Heat-assisted effects in ferromagnetic nanoparticles

A A Bukharaev\textsuperscript{1,2}, D A Bizyaev\textsuperscript{1}, T F Khanipov\textsuperscript{1,2}, N I Nurgazizov\textsuperscript{1} and A P Chuklanov\textsuperscript{1}

\textsuperscript{1} Zavoisky Physical-Technical Institute, 420029, Russian Academy of Sciences, Kazan, Tatarstan, Russia
\textsuperscript{2} Kazan (Volga Region) Federal University, 420008, Kazan, Tatarstan, Russia

E-mail: a_bukharaev@kfti.knc.ru

Abstract. The processes of the magnetization reversal by the external magnetic field of the Py particles have been studied by magnetic force microscopy in the temperature range of 300-650 K. The values of the switching field of the particle magnetization and the switching field distribution for the particles array have been determined. The switching field and the field distribution decrease significantly with increasing temperature.

1. Introduction

The analysis of modern technologies and experimental results makes it possible to conclude that one of the most perspective methods of data recording is heat-assisted magnetic recording (HAMR) [1-3]. In HAMR, data recording is carried out by the magnetic switching of the local area by the magnetic field of a recording head with additional heating of the area by the focused laser beam. The data density can be increased by using a medium composed of separately located ordered one-domain ferromagnetic nanoparticles (so-called patterned medium [3]). The theoretical limit of the data density achieved by HAMR is 10 Tb/in\textsuperscript{2}. Particles with two opposite orientations of the magnetization state corresponding to “0” and “1” are used for data recording in a binary code. Switching of the magnetization state of the one-domain nanoparticle is a physical base of data recording in the same devices. To implement HAMR, it is important to know the value of the switching field (SF) for the particle at the temperatures much higher than room temperature (up to the Curie temperature) because the coercive force of a ferromagnetic material is decreased by 3-4 times at heating [2, 4]. The control of the switching field distribution (SFD) of different particles is also essential for HAMR [5].

Magnetic force microscopy (MFM) is a convenient technique for studying the magnetization reversal of a single nanoparticle or particle arrays. Information about switching fields depending on the material, shape and sizes of particles was already obtained by MFM [5, 6]. The temperature dependence of magnetic reversal processes was usually studied in the temperatures range of 10-300 K [7, 8]. In this work, MFM was used for studying the magnetization reversal of the Py particles at temperatures from 300 to 650 K. The change of SF and SFD with increasing temperature was also estimated and the magnetization reversal mechanism was analyzed by using the computer simulation of MFM images.

2. Sample preparation and measurement techniques

The planar structures with the isolated ferromagnetic Py particles on SiO\textsubscript{2} surface was manufactured using the modified technique of scanning probe nanolithography (SPNL) described in [9]. According
to this technique, the lithographic mask was formed in a layer of poly-(methylmethacrylate) (PMMA) located on the SiO₂ surface by the probe of an atomic force microscope (AFM) Solver P47 (NT-MDT). At the next step, a ferromagnetic metal film was sputtered on the mask and the sacrificial layer was removed by the lift-off technique. The cantilevers NSG20 (NT-MDT, force constant 48 N/m) and NSC15 (MikroMasch, force constant 46 N/m) with the tip curvature radii of 10 nm were used. The PMMA film (50-60 nm) spin-coated on the substrate was used. The sample with the lithographic mask was coated by Py (Ni 78%, Fe 22%) at ultra high vacuum conditions (10⁻⁸ mbar) using an electron beam evaporator built into the UHV system Omicron Multiprobe P. The deposition rate was about 0.1 nm/min. Then the sample was rinsed in an ultrasonic bath with chlorobenzene to allow the lift-off of the sacrificial layer.

The AFM image of 30 submicron Py particles on the SiO₂ surface is presented in figure 1a. The lateral size of particles was in the range from 400x150 to 600x250 nm, the height of particles was 15 nm. The MFM image of the same area is shown in figure 1b. The SF dependence due to the range of the lateral size of particles and the SFD dependence on increase in the temperature were studied. The Solver HV system (NT-MDT) was used to study the magnetization reversal of the Py particles. The Solver HV system makes it possible to obtain AFM and MFM images and to heat a sample in the vacuum conditions and to apply an external magnetic field in the sample plane direction. The NSC19/Co-Cr (MikroMasch) magnetic tips were used and the phase change of oscillated cantilever was measured. The one-pass technique of MFM image registration was used. In one pass technique the magnetic probe scans a sample on the advance set height necessary to no magnetizing a particle by a probe field.

