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Comparison of the domain structure reaction of various ferromagnetic microparticles under uniaxial mechanical stress

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The results of studying the changes in the domain structure of a planar square microparticle with size $7.5 \times 7.5 \times 0.04\,\mu$m under uniaxial mechanical stress is presented. Microparticles were made from the following materials: permalloy (18% Fe, 82% Ni), permendur (50% Co, 50% Fe), halfenol (16% Ga, 84% Fe), Ni, terfenol ($Tb_{0.3}Dy_{0.7}Fe_{1.92}$). The conclusions about the promising of using these materials for fabrication microsensors for stress detection and for fabrication straintronic devices for processing and storing information were made.

Keywords: magnetoelastic effect, magnetic force microscopy, planar ferromagnetic particles, domain structure.

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1. Introduction

Recently, much attention has been paid to the influence of uniaxial mechanical stresses on the magnetic properties of various objects. Planar micro and nanostructures are of most interest, because they can be used to create devices for recording, processing and storing information. It has been theorized that magnetoelastic (Villari effect) devices can reduce the energy loss occurring when writing or processing a single bit of information by several orders of magnitude compared to conventional methods [1–4]. A homogeneously (or quasi-homogeneously) magnetized particle with two or more possible orientations of the magnetization direction is usually considered as the basis for device construction. The magnetoelastic effect is supposed to switch the direction of magnetization in such a particle. The use of ferroelectric substrates, which can provide the lowest power consumption [5–7], is considered the most promising, but other options are often used in exploratory research. The easiest to implement is the variant with mechanical bending of the substrate on which the particles [8–10] are located. Thermally induced magnetoelastic elastic effects are also possible, where mechanical stresses are induced by temperature changes in the sample due to differences in the thermal expansion coefficients of the substrate along different crystallographic axes [11,12] or due to changes in the dimensions of its crystal lattice during the phase transition [13].

However, when mechanical stress is imposed on particles, the question arises regarding the efficiency with which a change in the linear dimensions of the substrate is transferred to the particle, and the extent to which this affects its magnetic properties (in particular, a change in magnetization direction). It is clear that the less mechanical stress can be applied to change the particle magnetization direction, the more energy-efficient the device can become. One of the relevant tasks here is the selection of a particle material that will give it the necessary magnetic properties. It is obvious, that the higher the absolute value of the material magnetostriction, the more its linear dimensions change under the influence of an external magnetic field. This paper studies the effect of magnetostriction of a material on the change in its magnetic properties under uniaxial mechanical stress. For this purpose, the effect of uniaxial mechanical stress on the domain structure of equal planar microparticles of the square shape and size made from different ferromagnetic materials is evaluated.

2. Choosing the object of study

To test for changes in magnetic properties under mechanical stress, these changes need to occur smoothly. So, single-domain particles are poorly suited here. Their magnetization switching is threshold-dependent and can vary greatly from particle to particle with very little variation in geometric parameters. Therefore, a microparticle whose domain structure will smoothly vary with a change in the mechanical stress applied to it, and this change can be numerically characterized, could be the optimal microsensor for such a problem. The particle domain structure shall be simple enough to allow for an straight interpretation of the data on structure change under mechanical stress. Such microsensor size shall be comparable in dimensions

