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Magnetic force microscopy and simulation studies on $Co_{50}Fe_{50}$ elliptical nanomagnets

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Abstract. **We studied the magnetization reversal mechanism of single-layered $Co_{50}Fe_{50}$ nanomagnets by measuring the magnetization reversal and using the micromagnetic simulations. The magnetization reversal strongly depends on the thickness of the nanomagnets. In the remanent state, the magnetic force microscopy studies and the simulation data showed the formation of single and vortex states depending on the thickness of nanomagnets.**

Keywords. **Magnetic nanostructures; micromagnetic simulations; magnetic force microscopy; magnetization reversal; magnetic domains.**

1. Introduction

The study of small magnetic features and nanostructures is interesting because of their technological applications in magnetic data storage and fundamental research in magnetism. The study of these arrays of nanoelements is the basis for the development of magnetic memories and nanopatterned recording media [1,2]. In low-dimensional magnetic nanostructures, the magnetic properties strongly depend on the shape and size [1–10]. Apart from patterning (varying the size and shape), the magnetic properties of nanostructures can be considerably modified by different types of interactions with other magnetic materials.

For the characterization of magnetic nanostructures, visualization with greatest resolution is important. Among the visualization techniques, magnetic force microscopy (MFM) has become a powerful tool to see the submicron-sized domains and also to understand the magnetic behaviour of thin films and nanostructures. This is mainly due to its ease of use without any specific sample preparation and high lateral resolution of few 10 nm.

In this paper, we discuss the work on elliptical $Co_{50}Fe_{50}$ magnetic nanostructures. The formation of magnetic domains in the remanent state is explained by imaging the magnetic domains using MFM and capturing the domain orientation in micromagnetic simulations.

2. Experimental

The elliptical patterned nanostructures were fabricated on commercially available Si substrates using deep ultraviolet lithography at 248 nm wavelength. The details of the fabrication process are discussed in ref. [11]. The two dimensional (2D) $Co_{50}Fe_{50}$ films with thicknesses of 10 and 60 nm were deposited using electron beam evaporation technique. The films were deposited with a base pressure of 1×10^{-7} torr at a rate of 0.4 Å s^{-1}. During film deposition, a blank Si substrate was placed in the chamber and used as the reference film. To prevent the oxidation of magnetic layers, the films were capped with a 5 nm Cu layer. After depositing the film, the samples are ultrasonically agitated in a resist thinner (OK73) to remove the unexposed resist to the radiation.

The nanostructures are uniform and identical over a very large area. Their major and minor axes are 335 and 225 nm, respectively, and the separations between the nanostructures along the major and minor axes are 290 and 150 nm, respectively. Magnetization measurements were performed using vibrating sample magnetometer. The nanomagnets were first magnetized along the major axis and the magnetization loop was recorded while decreasing the field to zero and increasing in the opposite direction. Magnetic domain structure of nanomagnets was observed using MFM. For MFM measurements, the nanomagnets were completely magnetized along the major axis and the pictures were recorded in zero magnetic field.

2.1 *Simulation details*

To understand the magnetization reversal process in nanomagnets, micromagnetic simulations were carried out by using object oriented micromagnetic framework (OOMMF) code from the National Institute of Standards and Technology [12]. The material parameters used in the simulations are saturation magnetization $M_S = 1.9 \times 10^6$ A m^{-1}, exchange

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constant $A = 3 \times 10^{-11}$ J m^{-1} and anisotropy constant $K_1 = 0$ J m^{-3} [13,14]. The size of the unit cell used is 5 nm. During simulation, the magnetization was measured first by saturating the nanomagnets along the major axis in the negative field direction. The output of the simulation gives the normalized magnetization to compare it with the experiment, normalized magnetization is presented for experiment.

3. Results and discussions

Figure 1a and b shows the magnetization variation of 2D array 10 and 60 nm nanomagnets. The magnetization was measured by first saturating the nanomagnets along the major axis in the negative field direction. The magnetization reversal is sensitive to the thickness. The saturation magnetic field is high for 60 nm and remanence is high for 10 nm nanomagnets. The characteristic magnetization reversal process is dominated by coherent rotation in the 10 nm nanomagnets makes it high remanent [15]. The 60 nm nanomagnets showed an interesting behaviour in the hysteresis loop. The different stages of magnetization in the 60 nm are shown in figure 1b. When the field is increased from negative saturation to positive saturation at H_n nucleation of the vortex states takes place and the magnetization decreases rapidly from H_n to H_1. At H_1, complete formation of vortex state takes place and vortex moves inside the ellipse when the field is changed from H_1 to H_2 and at H_a annihilation of the vortex occurs.

