magnetic field. The nucleation angle is not affected by the removal of the perpendicular ellipses. However, the annihilation occurs at a higher angle when the

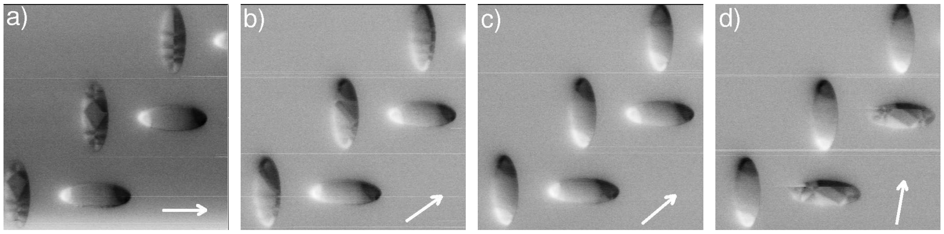

Figure 5. MFM image of the 6 μm$\times$2 μm ellipses in an applied magnetic field of 7 mT. The arrows indicate the applied field direction. a) shows the domain structure with the field applied along the long axes of the horizontal ellipses. This direction is defined as 0°. Here the horizontal ellipses are saturated and the vertical ellipses exhibit multi-domain states. In b) the field has been rotated to 35° and the multi-domain states in the vertical ellipses are distorted. The horizontal ellipses are still (nearly) saturated. The field is rotated further in c) to 40°. Here the distorted multi-domain states of the vertical ellipses are annihilated, while the horizontal ellipses maintain their (nearly) saturated states. In d) the field is rotated to 80° and multi-domain states are nucleated in the horizontal ellipses.

Table 1. The mean values of the angle for annihilation and nucleation of multi-domain states for the staircase pattern. Note that the annihilation angle refers to the vertical ellipses while the nucleation angle refers to the horizontal ellipses. Both the annihilation and the nucleation occur over a range of angles, see figure 6.

lateral size	B (mT)	annihilation	nucleation
6 μm$\times$2 μm	5	50°	63°
6 μm$\times$2 μm	7	38°	74°
3 μm$\times$1 μm	9	57°	63°
3 μm$\times$1 μm	13	43°	75°

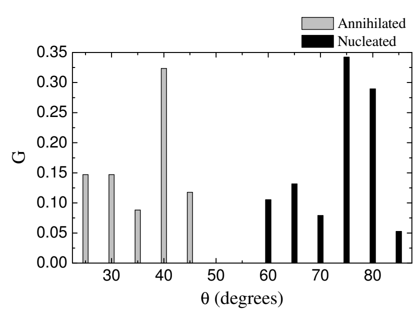

Figure 6. The distribution of angles for annihilation and nucleation of multi-domain states for the 6 μm$\times$2 μm ellipses in the staircase pattern. G shows the fraction of ellipses, in which the multi-domain states were annihilated or nucleated at different angles, θ, of the applied magnetic field of B=7 mT. Note that the annihilation angle refers to the vertical ellipses while the nucleation angle refers to the horizontal ellipses.

perpendicular ellipses are missing.

4. Discussion

The domain configuration of both sizes of ellipses show the same qualitative behaviour in rotated magnetic fields. This indicates that it is possible to use the 3 μm$\times$1 μm ellipses in transportation lines for single magnetic particles, if particles of appropriate size can be obtained.

Several different types of multi-domain states are seen, both in experiments and simulations. There is also agreement between experiments and simulations on the magnitude of the saturating field, and that the cross-tie structure is stable to higher fields than the domain structures.

Both annihilation and nucleation of multi-domain states occur over a range of angles. This is partially due to the fact that different types of multi-domain states switch at different field magnitudes. However, even a single type of multi-domain state switches over a range of angles.

There is a broader interval of angles in which saturated states are stable for the higher applied fields than for the lower applied fields for both lateral sizes of ellipses. This is expected since the component parallel with the long axis is large enough to sustain or create a saturated state for a broader interval of angles at a higher applied field.

The field component parallel with the long axes of the ellipses at the mean angle for annihilation is slightly larger for the larger applied fields. For nucleation the opposite is true so that for the mean angle of nucleation the field component parallel with the long axes of the ellipses is slightly smaller for the larger applied fields. However, the differences are small; the angle for which the field component parallel with the long axis of the ellipses would be the same for the smaller and larger applied fields lies within the range of angles for switching. This is true for both annihilation and nucleation.

The annihilation process involves displacement and annihilation of domain walls/vortices, while the nucleation process occurs via non-uniform spin rotation and vortex nucleation. These processes have been theoretically and experimentally studied for arrays consisting of circular permalloy dots, [6] and a clear effect of inter-dot magnetostatic interaction was evidenced for both processes. In our case, we only find an effect of inter-element magnetostatic interaction for the annihilation process, which is here tentatively attributed to the staircase pattern geometry and the resulting non-uniformity of the inter-element magnetostatic interaction field; the non-uniform interaction field aids in the displacement and annihilation of domain walls, while the same non-uniform field will have little or no effect on the stability of originally uniformly magnetized elements. This will be further investigated in the future.

Acknowledgments

This work was supported by the Swedish Research Council and the Swedish Foundation for Stratigic Research..

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