MFM probe control of magnetic vortex chirality in elliptical Co nanoparticles


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Abstract

Magnetic force microscopy (MFM) methods were applied to investigate the peculiarities of magnetization distribution in elliptical 400 × 600 × 27 nm Co particles. Reversible transitions between the uniform and vortex states under inhomogeneous magnetic field of MFM probe were observed. Possibility to control the chirality of a magnetic vortex in these particles by MFM probe manipulation was shown.

Keywords: Magnetic vortex; Magnetic nanoparticle; Magnetic force microscopy; Micromagnetic calculation

Investigation of ferromagnetic nanoparticle arrays is of great interest due to their possible applications as sources of an inhomogeneous magnetic field and as a recording medium (see, Ref. [1]). In this connection much attention has been focused in recent years on study of the magnetic states in nanoparticles by the magnetic force microscopy (MFM) methods and remagnetization processes directly under the magnetic field of the MFM probe [2–8]. MFM probe effects on the magnetic states of ferromagnetic nanoparticles of different shape were discussed in Refs. [6–8], but the efforts were basically concentrated on study of the magnetization reversal of uniform states. In this article we discuss MFM probe-induced transitions between the vortex state (VS) and the uniform state (US) in elliptical Co nanoparticles, which demonstrate a possibility to control the magnetic vortex chirality. A method to create VS with a definite orientation of the magnetic vortex (clockwise VS+ or counterclockwise VS−) under magnetizing in a homogeneous external field was suggested in Ref. [9]. To enhance the probability of vortex nucleation with selected orientation, authors used the factor of asymmetric particle shape. Here we propose a different approach based on a possibility to control the chirality in symmetric elliptic particles by means of two-stage VS+⇒US⇒VS− processes in the inhomogeneous magnetic field of the MFM probe.

The arrays of elliptical particles were fabricated by the E-beam lithography and subsequent ion etching of thin Co films prepared by magnetron sputtering on the silicon substrates [10]. AFM measurements showed that the surface roughness of Co films did not exceed 1 nm. The distribution of remanent magnetization and processes of local remagnetization were studied using a multimode SPM “Solver P7LS”. The MFM probes had a Co coating with the thickness in the range of 30–60 nm. The tips were magnetized before measurements along symmetry axes (Z) in 10^4 Oe external magnetic field. MFM measurements were performed in the noncontact constant height mode. Scanning height parameters for MFM imaging and for remagnetization procedure were optimized experimentally.

As it is well known, both US and VS can be realized in ferromagnetic small particles depending on a ratio of lateral sizes and height [11]. In our experiments we used arrays of elliptical Co particles with lateral sizes 400 × 600 nm. Micromagnetic modeling [12] and MFM
measurements show that for these particles there is a characteristic height \( h^* \) about 25 nm, which separates the regions of US and VS stability. When the height of particle \( h > h^* \), US is getting unstable and VS is realized in the particles [13]. For remagnetization experiments 400 × 600 × 27 nm (height slightly more than \( h^* \)) particles array were fabricated. The MFM image of Co particles array (Fig. 1) indicates that the remanent magnetic state of the particles corresponds to VS with different chirality. Indeed symmetry of MFM images for elliptical vortexes is unambiguously defined by vortex chirality. The magnetization distribution and corresponding MFM contrast calculated for VS+ and VS− are presented in Fig. 2(a–d). The typical black–white poles symmetry of the MFM images for elliptical vortex corresponds to quadrupole magnetic moment of magnetization distribution [4,5].

We performed some experiments directed on MFM tip-induced changing of VS chirality by special probe manipulations. The main idea was to use magnetic field of MFM probe for realization of VS+ (or VS−) → US transition between close energy states for uniform distribution preparation and subsequent US → VS− (or VS+) transition by tip-induced asymmetric magnetic disturbance of US state to create VS with definite chirality. The results of experiments, which illustrated chirality switching by the VS+ → US → VS− process, are presented in Fig. 3(a–c). The MFM image of initial state (Fig. 3(a)) was obtained in constant height mode with scanning height \( h_s \) about 50 nm. As it is clearly seen the initial state of the central particle (indicated by dash line in Fig. 3(a)) corresponds to the clockwise orientation of vortex (compare with Fig. 2(c)). The next image (Fig. 3(b)) was obtained in the following way. At the first stage, scanning was performed in the constant height mode with distance between probe and particles of about 50 nm. When the probe passed over the central particle, the scanning height was reduced to \( h_s = 15 \) nm in the scan line indicated by number 1 (Fig. 3(b)), whereupon the probe was lifted on 50 nm height again (see inset in Fig. 3(b)). The VS+ → US transition was registered as the sharp appearance of dipolar MFM contrast. Afterwards, when the probe reached the line indicated by number 2, scanning height was reduced to 15 nm again and US → VS− transition was observed. At last the constant height MFM image of final state with the counterclockwise vortex orientation in central particle is presented in Fig. 3(c).

