13

Influence of the thermally induced magnetoelastic effect on magnetization switching in Ni microparticles with configuration anisotropy

© A.A. Bukharaev, D.A. Bizyaev, N.I. Nurgazizov, A.P. Chuklanov

Zavoisky Physical-Technical Institute, FRC Kazan Scientific Center of RAS, Kazan, Russia
E-mail: a_bukharaev@mail.ru

Received July 11, 2024
Revised September 11, 2024
Accepted September 21, 2024

The effect of the thermally induced magnetoelastic effect on the switching field of quasi- homogeneous magnetization of planar Ni particles of micron size with configurational anisotropy is investigated. Square Ni particles of two types are formed on the surface of monocrystalline lithium triborate. It has been experimentally shown that when the temperature of the structure changes by $\pm 20^\circ$C relative to the particle formation temperature (50°C), both a decrease and an increase in the particle switching field are observed. This is due to the magnetoelastic anisotropy induced in them when the temperature changes due to the difference in the coefficients of thermal expansion of the substrate along different crystal axes.

Keywords: thermally induced magnetoelastic effect, submicron particles, switching field, magnetic force microscopy, quasi-uniform magnetization, configuration anisotropy.

DOI: 10.61011/TPL.2025.02.60618.20055

Ferromagnetic planar particles with configuration anisotropy may have several quasi-uniform magnetic states separated by sufficiently high energy barriers that ensure temporal stability of these states [1]. „Quasi-uniform magnetization“ (QUM) is understood here as a state of the magnetic subsystem of a particle (with dimensions noticeably larger than the radius of the single-domain state) in which, owing to shape anisotropy, it has a non-zero total magnetic moment [2,3]. This structure is typical of particles with lateral dimensions on the order of one micrometer elongated strongly in one direction or equilateral particles with sides concave toward the center [1–5]. Such particles are regarded as promising elements for the production of magnetoelectric random access memory (MeRAM) cells. A MeRAM cell consists of two planar ferromagnetic uniformly or quasi-uniformly magnetized particles with a fixed (magnetically hard) and relatively free (magnetically soft) magnetization orientation that are separated by a tunnel gap and deposited onto a piezoelectric substrate [4,5]. The magnetization orientation of a soft-magnetic layer on a piezoelectric may be reversed by mechanical stresses induced by deformation of the piezoelectric substrate under the influence of an electric potential or by the combined action of such stresses and an external magnetic field. The magnetization orientation of a hard-magnetic layer remains unchanged in this case. The electrical resistance of such a structure depends on the angle between the magnetization vectors in hard- and soft-magnetic ferromagnetic layers [6]. The resistance reaches its maximum and minimum when these vectors are rotated by 180° relative to each other and are parallel, respectively [4,5].

In addition to the piezoelectric effect, the deformation of ferromagnetic particles formed on a substrate (provided that this substrate is single-crystal in nature) may also be affected by the difference in its thermal expansion coefficients. We have demonstrated recently that the switching field of rectangular Ni particles with QUM formed on the surface of single-crystal lithium triborate (LiB_3O_5; hereinafter referred to as LBO) may change by a factor of 1.57 under a temperature variation of just 15°C [7]. This change was attributable to magnetoelastic anisotropy induced in the particles due to the difference in thermal expansion coefficients of the substrate along different crystal axes. Accordingly, the thermally induced magnetoelastic effect may also influence the switching field of other particles with QUM due to configuration anisotropy and, consequently, affect the operation of a MeRAM cell constructed based on them. In the present study, we estimate the influence of the thermally induced magnetoelastic effect on the switching field of planar Ni particles, which are micrometer-sized squares with varying degrees of concavity of their sides. As was demonstrated in [1], such particles have QUM, and their switching field depends on the mentioned degree of concavity. Since LBO crystals are characterized by large thermal expansion coefficients, a significant change in the switching field of particles formed on their surface under the influence of the thermally induced magnetoelastic effect is to be expected.

Two types of particles were examined: (1) particles with moderately concave sides (in what follows, these are referred to as CS-particles) and (2) cross-shaped particles (X-particles; see Fig. 1, a). Single-crystal LBO produced by HG Optronics was used as a substrate for particle formation. The plane on which particles were produced was formed by crystal axes x and z. According to the manufacturer, the coefficients of thermal expansion of LBO along axes x and z were $\alpha_x = 10.8 \cdot 10^{-5}\,^\circ\mathrm{C}^{-1}$ and $\alpha_z = 3.4 \cdot 10^{-5}\,^\circ\mathrm{C}^{-1}$, respectively. Ni particles had a polycrystalline structure and isotropic thermal expansion coefficient $\alpha_p = 1.3 \cdot 10^{-5}{}^\circ C^{-1}$ [7]. Owing to the difference in thermal expansion coefficients of LBO along different axes, compression of particles was induced when the sample temperature fell below the Ni deposition temperature. They got elongated when the temperature increased, and zero deformation was found at 50°C.

