In-plane reversal mechanisms in circular Co dots

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The reversal process of polycristalline circular Co dots is investigated for dot sizes for which the vortex state corresponds to the ground state configuration. Using magneto-optic Kerr magnetometry and magnetic force microscopy imaging, it is found that during the reversal of the magnetization, the system does not necessarily pass through its ground state configuration. For large dot diameters and thickness, the reversal occurs via nucleation, propagation, and expulsion of a single vortex, whereas for a dot thickness below 20 nm the reversal process may occur by a coherent rotation of the quasi-single-domain configuration. Furthermore, a double-vortex state formation has been evidenced for 1000-nm-large dots.
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Reduction of the system sizes of small magnetic elements leads to a discrete number of magnetic ground states. In particular, in circular Co dots, two simple configurations are distinguished. Micromagnetic investigations have shown that, depending on the dot diameter and thickness, either the single-domain (SD) or the vortex state corresponds to the zero-field ground state configuration.[1] Another approach to study equilibrium states is to investigate the magnetization reversal process. The shape of the hysteresis loop often provides signatures which are typical for specific reversal processes. For circular superPermalloy dots,[2] for an in-plane applied field, either a coherent rotation of the magnetization or a reversal through vortex formation were identified. Furthermore, the reversal of the vortex state has been investigated by magneto-optic Kerr effect (MOKE) and magnetic force microscopy (MFM)[3,4] and by Lorentz microscopy measurements.[5] It was found that in circular dots, under an in-plane field, the vortices always enter from the dot border. By sweeping the field from the vortex nucleation to the vortex annihilation field, the vortex core traverses the dot in a direction perpendicular to the applied field and annihilates at the opposite dot border, this mechanism being fully reversible.

Here, the evolution of the magnetization distribution during the in-plane reversal process is described for circular polycrystalline Co dots using MOKE magnetometry and MFM in correlation with micromagnetic simulations. Although for the size range investigated here the ground state is the vortex state, different types of reversal mechanisms were identified.

Arrays of polycrystalline circular Co dots of diameter varying in the range from 150 to 1000 nm, and thicknesses from 10 to 50 nm were fabricated by nanoimprint lithography and lift-off process.[6] The dots are arranged in a square lattice of $150\times150\ \mu m^2$. MOKE hysteresis loops, recorded with a 10 μm focal spot, were measured in the longitudinal geometry at room temperature. The magnetic field was applied in the plane of the dots. The interdot spacing, three times the diameter of the dots, is sufficiently large to neglect magnetostatic interactions between dots. The influence of the magnetostatic interactions on the reversal of the magnetization is discussed elsewhere.[7] The MFM measurements were performed in the phase detection mode (Nanoscope Dimension 3100) using commercial CoCr coated Si cantilever tips of pyramidal shape magnetized along the tip axis. The magnetic configurations were imaged at a lift scan height of 100 nm. An in-plane external magnetic field was applied during the image acquisition using two small movable permanent magnets.

Micromagnetic simulations have been performed in order to determine the zero-field ground state diagram[1] as a function of dot diameter and thickness, shown in Fig. 1. For larger dot diameters and thicknesses, a vortex state is energetically favored, while a transition to the SD state occurs upon decreasing thickness and diameter. This transition is explained in simple terms by the dominant energy contributions in the two configurations. The flux closure structure of the vortex state minimizes the demagnetizing field energy and contains dominant contributions only from the exchange energy. In contrast, for the SD configuration the dominant contribution arises from the demagnetizing field energy while the exchange energy is negligible. Upon decreasing the diameter, e.g., at constant thickness, the exchange energy of the vortex structure becomes comparable to the magneto-

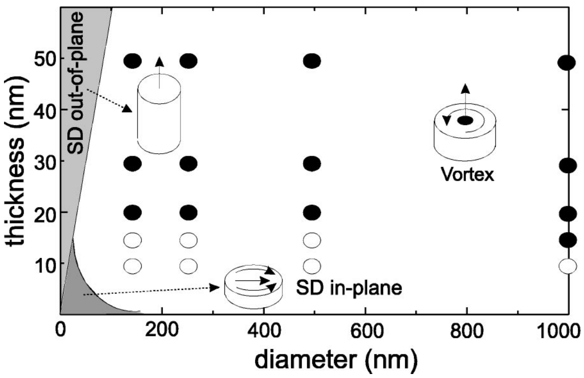

FIG. 1. Calculated ground state diagram for polycrystalline Co dots. The experimental points obtained from the hysteresis loops are indicated by open circles for a reversal yielding square hysteresis loops, respectively, by full circles for a reversal through vortex formation.

