Influence of clustering round magnetic nano-dots on magnetization reversal

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Abstract. Square and round magnetic nano-dots of varying dimensions exhibit a large amount of possible magnetization reversal processes, from domain wall nucleation and propagation to multi-vortex states. Clustering such single nano-dots, however, may strongly modify these magnetization reversal processes due to the interactions between neighboring particles. Here we thus investigate the difference between magnetization reversal processes in clusters of hexagonally arranged round nano-dots under different orientations of the external magnetic field in comparison with single particle behavior.

1. Introduction
Magnetic nanodots are highly interesting for magnetic storage devices and other spintronic applications. While excluding the core region results in significantly reduced stray fields during magnetization reversal which typically occurs via vortex states [1,2], full nanodots show out-of-plane stray fields of the vortex core, in this way allowing for using the vortex core orientation to define more different “bits” in data storage systems [3-5]. The interplay between shape anisotropy (also called configurational anisotropy) and magneto-crystalline anisotropy strongly depends on the dimensions of the nanodots and the material used to prepare them as well as on the production method, leading to epitaxial growth or arbitrary grain orientations [6-8].

Besides the often highly interesting magnetic states during magnetization reversal, found in nanodots of different shapes and dimensions [9-11], multiple magnetic states can occur at remanence, enabling new logic elements of multi-bit storage systems [12-14]. Especially in storage systems, however, it is necessary to investigate also the interactions between neighbouring nanodots which may strongly influence magnetization reversal behaviour [15,16], even in case of round nanodots [17-20].

Here we report on micromagnetic simulations of hexagonal arrays of round iron nanodots. We compare the magnetization reversal processes found depending on the nanodot thickness with the results of a previous study, dealing with a single round iron nanodot [10]. The influence of the magnetic field orientation is examined, aiming at optimizing the reliability of the vortex states which are often used for data storage. An out-of-plane magnetic field is tested as a possibility to define the polarity and the chirality (circulation direction) of the vortex states which are typically used to define different states [21,22] and can, e.g., be switched by rotating magnetic fields [23,24] or tilted magnetic fields [25].
2. Methods
Micromagnetic simulations were performed with the Object Oriented MicroMagnetic Framework (OOMMF) [26]. This program dynamically solves the Landau-Lifshitz-Gilbert (LLG) equation of motion.

As a typical material, iron (Fe) was chosen and modelled by common literature values: magnetization at saturation $M_s = 1700 \cdot 10^3$ A/m, exchange constant $A = 21 \cdot 10^{-12}$ J/m, magneto-crystalline anisotropy constant $K_1 = 48 \cdot 10^3$ J/m³ [27]. The anisotropies were randomly chosen per cell, simulating a sputtered system with varying anisotropy axes instead of an epitaxial one, as grown by molecular beam epitaxy [28]. By setting the Gilbert damping constant to $\alpha = 0.5$, a quasi-static case was simulated.

The single nanoparticles have lateral dimensions of 200 nm and distances between them of 200 nm, too. Small variations in the range of $\pm 10$ nm were introduced to take into account possible deviations from a perfect structure, as they can be expected for lithographically produced nanodots. Investigations were performed on hexagonal clusters of 7 such nanodots (Fig. 1). The dot height was varied between 5 nm and 40 nm. Numerical meshing was done with cell sizes of 5 nm.

![Figure 1](image.png)

**Figure 1.** Shape of the magnetic nanodot cluster under investigation and definition of the magnetic field orientations.

Magnetic field orientations are defined as shown in Fig. 1. The results show longitudinal magnetization components $M_L$ and transverse magnetization components $M_T$, defined as being parallel and perpendicular to the magnetic field orientation, respectively.

3. Results and discussion
Fig. 2 shows two exemplary magnetization reversal processes for different magnetic field orientations and nanodot thicknesses, as described in the figure caption. In both cases, magnetization reversal includes vortex states, as can be recognized by the dots with the upper or lower half being marked red (i.e. with the magnetization oriented to the right side, parallel to a field orientation of 0° and towards positive saturation) and the other half being marked blue, with the magnetization being oriented oppositely.

The corresponding hysteresis loops are given in Fig. 3. Here, the loop simulated for the thinner nanodot array (Fig. 3a) shows several steps, corresponding to single nanodots switching into the vortex state one after the other over a broad field range. For the thicker nanodots (Fig. 3b), magnetization reversal from positive saturation into vortex states and further into negative saturation occurs in a much smaller field range, as can be recognized from the “jumps” in the loop. Here, the closed part of the loop, crossing the origin of the graph, corresponds to the range in which all nanodots are in a vortex state.

From examinations of single nanodots, it is well-known that vortex states are reached earlier, i.e. for relatively large positive fields during magnetization reversal from positive to negative saturation, in case of thicker nanodots [10]. Thus, it is not unexpected that the arrays with thicker dots also show broader areas in which vortex states occur. On the other hand, a more detailed investigation of the slopes of the curves is necessary to understand the reliability of these vortex states, i.e. in which field ranges all nanodots are in the same (saturated or vortex) states.
Figure 2. Magnetization reversal processes of hexagonal arrays of nanodots (a) with height 20 nm and an external magnetic field orientation of 0°; (b) with height 40 nm and an external magnetic field orientation of 45°.