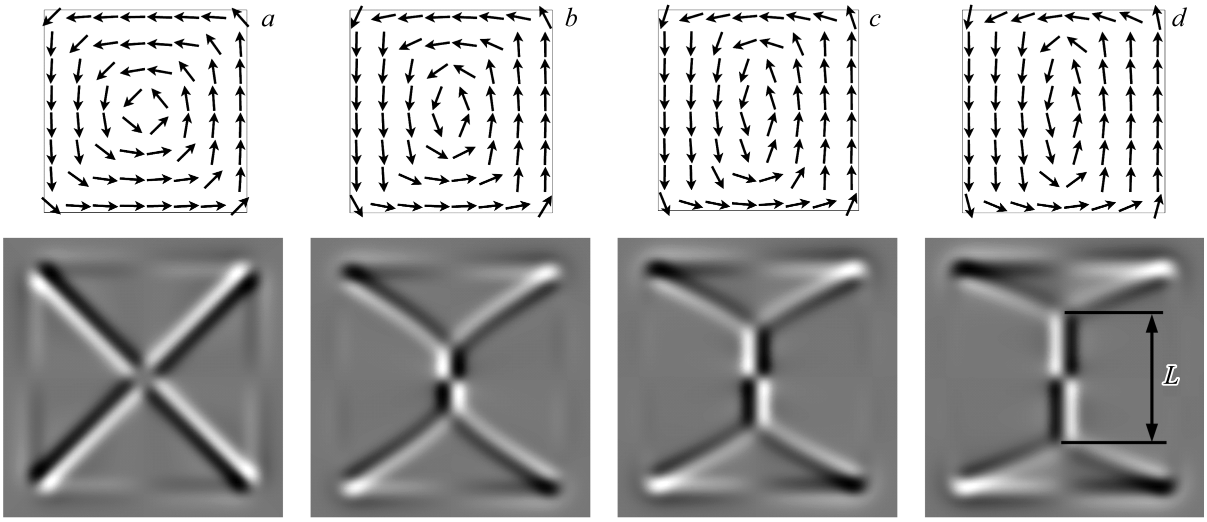

Figure 1. Simulated magnetization distribution in a planar CoNi microparticle (*a, b, c, d*) and virtual MFM image (*e,f,g, h*) at induced anisotropy energy corresponding to mechanical stress 0 MPa (*a, e*), 27 MPa (*b,f*), 43 MPa (*c,g*), 59 MPa (*d, h*). L — the length of the domain wall between the two domains that have increased in size. Scan size $9.5 \times 9.5\,\mu$m. The color gradations correspond to the phase spread 1°.

to the particles used to build devices working on the magnetoelastic effect.

Optimal microsensors, in our opinion, can be planar microparticles with a square shape. In a certain range of lateral sizes and heights, in the absence of external influences, such microparticles have a four-domain structure with the magnetization direction in the domain parallel to the side of their location, the so-called Landau structure (Fig. 1, *a*). The square particle shape allows uniaxial stress to be directed along one side, which, through a magnetoelastic effect, will produce an anisotropy axis collinear to the magnetization direction of the two domains to be resized at the expense of the other two. In this case, a domain wall is formed between the two domains that have increased in size (Fig. 1, *b–d*). The length of this domain wall (L) can be used to characterize the changes in the domain structure of a square microparticle, as we did earlier [8,12], or the ratio of the area occupied by domains with the magnetization direction perpendicular to each other [5]. In the case of a triangular particle shape, for example, the magnetization of only one domain may be directed along the anisotropy axis induced by the magnetoelastic effect. The magnetization direction of other two domains will be at an angle to this axis and interpretation of the resulting data can be difficult. It is optimal not to use the absolute length of the domain wall observed in a square microparticle, but to normalize it to the side length. This will make it possible to compare microparticles of different sizes with each other, and to study the size influence on magnetic properties.

In our case, the simulations were carried out for planar microparticles of sizes $7.5 \times 7.5 \times 0.04\,\mu$m. This is primarily due to the relatively simple technology of manufacturing such microparticles and the possibility of comparing the theoretical results with the experimental ones. To create these microparticles, sputtering through a mask in an ultrahigh vacuum is used by atomizing a solid target with an electron beam. A metal mesh is used as a mask, pressed firmly against the surface of the substrate. The mask is reusable and can easily be replaced with a new one, as it is a standard 2000 mesh for electron microscopy. The area the microparticles occupy on the substrate surface is a circle with a diameter of about 2 mm, which enables the use of not only magnetic force microscopy (MFM), but also other methods to study magnetic properties.

3. Modelling the domain structure of square microparticles

The software package OOMMF [14] was used to simulate the magnetization distribution in a microparticle. The aim was to compare the theoretical data on the domain structure behavior under uniaxial mechanical stresses with the experimental MFM measurements. For this purpose, a virtual MFM image was calculated from the magnetization distribution obtained using the previously developed „Virtual MFM“ [15] software.

