Investigation by MOKE and MFM of the domain structure transformation under mechanical deformations in permalloy microparticles

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Abstract. In this work, the change in the domain structure of planar permalloy microparticles due to mechanical stress has been studied. For this purpose, an array of particles in a mechanically stressed state was formed on a silicon substrate. In addition, the samples with the array of particles without tension were manufactured. The magnetic structure of the samples was visualized by magnetic force microscopy and hysteresis loops were obtained using the magneto-optical Kerr effect. It was established that the easy magnetization axis collinear to the direction of mechanical stress appears in particles due to mechanical compression. The distribution of magnetization of unstrained particles is mainly determined by the shape anisotropy.

1. Introduction
The possibility of using the Villari effect (or the magnetoelastic effect, in which the magnetic properties of a solid change under the mechanical action) for the process of the magnetization reversal of micro- and nanostructures has been intensively studied [1-7]. Using this effect, it is possible to significantly change the value of the external magnetic field necessary for the magnetization reversal of an individual particle, which can be used as the information storage. In some cases, the process of the magnetization reversal of a particle can be performed only by its mechanical stretching or compression [3, 4]. A significant change in the magnetization of the particle due to the mechanical action can be used to detect mechanical stresses arising in the particle. In the case of planar particles located on a solid surface, the change in their magnetization makes it possible to detect mechanical stresses in the near-surface layer of the substrate.

It is possible to study the magnetic structure of an individual microparticle in detail using a magnetic force microscope (MFM). To observe the changes in the magnetic structure of an array of particles, which cover the surface uniformly, one can use the magneto-optical Kerr effect (MOKE). In this paper, these two methods were used to study the magnetic properties of planar permalloy (Py) microparticles as a function of the external mechanical stress created in them.

2. Sample preparation
The study was carried out on samples being arrays of planar Py particles placed on the Si substrate with linear dimensions of $12 \times 3 \times 0.4$ mm$^3$. The permalloy composition was 79\% Ni, 16\% Fe and 4\% Mo. Each particle had dimensions of $7.5 \times 7.5 \times 0.03$ $\mu$m$^3$. The distance between particles was 5 $\mu$m. Using the
Si substrate doped with phosphorus makes it possible to avoid the accumulation of the electrostatic charge, which interferes with the MFM measurements. As described in our previous work [3], sputtering of permalloy through the metal mesh pressed to the substrate was used to produce an array of identical particles. Sputtering was carried out by electron beam evaporation of a solid Py rod in ultrahigh vacuum on an Omicron Multiprobe P setup.

Two types of samples were manufactured: samples with non-stressed particles and the samples with particles compressed along the long axis of the substrate. To create mechanical stress, the substrate was bent elastically in a sample holder prior to the permalloy deposition. The mesh was fixed in such a way that one of the sides of the square particle was parallel to the axis of compression. The measurements showed that mechanical stresses created in the particles remain constant for a long time (about several months), which makes it possible to study the sample by various methods. The process of substrate bending is often used to create stresses in thin ferromagnetic films or particles [2, 6, 7]. The size and shape of particles in the different parts of the sample was controlled by atomic force and optical microscopy. According to the measurements, the size and shape of the particles was the same throughout the entire sample. The uniformity control of the particles was important for carrying out MOKE measurements, when a signal from an array of particles is recorded simultaneously.

3. MOKE experiments

A scanning magneto-polarimetric (MOKE) setup based on an LEFT-3M-1 ellipsometer was used to record the hysteresis loops of the array of Py particles. The samples under investigation were rotated in the MOKE setup in the plane of the sample surface with a step of 5 degrees.

![Figure 1](image.png)

**Figure 1.** Hysteresis loops obtained by the MOKE technique for non-stressed (solid lines) and stressed (dashed lines) particles with the direction of the external magnetic field along the easy axis (a) and along the hard axis (b). The angular dependences of the normalized remanent magnetization (c) and the coercive field of the particles (d)
The initial orientation of the sample was parallel to one of the sides of the square particle. In addition, in the case of strained sample, the initial orientation was parallel to the axis of compression. The hysteresis loop was recorded by the MOKE technique at each rotation position from the region of the size of about $10^{-2}$ mm$^2$ (figure 1a,b). Each point on the hysteresis loop is the result of averaging over 200 measurements. Based on the obtained hysteresis loops, the azimuthal dependences of the remanent magnetization of the sample (figure 1c) and the coercive field of the particles were calculated (figure 1d).

Figure 1c shows that there are two in-plane easy magnetization axes on the sample with non-stressed particles. The directions of the easy axis are close to the direction of diagonals of particles, and coincide well with the domain walls observed in the MFM studies. One easy axis was formed in the stressed sample with the direction parallel to the direction of compression of particles. At the same time, a hard axis is formed in the perpendicular direction. The direction of the easy axis along the particle compression is due to the negative value of the magnetostriction coefficient of permalloy under study (at the positive value of the magnetostriction coefficient the easy axis would be perpendicular to the direction of particles compression). The mechanical stress in the particles leads to the increase in the coercive field of particles in 2-3 times in all directions, except for the hard axis, where the coercive field increases by less than 2 times (figure 1d).