Figure 1. AFM image of the array of 30 Py particles (a), MFM image of the same area obtained by the one-pass technique after particles were magnetized in one direction by the external magnetic field (b).

The magnetization reversal of Py particles at room temperature was studied in the same manner as in [10, 11]. At the first stage all particles were magnetized in the sample plane by the external field (of about 800 Oe) appreciably higher than the coercive force of Py particles. After that the magnetic states of all particles was checked by MFM (figure 1b). Then the magnetic field of 100 Oe was applied to the sample in the opposite direction (“magnetization field”). After that the magnetic field was switched off and the magnetization of the same particles by MFM was recorded and the quantity of the particles which have switched magnetization was calculated. The above procedure was repeated with the higher value of the magnetization field. The field was increased step-by-step until all Py particles were switched to the opposite direction. The value of the external field sufficient for the change of the magnetization of the particle to the opposite direction (according to the MFM image of the particle)
was fixed as the particle SF. To obtaining the MFM images of the same particles, special markers were created on a sample by the SPNL technique. The cantilever position relative to the markers was observed on a optical microscope.

The remanent magnetization of a separate particle (M) is estimated by the maximum change of the phase of the cantilever oscillation during scan of the particle along the long axis. Our earlier computer simulation of the MFM images [12] showed that such method of the analysis of the MFM images makes it possible to observe the relative change of the magnetization value of a single one-domain particle and to plot the hysteresis loop of the particle.

The particle magnetization at high temperature was studied on the modified Solver HV system. The special (home-built) sample holder with heating up to 800 K was used. To prevent the sample oxidation, the particle magnetizations at high temperature were carried out ex situ at the vacuum of about $10^{-2}$ mbar. At first, the particles were magnetized up to saturation ($M_S$) by the external magnetic field at room temperature. Then the sample was heated up to the preset temperature and the magnetic field was switched on in the opposite direction. The field magnitude was set significantly smaller than the switching field of particles at room temperature. The heating element was switched off, and the sample was cooled down to the room temperature in the external magnetic field. After that the MFM measurements of the particles array was carried out and the number of the switched particles was calculated. Such technique was used to prevent the MFM probe destruction at the high temperature. At the next step, the experiment was repeated at the higher preset temperature.

3. Results and discussion

According to MFM images, most particles have only two directions of magnetization along the long axis typical for the uniformly magnetized particle (figure 2a). The hysteresis loop of such particles (denoted as “A”) obtained by the analysis of the change of MFM images (phase contrast) has a rectangular shape. But some particles during the magnetization reversal process were observed in the intermediate state that differed from the uniform magnetization (figure 2b). In hysteresis loop this state corresponds to the non-uniform magnetization (figure 2b). The step on the hysteresis loop of such particles (denoted as “B”) is caused by the formation of a stable state with the low magnetization during the magnetization reversal (figure 2b). Similar results were observed in [6] when the magnetization reversal of the Py particles with the size close to ours and the aspect ratio of 4:1 were studied.

![Figure 2](image_url)

**Figure 2.** Experimental hysteresis loop for particle “A” (a) and particle “B” (b). The MFM images of the magnetic states insert on curves and the corresponding area indicate by arrows and circles (scale bars, 200 nm).

The computer simulation of magnetization processes of the particles was used to interpret experimental MFM images. The magnetization of particles “A” and “B” was simulated using the
OOMMF [13] program (figure 3a, c). The corresponding MFM images (figure 3b, d) were simulated using the “virtual MFM” program created before [12]. It follows from the analysis of the experimental and simulated MFM images that the non-uniform magnetization is caused by the formation of the vortex magnetization in the middle part of the particle. It is in good agreement with other results of the MFM investigation of the magnetization reversal of Py particles at room temperature [6].

![Simulated distributions of the uniform (a) and the non-uniform (c) magnetization state of the Py particles (lateral size of 510x160 nm and 460x190 nm respectively, height of 15 nm) and the simulated MFM images for these particles (b), (d) respectively.](image1)

**Figure 3.** Simulated distributions of the uniform (a) and the non-uniform (c) magnetization state of the Py particles (lateral size of 510x160 nm and 460x190 nm respectively, height of 15 nm) and the simulated MFM images for these particles (b), (d) respectively.

In spite of the small size dispersion, the studied Py particles had significant SF at room temperature (figure 4a). The SF value sufficient for the magnetization reversal of all 30 particles was 680 Oe at room temperature. The increase in the sample temperature led to the significant decreasing of the SF value. The SF value for the same particles was 200 Oe at the temperature of 650 K. The SFD was measured as the difference between the magnetic field required for switching of all 30 particles and the field required for switching of only the first particle. At room temperature the SFD was 220 Oe. The SFD significantly decreased and reached the minimum value of 90 Oe at the temperature increase to 650 K.

