

Investigation of the domain structure transformation under mechanical deformations in permalloy microparticles

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Abstract. Using magnetic force microscopy (MFM) and computer simulation it was shown that the mechanical compression of the permalloy microparticles leads to the increase in the effective anisotropy field and the noticeable decrease in the external magnetic field value necessary for the formation of the uniform magnetization in the compressed particle. The analysis of MFM images of microparticles covering the whole substrate surface made it possible to conclude about the uniform or nonuniform distribution of stresses induced in the particles in the different area of the substrate.

1. Introduction

At present the processes occurring in magnetic media under various external impacts are studied intensively [1]. This is associated with the fact that mechanical stress can decrease significantly the energy of one bit writing in magnetic data storage media. The study of processes of the magnetic anisotropy variation in the magnetostriction layer under the mechanical deformation and the possibility of using these processes to fabricate logic gates for micro- and nanoelectronics with the extremely low energy consumption led to the appearance of a new field of science – straintronics [2]. In addition, the Villari effect (the change of magnetic properties of the material under mechanical stress) can be used for the visualization of mechanical stress, since in the first approximation the induced magnetic anisotropy is proportional to the stress tensor [3].

Recently using magnetic force microscopy (MFM) we found out that the domain structure of square permalloy (Py) microparticles changes noticeably due to the mechanical compression [4, 5]. Here this effect is used for estimating the uniformity rate of the induced stress distribution in the particles covering the preliminarily bent substrate after straightening. In addition, the effect of mechanical compression on the formation of the uniform magnetization in Py microparticles under the external magnetic field is studied using MFM.

2. Results and discussion

Square Py microparticles with dimensions of $25 \times 25 \times 0.03 \mu\text{m}^3$ and $7 \times 7 \times 0.03 \mu\text{m}^3$ were formed for the studies on hard substrates. Particles were fabricated using the electron beam Py target evaporation through the grid with the appropriate hole size. The Py (Ni 75%, Fe 25%) layer with the thickness of 30 nm was deposited in ultrahigh vacuum. A Multiprobe P (Omicron) device was used for the sample preparation.



Particles with dimensions of $7 \times 7 \times 0.03 \mu\text{m}^3$ were fabricated on the Si substrate with dimensions of $10 \times 5 \times 0.35 \text{ mm}^3$. Samples with unstressed particles and samples with uniformly stressed particles along one of the substrate axis were fabricated. Uniformly stressed samples were prepared using a special method. At first the Si substrate was bent elastically in a special holder (figure 1f) prior to the Py target evaporation. The constant curvature radius of the holder makes it possible to strain the substrate uniformly during the Py deposition. After the deposition, sample was extracted from the holder, the substrate was unbent and particles were compressed uniformly on the substrate surface along one of the axis. MFM measurements of the fabricated Py particle array were carried out by Solver P47 Pro (NT-MDT) scanning probe microscope (SPM) using N18/Co-Cr (MikroScience) magnetic cantilevers. The magnet integrated to SPM gave the possibility to vary the magnetic field in the plane of the sample up to 200 Oe.

According to MFM measurements, unstressed particles had the four-domain magnetic structure with single-size domains (figure 1a). Stressed particles also had the four-domain structure. However, domains with the magnetization perpendicular to the direction of the compression were larger than those with the magnetization parallel to the direction of the compression (figure 1d). The characteristic bridge was formed between two large domains. According to our studies, the length of the bridge depends on the mechanical stress value in the particle and it can be used as a parameter to characterize the compression rate [4, 5]. MFM measurements of the stressed sample showed that almost all microparticles had the bridge with the same size (figure 1d). It indicates the uniformity of the particle compression over the sample.