Of particular interest in the simulations were materials with giant magnetostriction values at room temperature. These include the alloys terfenol ($Tb_{0.3}Dy_{0.7}Fe_{1.92}$) and galfenol (16% Ga, 84% Fe). The domain structure of microparticles made of permalloy (Py) (82% Ni, 18% Fe), permendur alloy (50% Co, 50% Fe), CoNi alloy (18% Co, 82% Ni), and nickel (Ni) were also modelled. The parameters shown in the table were used in the modelling. The microparticle was split into lattice cells of size $5 \times 5 \times 40$ nm. The direction of uniaxial mechanical stresses

Parameters of materials used in modelling the magnetization distribution in microparticles. The maximum possible values are shown in brackets

Material	Magnetization of saturation (kA/m)	Constant of exchange of interaction $\times 10^{-12}$ J/m^3)	Magnetostriction of saturation ($\times 10^{-6}$)
Py (82% Ni, 18% Fe)	800	13	−3
CoNi (18% Co, 82% Ni)	650	11.2	−25
Nickel	490	9	−35
Permendur (50% Co, 50% Fe)	1950	18	60
Galfenol (16% Ga, 84% Fe)	1432	10	200 (400)
Terfenol ($Tb_{0.3}Dy_{0.7}Fe_{1.92}$)	800	9	800 (2000)

in the simulation was set along one side of the microparticle. The influence of induced mechanical stresses on the magnetization distribution was taken into account by introducing the uniaxial anisotropy constant (K_{eff}) into the calculations, the value of which was increased from 0 to 2000 J/m^3 in steps of 200 J/m^3, from 2000 to 5000 J/m^3 in steps of 400 J/m^3, for some microparticles, additional calculations were carried out in the range 5000 to 15000 J/m^3 in steps of 1000 J/m^3. The value of K_{eff} can be converted into the value of the mechanical stress (σ) applied to the microparticle, based on the formula: $\sigma = -2/3 \cdot K_{\mathrm{eff}}/\lambda_s$, where λ_s — is the saturation magnetostriction constant of the material used [5].

The results as a function of the bridge length and the mechanical stress applied to the microparticle are shown in Fig. 2. The microparticle made of permalloy with a magnetostriction value $-3 \cdot 10^{-6}$ was expected to be the least responsive to mechanical stress. Next is permendur despite the fact that it has a fairly high magnetostriction value. However, it has the highest value of saturation magnetization and exchange interaction, which leads to this effect. Despite the high magnetostriction value of galfenol (200×10^{-6}), its domain structure is less responsive to induced mechanical stresses than that of nickel (-35×10^{-6}), which also appears to be related to the high saturation magnetization value. The domain structure changes most in microparticles made from terfenol, which seems to be related to the highest magnetostriction value and average saturation magnetization values. Stresses in the range 0.5–10 MPa are sufficient to change the domain structure of such a microparticle. Higher stress values are likely to result in a quasi-uniform magnetization state of the microparticle.

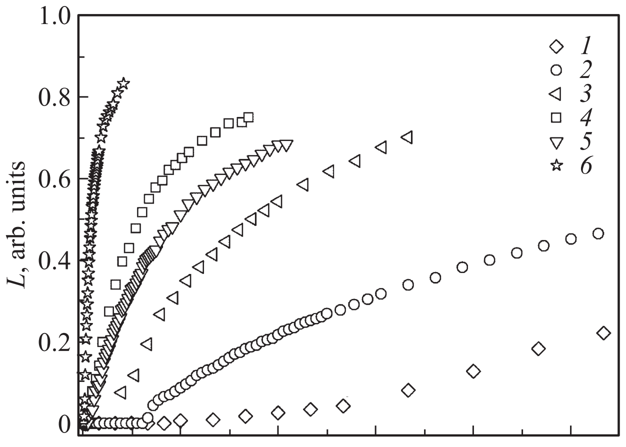

Figure 2. Dependence of the domain wall length (L) on the uniaxial mechanical stress induced in a square microparticle formed from different materials: *1* — Py, *2* — CoFe, *3* — CoNi, *4* — Ni, *5* — galfenol, *6* — terfenol.