Depending on the particle sizes, the magnetization reversal can take place by the coherent rotation of all magnetic moments of particles (Stoner-Wohlfahth model [14]) or by the formation of the intermediate state with the residual vortex magnetization (Neel-Brown model [6, 8]). Since the size of our particles is much larger that the exchange interaction length (of about 10 nm for Py [8]), the coherent rotation of the magnetic moments is improbable. It is obvious that the transition from one state with the uniform magnetization to another state with the opposite magnetization occurs through the formation of the vortex structure (similar to the magnetization reversal in [6]). The same as in work [6], we observed the particles “B” with the stable vortex state. The particles “A” demonstrated only two magnetization states and they had the rectangular shape of the hysteresis loop. It is obviously connected with the stability of the vortex state in a very narrow interval of the external magnetic field. The observation of such state by MFM is improbable because the external magnetic field in the experiments is changed with the limited step (no less than 3 Oe).

![Number of switching particles dependence on the external magnetic field at different temperatures for the array of 30 Py particles.](image2)

**Figure 4.** Number of switching particles dependence on the external magnetic field at different temperatures for the array of 30 Py particles.

The decrease in the switching field value with increasing temperature is explained by the known thermo-activation Neel-Brown model of particles switching from one magnetization state to the opposite state [15]. The energy barrier between two stable states of the opposite magnetizations of the particle decreases significantly when the external magnetic field is applied [4, 14], therefore the low
field is enough for the magnetic reversal of the Py particle at temperatures of about 500 K. The reduction of the SFD with the increase in the temperature to 500-550 K for particles with the wide size distribution is interesting from the application point of view, because this phenomenon is important for implementing of the high-density data recording using HAMR.

4. Conclusion
The ordered Py particles with the uniform magnetization were manufactured on the SiO₂ surface by the scanning probe nanolithography technique. The processes of the magnetization reversal of the Py particles in the temperature range from 300 to 650 K were investigated by MFM. It was shown the magnetic field necessary for switching from one direction of the uniform magnetization to the opposite direction decreases from 680 to 200 Oe with the increase in the particle temperature to 650 K. The switching field distribution is decreased by more than two times. It follows from the analysis of the experimental and simulated MFM images indicating the structure of the particle magnetization that the switching of the uniformly magnetized particles takes place by the formation of the intermediate vortex structure.

Acknowledgements
This work was supported by a RFBR grant 12-02-00820 and a program of the Russian Academy of Sciences.

References
[1] Inaba Y, Nakata H and Inoue  2011 Fuji Electric Review 57 42
[2] Kryder M, Gage E, McDaniel T, Challener W, Rottmayer R, Ju G, Hsia Y and Erden M 2008 Proceedings of the IEEE 96 1810-35
[3] Şendur K and Challener W 2009 Appl. Phys. Lett. 94 032503
[4] Zeng H, Skomski R, Menon L, Liu Y, Bandyopadhyay S and David J 2002 Phys. Rev. B 65 134426
[5] Tabasum M, Zighem F, De La Torre Medina J, Encinas A, Piraux L and Nysten B 2013 J. Appl. Phys. 113 183908
[6] Zhu X, Grutter P, Metlushko V and Illic B 2002 Phys. Rev. B 66 024423
[7] Shaw , Russek S, Thomson T, Donahue M, Terris B, Hellwig O, Dobisz E and Shaw M 2006 Phys. Rev. B 78 024414
[8] Shi J, Li J and Tehrani S 2002 J. Appl. Phys. 91 7458
[9] Bizyaev D, Bukharaev A, Lebedev D, Nurgazizov N and Khanipov T 2012 Technical Physics Letters 38 645
[10] Bukharaev A, Ovchinnikov D, Nurgazizov N, Kukovitski E, Klaber M and Wiesendanger R 1998 Physics Of The Solid State 40 1163
[11] Ovchinnikov D, Bukharaev A, Borodin P and Biziaev D 2001 Physics of Low-Dimensional Structures 3 103
[12] Ovchinnikov D and Bukharaev A 2001 Technical Physics 46 1014
[13] http://math.nist.gov/oommf/
[14] Stoner E and Wohlfarth E 1948 Phil. Trans. R. Soc. Lond. A240 599
[15] Wirth S and von Molnar S 2006 Handbook of Advanced Magnetic Materials vol 1 ed Y Liu, D Sellmyer and D Shindo (New York: Springer) pp 294-338