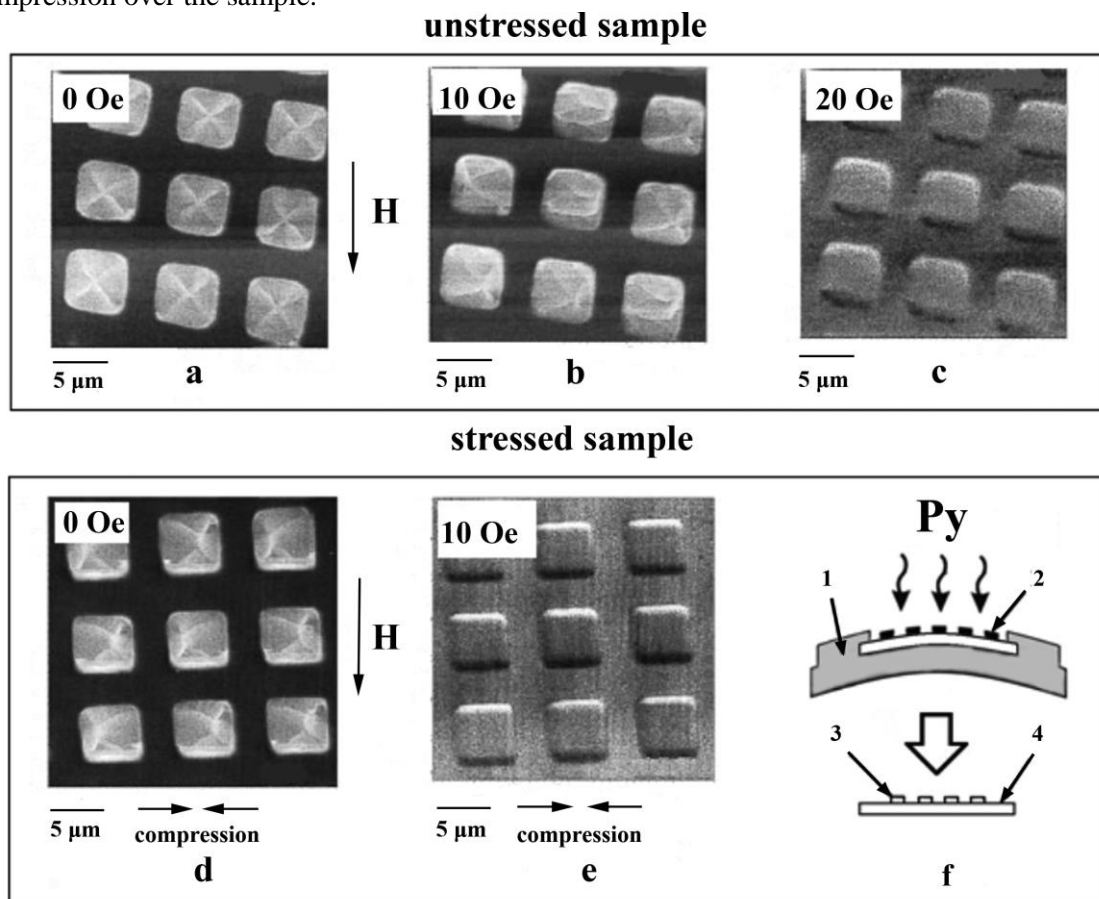


Figure 1. MFM scans of unstressed Py particles with dimensions of $7 \times 7 \times 0.03 \mu\text{m}^3$ in the external magnetic field: a) 0, b) 10, c) 20 Oe. MFM scans of stressed Py particles with dimensions of $7 \times 7 \times 0.03 \mu\text{m}^3$ in the external magnetic field: d) 0, e) 10 Oe. Scheme of the preparation of a stressed sample – f (1 – holders; 2 – metal grid; 3 – Py microparticles, 4 – Si substrate).

The formation of the uniform magnetization in uncompressed and compressed microparticles with dimensions of $7 \times 7 \times 0.03 \mu\text{m}^3$ in the external magnetic field applied in the plane of the sample surface was studied using an SPM with the integrated magnet (figure 1b, c, e). When the uniform magnetization state is formed in microparticles, the domain walls vanish and their MFM images have the characteristic shape owing to the formation of two magnetic poles on opposite sides of microparticles (figure 1c, e). The experiments showed that the uniform magnetization state is formed in the field of 10 Oe for compressed particles, while for uncompressed particles this field is twice as large (figure 1c, e). This result is in agreement with result [6], where it was shown that the combination of the mechanically induced stress and magnetic field makes it possible to form the uniform magnetization in the given direction in ferromagnetic microparticle. This effect can be used for straintronics magnetic data storage [2].