4. Experimental evidence on the change in the microparticle domain structure under uniaxial mechanical stresses

The calculated data on the effect of uniaxial mechanical stresses on the microparticle domain structure have been experimentally tested on the microparticle made of CoNi and Ni. For this purpose, microparticle arrays of $7.5 \times 7.5 \times 0.04\,\mu$m were formed on the surface of optically polished $LiNbO_3$ (CLN) single-crystalline lithium niobate substrates. Microparticle were sputtered under ultrahigh vacuum at room temperature. The metal mesh used as a mask to create the microparticles was oriented so that the sides of the resulting microparticles were parallel to the axes „*a*“ and „*c*“ of the crystal substrate. Because the CLN coefficient of linear expansion along the axis „*a*“ ($\alpha_1 = 15 \cdot 10^{-6}\,\mathrm{K}^{-1}$) is twice as high as along the axis „*c*“ ($\alpha_3 = 7.5 \cdot 10^{-6}\,\mathrm{K}^{-1}$), uniaxial mechanical stresses in microparticles could be created by changing the sample temperature. Based on the thermal expansion coefficients of Ni ($13 \cdot 10^{-6}\,\mathrm{K}^{-1}$) and Co ($12 \cdot 10^{-6}\,\mathrm{K}^{-1}$), heating the sample should result in the compression of microparticles along the axis „*with*“ the substrate.

The scanning probe microscope (SPM) Solver P47 (NT MDT) was used to control the geometric parameters

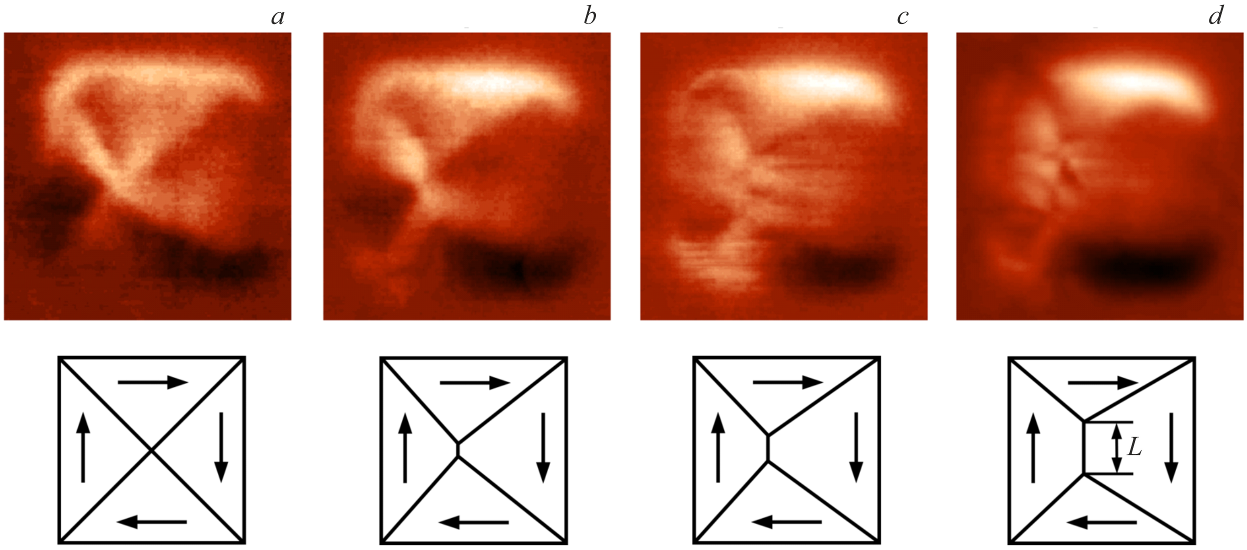

Figure 3. MFM imaging of CoNi microparticles under uniaxial mechanical stress: 0 MPa (*a*), 15 MPa (*b*), 23 MPa (*c*), 30 MPa (*d*). The microparticle is compressed along the vertical axis. The domain structure of the microparticle L — the domain wall length between the two domains having increased in size is schematically shown below the MFM image. Scan size $10.5 \times 10.5\,\mu$m. The color gradations correspond to the phase spread 0.5°.