Figure 3. Hysteresis loops of hexagonal arrays of nanodots (a) with height 20 nm and an external magnetic field orientation of 0°; (b) with height 40 nm and an external magnetic field orientation of 45°.

Next, Fig. 4 depicts comparisons of three hysteresis loops for nominally identical situations. Deviations occur due to the arbitrarily chosen anisotropy orientations per unit cell – a realistic approach for commercially produced future data storage media.

While in both figures, deviations between the single curves near the coercive fields are visible, only in case of the array with height 5 nm severe differences between simulation no. 1 (black line) and both other simulations (being identical which is why the red line is hidden behind the green one) were found. In these thin nanodots, magnetization reversal occurs without vortex states, but by forming a 180° domain wall perpendicular to the external magnetic field [10]. Such states naturally have larger stray fields and thus influence their neighbours stronger than the thicker nanodots which in most cases were found to reverse magnetization along vortex states.

It should be mentioned that this effect is naturally much more pronounced if cobalt (Co) is used for simulation or experiment since this material has an approximately one order of magnitude higher anisotropy constant than Fe, resulting in a correspondingly stronger influence of the arbitrary orientation of the anisotropy axes [7].
A more detailed overview of the reliability of the different states for magnetization reversal from positive to negative saturation is given in Fig. 5. The values depicted here are the “worst” of 5 simulations per thickness, i.e. giving the narrowest regions with purely saturated or purely vortex states. Simulations for arrays with thickness 5 nm are not shown here since they don’t reverse magnetization via vortex states.

Generally, both phase diagrams in Fig. 5 are similar; however, they differ quantitatively. This underlines the importance of taking into account interactions between neighbouring nanoparticles, even if a vortex state is found at remanence, as it is the case for nanodots of thicknesses 30 nm and 40 nm. It must be mentioned, nevertheless, that in a real storage device, the vortex polarity or chirality is switched by field pulses or out-of-plane fields, thus magnetization reversal does not follow these phase diagrams with the saturated states included.

For such vortex-based storage devices, it is necessary to include the x-axis, i.e. the remanence, in the green marked vortex area. Highest stability is reached when the blue line, depicting the negative phase border at which the first vortices switch into saturated states, is far away from remanence. Here, apparently relatively thick nanodots work best.
It must be mentioned, however, that the vortex states are reversible states. If, e.g., a vortex state is approached in case of a thickness of 15 nm and a field orientation of 0° by sweeping the external magnetic state from positive saturation into the green vortex area, then this vortex will resist positive and negative fields of more than \( \pm 100 \) mT. This means that even nanodots of smaller thicknesses, which may be produced lithographically more reliably, can be used for such magnetic vortex-based storage media.

Finally, the influence of constant out-of-plane magnetic fields is investigated for an array of nanodots with thickness 30 nm. The resulting phase diagrams are depicted in Fig. 6. While again quantitative differences are visible between both field orientations which can be attributed to interactions between neighbouring nanodots, here it is also visible that with larger out-of-plane fields, the white areas between the phase borders, i.e. the field ranges of non-homogeneous magnetic states of the nanodots in the array, become smaller and smaller, until for an out-of-plane magnetic field of 1.5 T, the magnetization reversal process becomes fully reversible, without any jumps in the hysteresis loops, and occurs simultaneously in the whole cluster. Apparently, large out-of-plane fields can at least be supportive for the initial writing process, while continuously applying such large fields may cause problems in data storage applications.

![Figure 6](image_url)

**Figure 6.** Out-of-plane field-dependent phase diagrams of hexagonal arrays with an external magnetic field orientation of (a) 0°; (b) 45°.

4. Conclusion
Magnetization reversal processes of clusters of round nanodots were investigated, varying the nanodot thickness and the angle of the external magnetic field. For thicknesses of minimum 10 nm, magnetization reversal occurred via a vortex state. Higher thicknesses resulted in higher reliability of the magnetic fields where magnetization reversal processes occurred, while thin nanodots showed more steps along the slopes of the hysteresis loops, indicating broad field ranges along which the single nanodots switched into different magnetic states, and in addition smaller vortex areas.

The mixed-state areas between the field ranges of purely saturated or vortex states could significantly be reduced by applying an out-of-plane magnetic field, until for a field of 1.5 T magnetization reversal became fully reversible, and the non-homogenous magnetic states in the array were eliminated. On the other hand, the vortex state field range was reduced in this way which reduces the stability of the states typically used for data storage.
This finding suggests further examinations of the impact of constant fields of field pulses along different in-plane and out-of-plane orientations, aiming at optimizing the stability of the vortex area as well as the reliability of the magnetic states of the single nanodots.

5.References
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