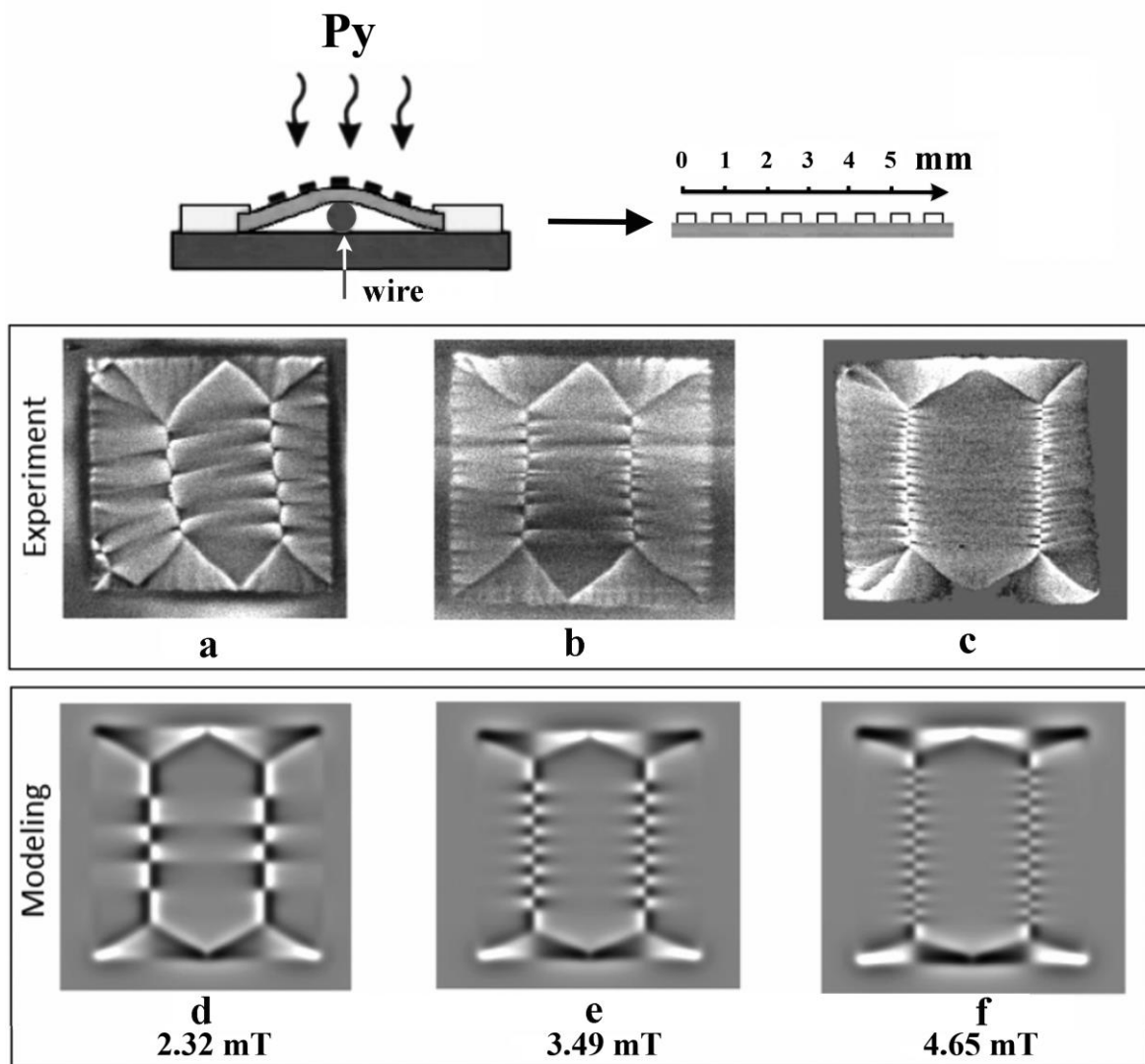


Figure 2. Scheme of the preparation of the wire-stressed sample (top), MFM scans of Py particles with dimensions of $25 \times 25 \times 0.03 \mu\text{m}^3$ on different substrate regions (bottom). Experimental: a) 0.1 mm from the substrate edge, b) 1.6 mm from the substrate edge, c) 2.6 mm from the substrate edge (sample center). Modelling: d, e, f. Corresponding effective anisotropy fields H_{eff} (2.32, 3.49 and 4.65 mT) for each particle used for the simulation.

Py microparticles with dimensions of $25 \times 25 \times 0.03 \mu\text{m}^3$ were fabricated on the 0.30 mm thick glass surface. Using glass substrates and their nonuniform bending ability made it possible to fabricate samples with the elastic stress gradient increasing from the edge to the center of the substrate (analogously to [3], where the same technique was used for preparing mechanically stressed ferromagnetic films). The substrate was bent elastically in a holder by the $80 \mu\text{m}$ diameter wire placed under it prior to the Py deposition (figure 2). The particles were compressed uniaxially with the rate different for different places of the sample after straightening of the substrate.

MFM scans of stressed particles made it possible to establish that they have a seven-domain structure, which depends on the position of the particle on the substrate (figure 2a– c). Computer simulation was used to estimate the value of the induced magnetoelastic anisotropy in particles and its dependence on the location on the substrate. At the first stage, the magnetization distribution was calculated using the OOMMF program [7]. Topography scans of the particle obtained during MFM measurements were used in calculations. The effective anisotropy field H_{eff} was set as a variable parameter. At the second stage, the MFM scan of the particle was simulated by the “Virtual magnetic force microscope” program [8] using the magnetization distribution obtained with the OOMMF program. The parameter H_{eff} was varied until simulated and experimental MFM scans coincided.

The value of the effective anisotropy field of Py microparticles was estimated as a function of the mechanical stress by simulation their MFM images (figure 2). It was shown that the effective anisotropy field in wire-stressed samples increases in comparison with that in unstressed samples. Owing to the nonuniform distribution of the stress tensor the H_{eff} value of the particles increases from 2.32mT (the least compressed particles) on the edge of the sample to 4.65mT (the most compressed particles) in the sample center.

3. Conclusions

Using MFM measurements and computer simulation it was shown that the mechanical compression of the Py microparticles results in the increase in its effective anisotropy field. The redistribution of the particle magnetization is caused by the change of the H_{eff} value of the particle and depends on the stress tensor of the substrate in place where the particle is located. In general, when the substrate is stressed nonuniformly, MFM images of similar Py particles differ noticeably so it makes it possible to estimate the nonuniformity rate of stress induced in the substrate.

The mechanical compression of the permalloy microparticles leads to the noticeable decrease in the external magnetic field value necessary for the formation of the uniform magnetization in the compressed particle.

Acknowledgments

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