The external magnetic field of 80 Oe is necessary for the uniform magnetization of a stressed particle along the hard axis, while for a non-stressed particle the magnetic field of 37 Oe is sufficient. The value of the external magnetic field necessary for the uniform magnetization of the particle along the easy axis is 24 Oe for the stressed particle and 28 Oe for the non-stressed particles. The small difference in the uniform magnetization fields for non-stressed particles in easy and hard directions indicates the weak anisotropy. The MOKE data allow us to conclude that the anisotropy of the non-stressed particles is determined primarily by their geometric shape. The mechanical stress in the particles leads to the uniaxial anisotropy. In this case, the value of the external magnetic field necessary for the uniform magnetization decreases in the direction of the easy axis and significantly increases in the direction of the hard axis.

4. MFM of the samples in the external magnetic field
A Solver P47 scanning probe microscope (SPM) (NT-MDT) and a N18 Co-Cr magnetic cantilever (MikroScience) were used to perform MFM studies. In addition, the SPM was equipped with an external magnetic field source with the intensity of up to 200 Oe, which can be applied in the plane of the sample. The magnetic structure of the particle studied in the external magnetic field applied parallel and perpendicular to the axis of compression. A series of experiments on the magnetization reversal in the external field was also carried out on non-stressed particles. The MFM measurements were performed using a two-pass technique, in which the probe scans the sample topography at the first pass, and the phase shift of cantilever oscillations (MFM image) is recorded at the second pass. The phase shift is proportional to the gradient of the magnetic force of the interaction between the probe and the sample in the given point.

To determine the distribution of magnetization in the particle from the MFM images, the following approach was used. First, based on the three-dimensional image of the particle obtained on the SPM, the distribution of the local magnetic moments in the particle was simulated using the OOMMF computer program [8]. Then, based on the distribution of magnetization, a virtual MFM image of the particle was simulated by our previously developed program “Virtual microscope” [9]. The resulting image was compared with the experimental one. In order to achieve the coincidence with the experimental images, the anisotropy coefficient was varied and the next cycle of the OOMMF calculation was performed. When the simulated and experimental images coincided, the conclusion was drawn that the calculated distribution of the magnetization in the Py particle coincides with the real one.

The experimental MFM images of Py particles in the external magnetic field applied along one of the sides showed the following. In the external magnetic field with the absolute value greater than 40 Oe the non-stressed particles remain magnetized uniformly and the characteristic black-and-white contrast
is observed on opposite sides of the particle (figure 2f). The particle becomes quasi-single-domain at the magnetic field in the range from 35 to 40 Oe modulo and the black-and-white contrast regions on the opposite sides of the particle increase (figure 2e). The particles are in the four-domain state at the magnetic field from 0 to 30 Oe modulo. One of the magnetic domains with the direction of magnetization parallel to the external magnetic field is much larger than the domain with the opposite direction (figure 2e).

Figure 2. MFM images of two Py particles and the corresponding magnetization structure in the case of: non-stressed particles without the external magnetic field (a), stressed particles without the field (b), non-stressed particles in the field of -15 Oe (c), stressed particles in the field of -15 Oe (d), non-stressed particles (quasi-single-domain) in the field -35 Oe (e), uniformly magnetized particles in the field of -80 Oe (f). The white arrows show the direction of compression. The scanning range is 22×9 µm.

For stressed particles with the direction of the external magnetic field along one of the particle sides and parallel to the axis of compression of particles (or the easy axis) the similar behavior of the magnetization was observed. The particle remains magnetized uniformly in the magnetic fields higher than 30 Oe modulo, becomes quasi-single-domain (similar to figure 2e) in the fields of 20-25 Oe, and four-domain in 0-20 Oe (figure 2d).

If the magnetic field was applied along one of particle side and perpendicular to the axis of compression (along hard axis), the behavior of a particle changes. The particle remains magnetized uniformly in the magnetic field higher than 60 Oe modulo. The quasi-single-domain state of the particle is observed at the interval of absolute values of the magnetic field of 45-55 Oe. In the fields of 0-40 Oe modulo, both the four-domain and seven-domain structures are observed. According to the MFM
measurements, the higher external magnetic field is required for the uniform magnetization of the stressed particle in the direction of the hard axis, which coincides with the results observed with the MOKE technique.

The behavior of the magnetic structure of the studied Py particles in the external magnetic field is typical for multidomain particles [10]. The area of the domain with the direction of magnetization, which coincides with the direction of the magnetic field, increases with increasing magnetic field. It is due to the reduction in the size of the domain with the magnetization of which is in the opposite direction (figure 2c,d). This stage of remagnetization of particles is visualized well in the MFM measurements. After absorbing the domain with magnetization opposite to the direction of the magnetic field, the particle becomes a quasi-single-domain and its MFM image changes slightly with the increase in the external magnetic field. Therefore, it is not always possible to clearly establish the value of the field, at which the particle becomes single-domain. This may lead to some discrepancy in the MFM and MOKE results.

5. Summary
The measurements showed that the mechanical compression of the planar Py microparticles leads to the formation of the easy axis of magnetization, the direction of which coincides with the direction of compression. According to the MOKE and MFM data, the value of the external magnetic field necessary for the uniform magnetization of particles in the direction of the easy axis decreases for compressed particles. At the same time, the significant increase in the external magnetic field intensity necessary for the uniform magnetization of the particle occurs in the direction of the hard axis. This is due to the redistribution of magnetization of particles because of the magnetoelastic effect during compression of the particle. Due to the negative magnetostriction coefficient of permalloy, the size of the domains with direction of magnetization parallel to the compression axis increases. The changes in the magnetic properties of a particle under the mechanical stress detected using MFM and MOKE techniques can be used for the detection these mechanical stresses.

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