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Remanent state studies of elliptical magnetic particles

Alexander Alexeev[a,*], V.A. Bykov[a], A.F. Popkov[a], N.I. Polushkin[b], V.I. Korneev[c]

[a] *NT-MDT Co, State Research Institute of Physical Problems, Moscow 124460, Russia*
[b] *Institute of Microstructure Physics, Russian Academy of Science, Nizhnii Novgorod 603950, Russia*
[c] *Moscow Institute of Electronic Engineering (Technological University), Moscow 124482, Russia*

Abstract

Magnetization configurations in an elliptical ferromagnetic particle with sizes $0.6 \times 0.3 \times 0.015\,\mu m^3$ are simulated. Starting at the saturated state along the particle's long axis and magnetizing the particle along its short axis, we have obtained a new skew-symmetric state at remanence with pinning of the magnetization at the particle's edges. Such a non-uniform state precedes a single-vortex one which can be achieved by two passes across zero field. These results are found to be in agreement with those obtained from our magnetic force microscopy observations of the magnetization in patterned Fe–Cr particles.

Keywords: Magnetic particle; Micromagnetic simulations; Remanent states; Magnetization reversal; Magnetic force microscopy

In recent years a progress in thin-film technology and fabrication of nano-size devices stimulated numerous studies of micromagnetism in magnetic nanostructures and patterned magnetic dots [1–4]. In particular, it is argued [4,5] that in the magnetization processes of nanoscale elements the effect of edge pinning plays a key role. This can modify essentially the features of magnetization reversal, namely, can result in the occurrence of multiple modes and finally in the giant instability of switching fields associated with the thermally induced changes of the magnetization reversal mode near the saturation state [5].

The use of the elements, which have non-rectangular shapes and sharp edges, is believed to be one of the possible ways for suppressing this instability. At least, the formation of alternative magnetization configurations associated with the spin pinning near the narrow poles of a magnetized particle is not highly probable. In this study we report the results of our simulation of the remanent states in the particles with elliptical shapes and submicron lateral dimensions. Also, some experimental data on magnetic force microscopy (MFM) studies of laser-patterned $Fe_{0.7}Cr_{0.3}$ elements [6] are presented.

Magnetization reversal processes are numerically modeled by integrating the Landau–Lifshitz equations with the free boundary conditions. The results of the calculations presented here are for an ellipse-like particle that has the 0.6-μm long axis, the 0.3-μm short axis, a thickness of 0.015 μm, zero crystalline anisotropy, the saturation magnetization of 1300 G, which is typical of $Fe_{0.7}Cr_{0.3}$ alloys, and an exchange constant $A = 10^{-6}$ erg/cm.

Our simulation of magnetization reversal along the easy direction (parallel to the 0.6-μm dimension) indicates that the major hysteresis loop has a rectangular shape with the switching field of $H_{c1} = 300$ Oe. The remanent state corresponds to a full magnetic polarization of the particle along the easy direction as shown in Fig. 1a. Starting at this saturated state, we follow changes in the magnetization at applied external magnetic field along the hard direction of magnetization (parallel to the 0.3-μm dimension). As the field is increased from zero, the magnetization initially rotates in central part of the particle; the magnetization along the particle's edges retains the memory of its direction at zero field up to the applied field of 600–700 Oe. This rotation of the magnetization is reversible: if the magnetic field is returned to zero, the magnetization returns to the state shown in Fig. 1a. When the applied

*Corresponding author.
E-mail address: alexander@ntmdt.ru (A. Alexeev).

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field exceeds the critical value, $H_{c2} = 950\,\mathrm{Oe}$, at which the particle is saturated in the hard direction, the initial polarization is not restored. Note that the pinning of the magnetization at the particle's edges delays the transition to the saturated state, and the critical value is greater than that deduced from the Stoner and Wohlfarth's model for uniform magnetization rotation [7].

As the applied field decreases from the saturation state to zero, magnetic moments in the central part have a tendency to rotate for alignment with the long axis, so a skew-symmetric state is formed at zero field (Fig. 1b). With changing the sign of the field such a skew-symmetric state remains up to the field $H_{c3} = -50\,\mathrm{Oe}$, above which a new two-vortex state arises [8]. When the negative field returns to zero the latter state transforms into a demagnetized state with two vortices located at the corners of the diamond-shaped domain in the central part. If we start at the two-vortex remanent state and the field is again increasing in the hard direction, the vortices are gradually expelled from the particle at the field exceeding $H_{c4} = 1650\,\mathrm{Oe}$. Before the magnetization becomes saturated ($H < H_{c4}$) we mark the transition to a more stable, asymmetric one-vortex state, which turns into a symmetric demagnetized state with a single vortex at particle's center at zero field (Fig. 1c).

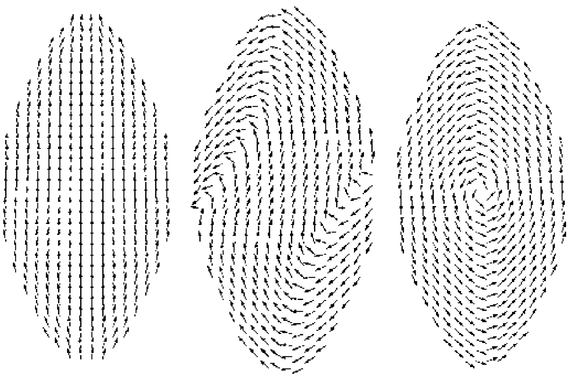

Fig. 1. Remanent magnetization states of an elliptical magnetic particle with sizes $0.6 \times 0.3 \times 0.15\,\mu\mathrm{m}^3$. Magnetization: (a) uniformly magnetized state along the long axis, (b) vortex-free state with skew-symmetric spin pinning and (c) one-vortex state.