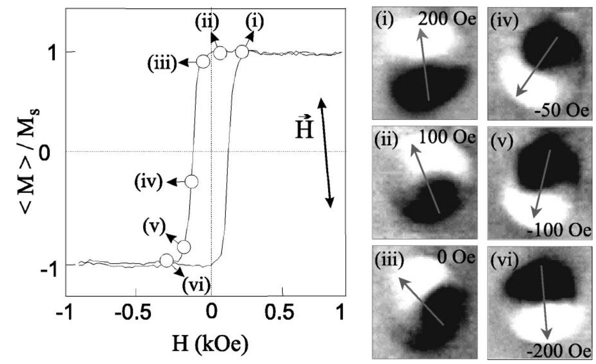

FIG. 3. Reversal of the magnetization by coherent rotation for a 10-nm-thick and 500-nm-large dot. The MFM images (i)–(vi) display the magnetic contrast corresponding to the distribution of the magnetization at different applied field values.

static energy of the SD state. Consequently, below a critical diameter, the flux closure configuration can no longer be maintained and the SD state becomes energetically favorable. Similar arguments apply for reducing the dot thickness at constant diameter.

For the thickness and diameter range of the Co dots investigated here, the ground state of the system is represented by the vortex state. However, two distinct types of reversal process can be distinguished from the MOKE hysteresis loops. These reversal types are indicated by full circles or open circles on the state diagram in Fig. 1. For larger thicknesses the loops display a small remnant magnetization and two critical fields at which the magnetization changes abruptly (see the hysteresis loop in Fig. 2). This behavior is consistent with a reversal by vortex formation at the nucleation field H_n, a zero-field vortex configuration, and an expulsion of the vortex at the annihilation field H_a. The second type of loop (hysteresis loop in Fig. 3) is almost square with a high remanence and a low coercive field and is characteristic for small dot thickness (below 20 nm). This type of loop is consistent with a coherent rotation of the magnetization and a zero-field SD configuration. The latter process means that during the in-plane reversal, the system does not necessarily reach its ground state.

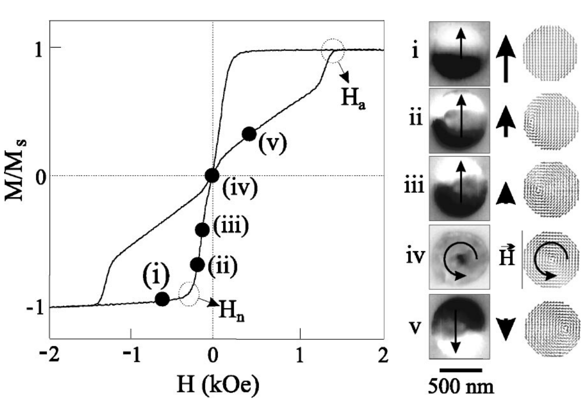

FIG. 2. Reversal of the magnetization through vortex formation for a 30-nm-thick and 500-nm-diam dot. Different points on the hysteresis curve, from (i) to (iv), are visualized by MFM.

These conclusions, obtained for an average ensemble of dots, from the MOKE loops, are confirmed by MFM studies on individual dots for which the in-plane reversal process has been imaged as a function of the applied field.

Let us consider first the magnetization reversal of 30-nm-thick and 500-nm-large Co dots, whose hysteresis loop is shown in Fig. 2. For large negative values of the external field, the dots adopt an in-plane SD configuration [Fig. 1(b)-i], with a characteristic black and white contrast. Starting from this configuration and increasing the field, the net magnetization drops at the nucleation field H_n, where a vortex nucleates at the dot border [Fig. 1(b)-ii]. By further increasing the field, the vortex moves towards the dot center [Fig. 1(b)-iii] and a completely symmetric configuration is stabilized at zero field [Fig. 1(b)-iv]. In this particular state, the circular flux closure of the magnetization does not produce any magnetic stray field, the only contrast arises from the vortex core located at the center of the dot. Upon increasing the field, the net magnetization progressively reappears as the vortex core moves towards the opposite dot border, giving rise to a dipolar contrast which gradually develops, as shown in Fig. 1(b)-v. Upon increasing the field above the annihilation field H_a, the vortex is expelled from the dot and the SD state is again established. The evolution of the internal structure of the magnetization is clearly illustrated by the simulated configurations.[8]

The reversible displacement of the vortex core provides a simple way to determine the rotation sense of the vortex. For a given orientation of the applied field, the vortex core moves either up or down depending on the rotation sense of the flux, which can be either clockwise or counterclockwise [image (v) in Fig. 2].