We performed computer micromagnetic simulations to describe the remagnetization processes, which were observed under MFM probe manipulations. In calculations the MFM probe was approximated as a single dipole [14,15] with effective magnetic moment \( \mathbf{m}_{\text{eff}} = M_s \mathbf{V}_{\text{eff}} \) (\( M_s \) is the remanent magnetization of capping material, \( \mathbf{V}_{\text{eff}} \) the effective volume of the interactive part of magnetic layer). In calculation we used typical values \( M_s = 1400 \) Oe, \( \mathbf{V}_{\text{eff}} = 1.25 \times 10^{-5} \) nm³ and scanning height 15 nm. Stationary solutions of the Landau–Lifshits–Gilbert equations corresponding to the equilibrium distribution of magnetization have been found for the particles in the presence of inhomogeneous MFM tip field.

The vortex state VS+ was the initial state in calculations. When the probe moves along the central part of a particle, the vortex shifts to the edge (Fig. 4(a,b)) and is annihilated, so a uniform magnetization distribution appears in the area behind the probe (Fig. 4(c,d)). This effect is observed apparently on the line 1 as sharp dipolar contrast formation (Fig. 3(b)).

The symmetry of US distribution can be destroyed by scanning near the particle edge. Formation of VS in this case is defined by symmetry of the probe magnetic field and probe location near the particle. The US → VS− process is illustrated in Fig. 5(a–d). At the first stage, when the probe approaches the particle (Fig. 5(a)), chirality of magnetization distribution with direction defined by the MFM probe field is appeared. Indeed, estimation on the base of the Landau–Lifshits–Gilbert equation shows that the volume averaged \( Z \) component of chirality for the initial stage is described by the following expression:

\[
\left\langle \frac{d}{dt} (\mathbf{rot} \, \mathbf{M}_\infty) \right\rangle_z = x \frac{\partial H_x}{\partial y},
\]

where \( \mathbf{M}_\infty \) is the perturbation of magnetization distribution relative to US, \( x \) the damping constant, volume averaging is indicated as \( \langle \cdot \rangle \). As clearly seen, the averaged \( Z \) component of chirality for the initial stage is determined by inhomogeneity of the \( x \) component of the MFM probe field. From this point of view, the situation presented in Fig. 5(a) corresponds to the vortex nucleation with the counterclockwise orientation. At the next move of the probe a characteristic fold of magnetization is formed near

Fig. 1. Constant height mode MFM image of the Co particles array. Frame size are 4 × 4 μm.
the particle boundary (indicated by arrow in Fig. 5(b)).
The magnetic vortex is nucleated in this fold as shown in
Fig. 5(c). After nucleation, the vortex shifts quickly to the
center of particle while the probe go out. The similar
US $\Rightarrow$ VS$^-$ effect is observed apparently on the line number
2 (see Fig. 3(b)) when dipolar contrast is changed into
contrast corresponding to VS$^-$.

The modeling results show that the chirality direction in
the US $\Rightarrow$ VS process is determined by the position of
probe relative to particle. According to the situation
presented in Fig. 5, if the probe is moved along the top
dege of particle, a vortex with the counterclockwise
orientation is nucleated. In the opposite case, when the
probe is moved along the bottom region of particle, vortex
nucleation with the clockwise orientation is observed.

It seems, that for elliptical particles with small lateral
sizes one-stage process of chirality changing is possible.

The vortex annihilation and subsequent nucleation can be
realized by single asymmetric passing over particle. In this
case the MFM probes with high magnetic moment, that
extremely perturb particle magnetization, should be used.
The same one-stage process should be observed if the
MFM tip traverses the elliptical particle in parallel with
short axis. The asymmetry in particle shape and in probe
passing is very important. For instance, one-pass MFM tip
induced chirality changing in circle particles is impossible
since any position of probe around particle is symmetric
and vortex nucleation with right or left orientation will be
realized in a random way. But of course, one stage
processes need further theoretical and experimental in-
vestigations.

In conclusion, our MFM experiments and micromag-
netic simulation show that the magnetic field of the MFM
probe can change the magnetic configuration within
Fig. 4. The transition $V^+ \rightarrow U$ under MFM probe movement. Probe position is indicated by black circle. Scanning direction is shown by arrow.

Fig. 5. The transition $U \rightarrow V^-$ under MFM probe movement. Probe position is indicated by black circle. Scanning direction is shown by arrow.
ferromagnetic nanoparticles. The character of the remagnetization processes depends on particle geometry (thickness and aspect ratio), the magnetic moment of the probe, the probe position relative to the particle and the height during scanning. The MFM probe induced vortex chirality changing in elliptical $400 \times 600 \times 27 \text{nm}$ Co particles by two stage $VS \Rightarrow US \Rightarrow VS$ transitions was demonstrated.

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References

[12] (http://math.nist.gov/oommf/)