OOMMF simulations were carried out on 2D elliptical nanomagnets. We assumed that the intrinsic uniaxial anisotropy of the bulk $Co_{50}Fe_{50}$ film is negligible when compared with the shape-induced anisotropy of the nanomagnets. The shape of the ellipse in the simulations was based on the mask prepared from scanning electron microscope (SEM) image. During simulation, the magnetization was measured first by saturating the nanomagnets along the major axis in the negative field direction. Figure 2a and b shows the generated curves of magnetization in simulations. The variation of magnetization is similar to that of the experimental data. The small variations could be due to the thermal fluctuations, magnetostatic interactions between the neighbouring nanomagnets and the switching field distribution [16]. To understand the thickness dependence of magnetization, the remanent state magnetizations were captured. Figure 2a and b also shows the captured remanent state of nanomagnets. The 10 nm nanomagnet shows the formation of single domains and the 60 nm shows the formation of vortex states.

To verify the simulation data of the remanent states of magnetization, MFM studies were done on nanomagnets. Figures 3 and 4 show the atomic force microscopy (AFM) and MFM pictures of 10 and 60 nm nanomagnets, respectively. Before taking the MFM images, the nanomagnets

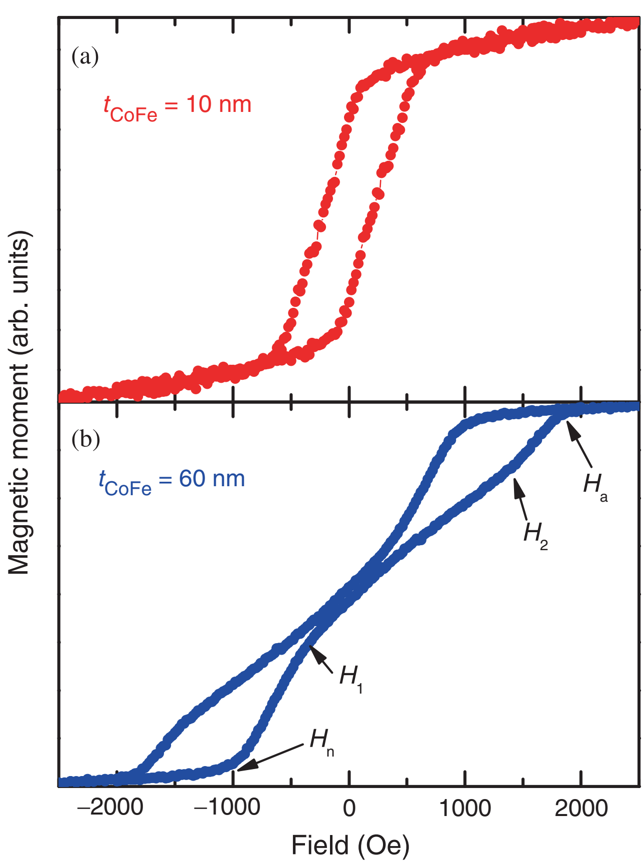

Figure 1. Variation of magnetization of $Co_{50}Fe_{50}$ elliptical nanomagnets of thickness (**a**) 10 and (**b**) 60 nm.

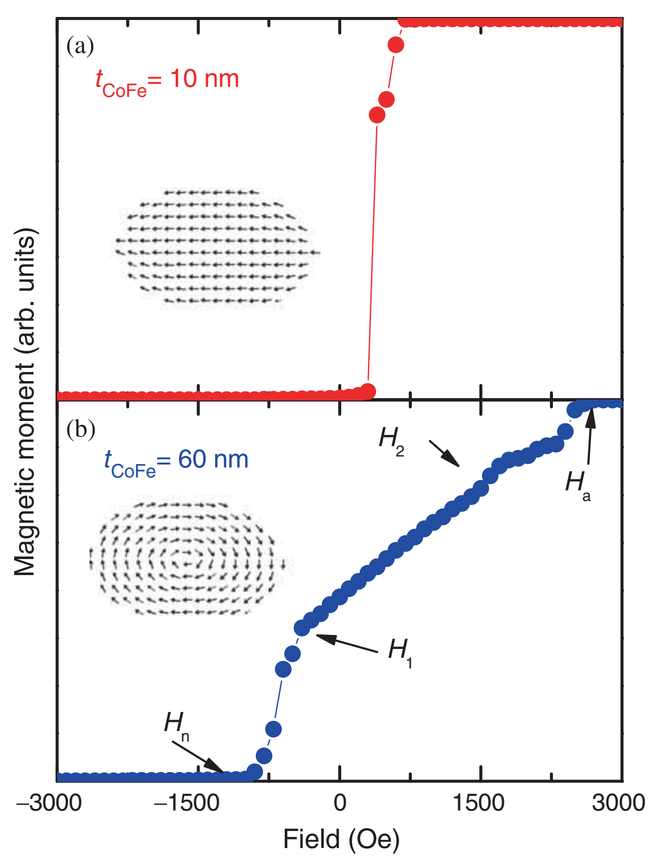

Figure 2. Simulation study of $Co_{50}Fe_{50}$ elliptical nanomagnets of thickness (**a**) 10 and (**b**) 60 nm.