To compare these results of our modeling with the experimental MFM data, we have calculated the MFM images of the magnetization configurations in Fig. 1. This simulation has been performed under the assumption that the MFM tip is a point dipole and interacts with a sample by its stray fields [8]. The simulated MFM signals were treated as cantilever's resonance frequency shifts for the tip-sample distance $z = 0.1\,\mu\mathrm{m}$, and the calculated images are given in Fig. 2.

Experimental MFM measurements were done on a Solver P47 scanning probe microscope (NT MDT, Moscow). As the samples in these experiments we used the submicron ferromagnetic regions directly patterned in a (super)paramagnetic Fe–Cr layer by interfering laser beams [6]. Fig. 3 shows topographic (a,c,e) and MFM (b,d,f) images of the patterned regions. Topographic images demonstrate the laser-induced surface modifications with elliptical shapes. These modifications correspond to the pronounced MFM contrast. A uniformly polarized remanent state obtained by saturating the regions along their long axes is shown in Fig. 3b. A vortex-free state with skew-symmetric spin pinning was obtained experimentally by magnetizing the regions by using an external magnetic field directed along the short axes (Fig. 3d). As a result of a two-time pass across zero field, a one-vortex remanent state was also observed (Fig. 3f).

In conclusion, we have investigated both theoretically and experimentally the micromagnetic properties of a submicron ($0.6 \times 0.3 \times 0.015\,\mu\mathrm{m}^3$) ferromagnetic particle with elliptical shape. By solving the magnetodynamics equations, it is argued that different remanent states can

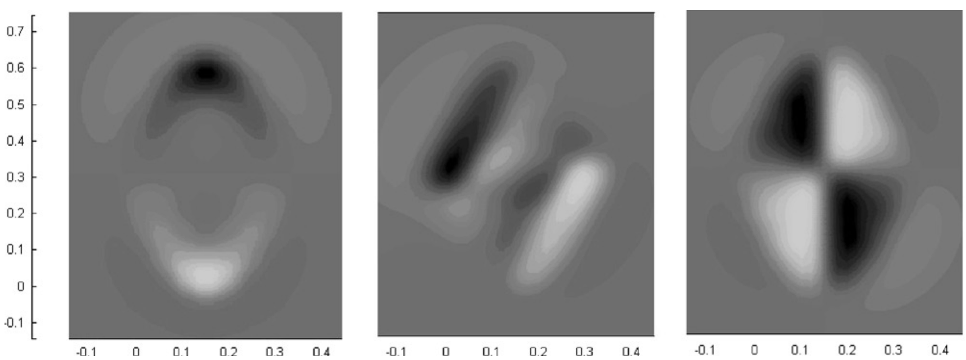

Fig. 2. Calculated MFM images of remanent configurations shown in Fig. 1: (a) fully polarized particle, (b) skew-symmetric state and (c) one-vortex state.

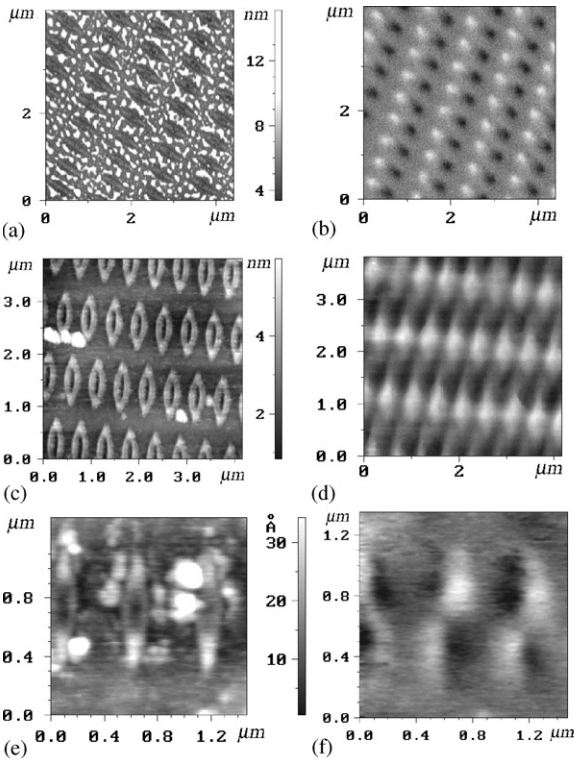

Fig. 3. Topography and MFM images of the patterned regions in Fe–Cr layers: (a), (c), (e) show topography of the patterned regions; (b), (d), (f) are the corresponding MFM images.

be obtained. When the particle is saturated along its long axis, a uniformly magnetized state persists at remanence. Starting at this state and magnetizing the particle along its short axis up to saturation, we obtain a non-uniform skew-symmetric remanent state which is free of vortices. This non-uniform state results from pinning of the magnetization at the particle's edges. In order to achieve the vortex remanent states, the negative field has to be applied. The results of our simulation are compared with those of experimental studies of patterned ferromagnetic regions in Fe–Cr layers. This comparison shows a good agreement between the theoretical and experimental data.

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