The MOKE hysteresis loop and the corresponding MFM images obtained for an array of 10-nm-thick and 500-nm-large Co dots are shown in Fig. 3. MFM images [from (i) to (vi)] were taken at different field values, as shown in the figure. The first image—(i), recorded at 200 Oe, is indicative for a uniformly magnetized dot, with the magnetization oriented parallel to the direction of the field. Reducing the field from positive saturation, the net magnetization starts to tilt away from the field direction and correspondingly the MFM contrast rotates. At -200 Oe, image (iv), the magnetic con-

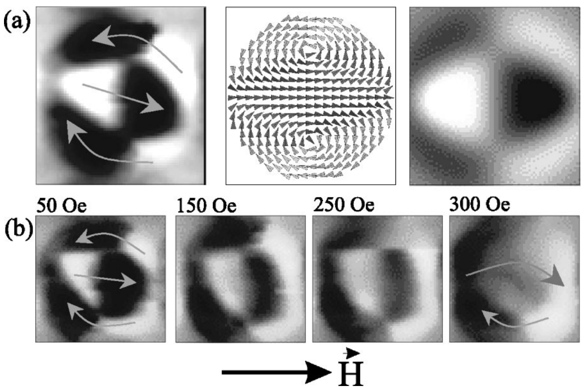

FIG. 4. (a) On the left, the MFM contrast corresponds to a double vortex state, observed in a 30-nm-thick and 1000-nm-large dot. In the center the simulated micromagnetic configuration is shown. On the right, the gray scale representation of the calculated divergence of the magnetization distribution corresponds to the micromagnetic configuration. (b) MFM images series under applied field showing the expulsion of one vortex.

trast is completely reversed. During the MFM observations, the stray field arising from the MFM tip, which acts as a small perturbation, can induce an irreversible transition of the SD state to the vortex state, which is the ground state of the system for these dot dimensions. Thus, even the shape of hysteresis loop did not indicate a reversal through vortex formation, in the MFM images, recorded for the same array at a lift scan height of 100 nm, about 30% of the total number of dots are in the vortex state. In order to diminish the influence of the magnetic tip, lift scan heights of 200 nm were used to investigate the reversal process in this case and the number of transitions to the vortex state is considerably reduced.

As a final point, we would like to address the formation of double vortices during the reversal of the magnetization for large dot diameters (1000 nm). The MFM images indicate that, during the reversal of the magnetization about 20% of total number of the investigated dots pass through a double-vortex state. The double-vortex configuration may be viewed as a multidomain structure where a central part is surrounded by two parts magnetized antiparallel to the central part, as shown by the micromagnetic calculations [Fig. 4(a)]. The magnetic contrast can be evaluated from the calculated micromagnetic configuration and is in good agreement with the MFM contrast. It is interesting to note that, for the same direction of the magnetization in the SD state and in the central part of the double-vortex state, the magnetic contrast appears reversed. This difference can be explained by the different distribution of the magnetic charges in the two cases. While the contrast in the SD state arises from the surface charges, the contrast of the double vortex is dominated by magnetic volume charges.

For a given dimension of the dots, the double-vortex state is energetically less favorable than a single-vortex state. The presence of two vortices contributes to an increase in the exchange energy while the flux closure maintains an almost unmodified magnetostatic energy. Again, as shown already for low thicknesses, we conclude that the system does not necessarily pass through its ground state. The stabilization of metastables states during the magnetization reversal arises primarily from the restrictions on the possible configurations imposed by the Zeeman energy term. Structural defects in the dot morphology can also contribute to trap a metastable state.

A further interesting point concerns the dynamics of the reversal mechanism through double-vortex state formation. Micromagnetic simulations[9] indicate that the two vortices are nucleated tilted with respect to the external field direction and these vortices rotate together with the central part as the field is reduced. Reversing the field, the central part expands and at a critical field one of the vortices is expelled [Fig. 4(b)].

In conclusion, we have shown by correlated MOKE and MFM studies that the magnetization reversal process in submicron circular Co dots can occur in a variety of ways including coherent rotation, single-vortex, and double-vortex nucleation and annihilation. Coherent rotation dominates for thicknesses below 20 nm while vortex nucleation occurs for larger thicknesses. A double-vortex formation is found in dots with 1000 nm diameter.

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