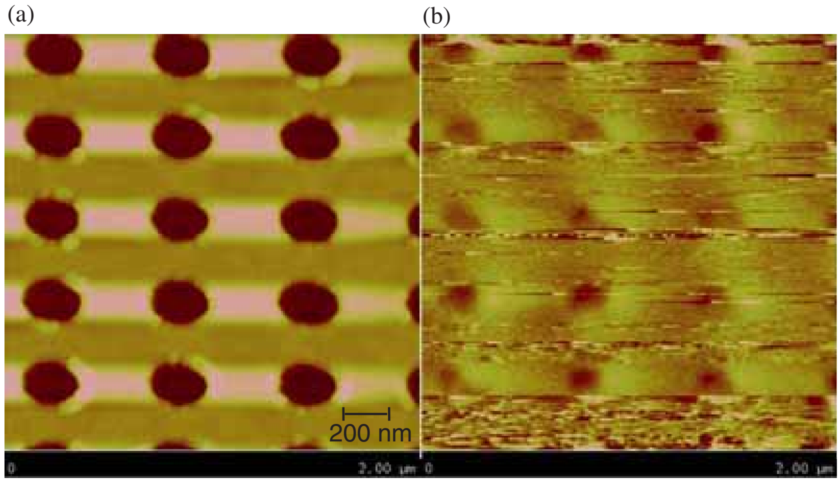

Figure 3. (**a**) AFM and (**b**) MFM pictures of $Co_{50}Fe_{50}$ nanomagnets of thickness 10 nm.

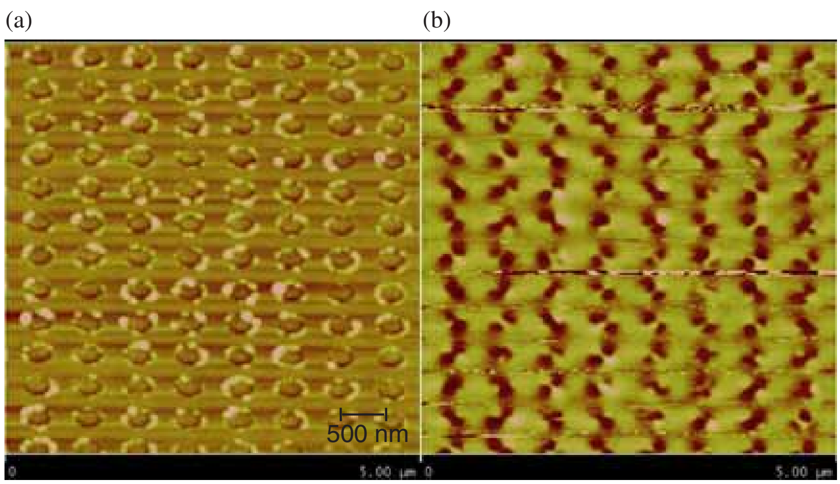

Figure 4. (**a**) AFM and (**b**) MFM pictures of $Co_{50}Fe_{50}$ nanomagnets of thickness 60 nm.

were completely magnetized along the major axis by applying a field of 2000 Oe and then reduced the field to 0 Oe. Figures 3a and 4a show the AFM images of the 2D patterned array of $Co_{50}Fe_{50}$ elliptical nanostructures. By comparing the AFM and MFM images, it is clear that the topography and magnetic contrast are well separated. The MFM image of the 10 nm nanomagnets shows the formation of single domains in the remanent state (figure 3b). The simulation study on 2D 10 nm nanomagnets also reveals the formation of the single domain state at zero fields (figure 2a). The MFM image in figure 4b of 60 nm nanomagnets shows the alternate bright and dark areas indicating the formation of the vortex in demagnetized state. This configuration minimizes the magnetostatic energy. Simulation study also confirms the formation of the vortex state for 60 nm nanomagnet. Similar type of MFM images were reported for permalloy circular nanostructures [17]. The simulation studies indicate the formation of vortex state.

4. Conclusions

Magnetization study on 2D array of $Co_{50}Fe_{50}$ elliptical nanomagnets of thickness 10 and 60 nm were carried out systematically by measuring magnetization, by doing micromagnetic simulation and by imaging the domains in the remanent state using MFM. The simulation and experimental data are very well coincide with each other. The MFM images showed the formation of single domains for 10 nm and vortex states for 60 nm thick nanomagnets. The images captured in simulation are also showing the same for the respective nanomagnets.

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