Particles were produced by the lift-off method after metal deposition through a mask under ultra-high vacuum conditions at a substrate temperature of 50 °C. The deposition mask was formed using scanning probe lithography in a thin (approximately 100 nm) layer of polymethyl methacrylate applied to the LBO surface by spin coating [8]. Two arrays of 35 separate CS- and X-particles were formed. The distance between the edges of particles in the array was 3.5 μm. Individual CS- and X-particles imaged with an atomic force microscope are shown in Fig. 1, *a*. Their lateral dimensions may be characterized by the side length of a square into which a particle is inscribed. This dimension was 1.1 μm, and the particle height was 30 nm. Particles were formed in such a way that the sides of the square into which a particle was inscribed were oriented along the crystalline axes of the substrate (Fig. 1, *a*).

An Ntegra scanning probe microscope operating in the atomic force microscope (AFM) and magnetic force microscope (MFM) modes was used to form the mask and examine the obtained particles further. MFM measurements were performed in a single pass in order to reduce the influence of the MFM probe on the obtained results. The switching field was measured *in situ* with the use of a thermal cell built into the MFM at three temperatures: 30, 50, and 70°C. The switching field of a particle was assumed to be equal to the external magnetic field magnitude at which the QUM direction was reversed. In MFM images, this resulted in inversion of the particle image (see Figs. 1, *b, c* or Figs. 1, *d, e*). When the switching field was measured, the sample was oriented in such a way that the axis of magnetoelastic anisotropy induced by uniaxial deformation of particles was perpendicular to the direction of the external magnetic field at 30°C and parallel to it at 70°C (Fig. 1, *a*).

The possible distribution of magnetization in particles was simulated in OOMMF [9] based on their experimental AFM images. The modeling results are presented in the insets of Figs. 1, *b–e*, where small dark arrows indicate the local distribution of magnetization in a particle and large dark arrows represent the orientation of the average magnetic moment (**M**) of the entire particle. Since the simulated and experimental MFM images matched, it was concluded that a quasi-uniform distribution of magnetization is indeed established in particles and that the magnetization direction switches under the influence of an external field.

The obtained MFM images were used to determine the normalized number of particles (N) with a switched magnetization direction at given values of temperature and external magnetic field (Fig. 2). The resulting dependences were normalized to the total number of particles to make

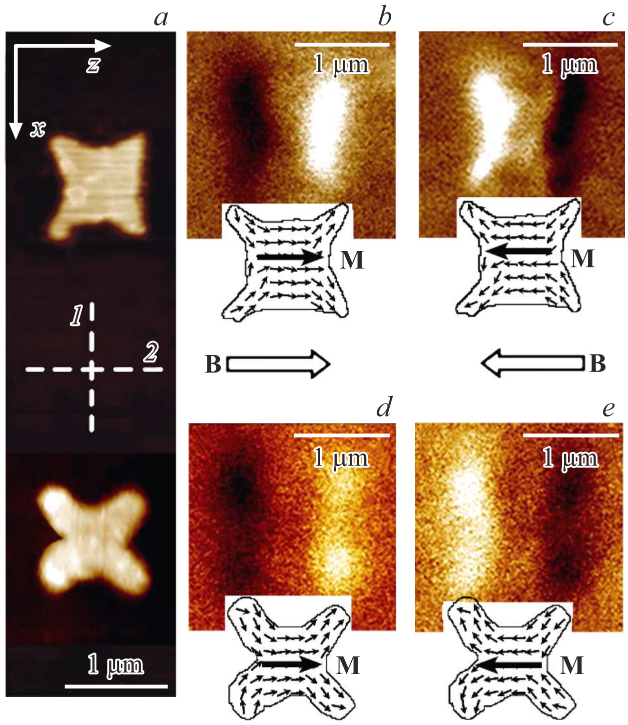

Figure 1. *a* — Experimental AFM images of CS-particles (top) and X-particles (bottom) with the direction of the crystal axes of the LBO substrate indicated by arrows. Dashed lines represent the directions of induced magnetoelastic anisotropy at 30 (*1*) and 70°C (*2*). *b–e* — MFM images: initial magnetization state in a CS-particle (*b*) and an X-particle (*d*); after the rotation of magnetization by 180° in a CS-particle (*c*) and an X-particle (*e*). The insets show magnetization distributions simulated based on geometric data for the corresponding particles. Dark and light arrows indicate the orientation of the average magnetic moment (**M**) in particles and the magnetic field (**B**) direction, respectively.

them more illustrative and better suited for a possible comparison with other data. To find the average value of the particle switching field, the experimental dependences were approximated by a standard function of the form $N = 1/(1 + \exp[(B_{av} - B)/S])$, where B_{av} and S were fitting parameters. Parameter S characterized the slope of the obtained curves, while B_{av} is the (average) switching field of particles. According to the obtained data, a reduction in sample temperature from 50 to 30°C leads to an increase in switching field magnitude from 10 to 14 mT for CS-particles and from 19 to 22 mT for X-particles due to uniaxial compression of Ni particles. When the sample temperature increases from 50 to 70°C, the switching field decreases from 10 to 8 mT for CS-particles and from 19 to 14 mT for X-particles due to their uniaxial elongation. The weakest magnetization switching field observed in experiments on heating from 30 to 70°C for CS- and X-particles formed on LBO was 6 mT (a 1.75-fold reduction) and 8 mT (a 1.53-fold reduction), respectively.