of the obtained microparticles and study their domain structure. The SPM was additionally equipped with a thermocell which allowed the sample to be heated to a temperature of 110°C. MFM measurements were carried out using a single-pass method (when the probe is at a constant distance from the examined surface during scanning) in order to reduce the possible influence of the probe on the magnetization distribution in microparticles. Magnetic cantilevers „Multi75M-G“ (BudgetSensor) and „PPP-LM-MCMR“ (Nanosensor) were used for measurement. In the experiments performed, one MFM-scan contained an image *4* or *9* of microparticles, for each of which the domain wall length (L) was found between two domains having increased in size at a given temperature. The values obtained were averaged. The temperature step was 5°C. The sample heating temperature did not exceed 65°C, as further heating could lead to irreversible changes in the domain structure of the microparticles. At temperatures below 65°C, once the sample had cooled to room temperature, its domain structure returned to its original form. The microparticles exhibited a classical four-domain structure at room temperature, as shown by MSM measurements (Fig. 3, *a*). A schematic representation of the domain structure of such a CoNi microparticle is shown below the MFM image. The small difference in domain area observed in Fig. 3, *a* in contrast to the model microparticle (Fig. 1, *a*) is, in our opinion, due to the non-ideal square shape of the microparticle.

Sample temperature increase by 5°C practically does not change the observed microparticle domain structure in Fig. 3, *a*. The change becomes noticeable when heated to 10°C (which corresponds to a mechanical stress of ~ 15 MPa), a bridge appears between the domains whose length (L) can be measured from the MFM image (Fig. 3, *b*). A further increase in temperature leads to an increase in the length of this domain wall (Fig. 3, *c, d*). Nickel microparticles show similar changes in domain structure, only they occur at lower values of mechanical stress acting on the microparticle.

The experimental data obtained on the change of domain wall length for Ni and CoNi microparticles are shown in Fig. 4. The agreement is observed between the experimental results and the simulation results. Uniaxial mechanical stress

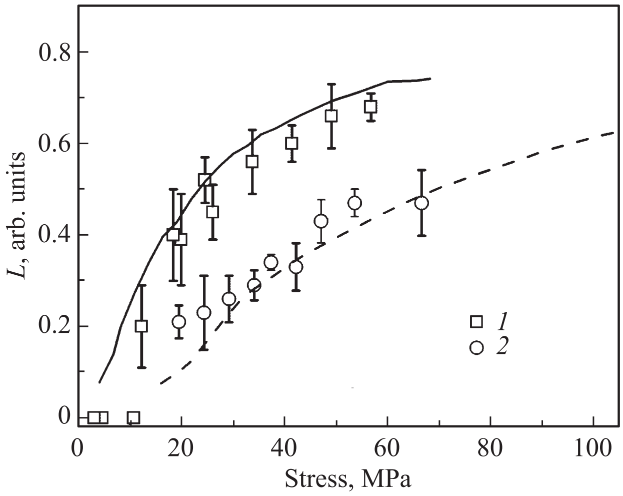

Figure 4. Experimental dependence of the domain wall length (L) on the uniaxial mechanical stress induced in a square microparticle ($7.5 \times 7.5 \times 0.04\,\mu$m) made of Ni (*1*) and CoNi (*2*). Solid line — OOMMF calculations for Ni microparticles, dashed line — for CoNi.

of the same magnitude leads to nearly twice the change in domain wall length of Ni microparticles as compared to CoNi.

This research shows that a square planar microparticle can be used as a microsensor for mechanical stress detection. By changing the material from which the microparticle is made, it is possible to select, for example, the most sensitive material to mechanical stress, or to select a material whose domain structure will change over a certain range of mechanical stresses.

5. Conclusion

It has been shown that the change in the magnetic structure of a ferromagnetic microparticle depends not only on the magnetostriction, but also on the saturation magnetization of the material used. The higher the magnetostriction modulus of a microparticle, and the lower its saturation magnetization, the more its domain structure changes under the influence of mechanical stress. The simulation of change in the domain structure of microparticles under mechanical stress matched well with experimental results on the behavior of the domain structure of Ni and CoNi microparticles. Terfenol is the most promising material among those studied in this paper in terms of mechanical stress response.

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Conflict of interest

The authors declare that they have no conflict of interest.

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