The method of fabrication of masks (scanning probe lithography) gave rise to a shape and size variation of

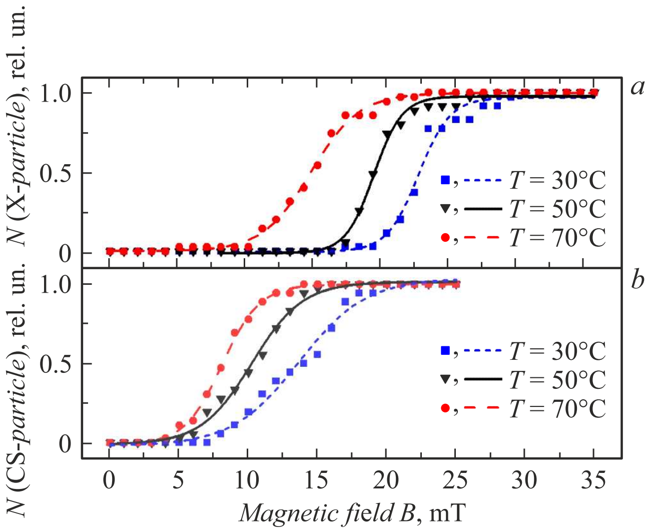

Figure 2. Dependences of the normalized number (N) of X-particles (a) and CS-particles (b) with a switched magnetization direction on the external field at different temperatures. Symbols and curves represent the experimental data and the fitting results for the corresponding temperatures.

formed particles. This leads to a change in the switching field for each of them, and the obtained dependences are sloping (Fig. 2). In addition, the shape of particles affects the observed nature of variation of magnitude of the switching field during heating/cooling, since the direction of the induced magnetoelastic anisotropy also changes in this case (Fig. 1, a).

Thus, it was established that configuration anisotropy enables the preservation of a quasi-uniform structure of magnetization in Ni particles at sizes exceeding significantly the radius of the single-domain state. It was demonstrated that even a slight change in temperature of a sample consisting of a single-crystal substrate with different thermal expansion coefficients and ferromagnetic particles (with configuration anisotropy and a quasi-uniform magnetization structure) formed on it may lead to a significant change in the switching field of such particles.

Funding

This study was supported by the Russian Science Foundation (grant No. 23-29-00085).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] B. Lambson, Z Gu, M. Monroe, S. Dhuey, A. Scholl, J. Bokor, Appl. Phys. A, **111**, 413 (2013). DOI: 10.1007/s00339-013-7654-y

[2] R.V. Gorev, O.G. Udalov, Phys. Solid State, **61**, 1563 (2019). DOI: 10.1134/S1063783419090087.

[3] J. Cui, S.M. Keller, C.-Y. Liang, G.P. Carman, C.S. Lynch, Nanotechnology, **28**, 08LT01 (2017). DOI: 10.1088/1361-6528/aa56d4

[4] S. Bandyopadhyay, J. Atulasimha, A. Barman, Appl. Phys. Rev., **8**, 041323 (2021). DOI: 10.1063/5.0062993

[5] A.A. Bukharaev, A.K. Zvezdin, A.P. Pyatakov, Yu.K. Fetisov, Phys. Usp., **61**, 1175 (2018). DOI: 10.3367/UFNe.2018.01.038279.

[6] A.A. Bukharaev, D.A. Bizyaev, N.I. Nurgazizov, A.P. Chuklanov, N.Kh. Useinov, J. Magn. Magn. Mater., **500**, 166315 (2020). DOI: 10.1016/j.jmmm.2019.166315

[7] D.A. Bizyaev, A.P. Chuklanov, N.I. Nurgazizov, A.A. Bukharaev, JETP Lett., **118**, 591 (2023). DOI: 10.1134/S0021364023602968

[8] D.A. Bizyaev, A.A. Bukharaev, A.S. Morozova, N.I. Nurgazizov, A.P. Chuklanov, Tech. Phys., **68**, 849 (2023). DOI: 10.61011/TP.2023.07.56626.56-23

[9] M.J. Donahue, D.G. Porter, *OOMMF User's Guide. Version 1.0* (Natl. Inst. Standards Technol., Gaithersburg, USA, 1999). http://math.nist.gov/oommf

Translated by D.Safin