Observation of MFM tip induced remagnetization effects in elliptical ferromagnetic nanoparticles

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We report on our observations of remagnetization in elliptical Fe(Co) nanoparticles by the tip of magnetic force microscope. It is found out that the particles with a high aspect ratio (1:2) show reversible switching of the single-domain state, whereas those having a low aspect ratio (1:1.5) exhibit tip-induced transitions between the single-domain and the vortex state of magnetization.

Introduction

Arrays of ferromagnetic nanoparticles are actively studied currently, because of their potential applications as magnetic storage devices with ultrahigh density (up to 1Tbit/inch). MFM studies of magnetic configurations in such nanoparticles and MFM tip induced transitions between the magnetic states have therefore attracted considerable attention in recent years. Tip induced magnetization reversal effects in Co and permalloy ($Ni_{80}Fe_{20}$) particles of different shapes have been partially studied in [1-6]. In this article we demonstrate the results of MFM measurements of single domain (SD) and single vortex (SV) states within Fe-Cr and Co nanoparticles and MFM tip induced effects of magnetization reversal (SD $\Leftrightarrow$ SD transitions) and remagnetization processes (SV $\Rightarrow$ SD $\Rightarrow$ SV) in these nanomagnets.

Experimental technique

Two types of particle arrays were studied, (1) arrays, fabricated by four-beam interference laser annealing of thin composite Fe-Cr films [7] and (2) by E-beam lithography and subsequent ion etching of thin Co films [8]. The magnetic properties of the structures were measured by the MOKE technique (magneto-optical Kerr effect) and Hall magnetometry. Distribution of remanent magnetization and processes of local magnetization reversal within the particles were studied using multimode SPM "Solver" ("NT-MDT" company, Zelenograd, Russia). MFM measurements were performed in the noncontact single pass method [9] and standard double pass tapping/lift mode. Standard Co-coated silicon cantilevers ("NT-MDT" and "MicroMasch", Tallinn, Estonia) magnetized along the tip axis prior to magnetic imaging were used in the MFM experiments.

MFM induced magnetization reversal in Fe-Cr nanoparticles

Patterned arrays of ferromagnetic nanoparticles were fabricated by four-beam interference laser annealing of thin (10-20) composite Fe-Cr films [7]. Fig. 1(a) shows a topography image of a patterned Fe-Cr layer. As seen from this picture, the laser modified areas correspond to elliptical-shape particles with approximate size of 800 × 280 nm (aspect ratio 3:1). The MOKE measurements have shown that after patterning the sample has acquired ferromagnetic properties. Along the long axis of the elliptical regions the saturation magnetization was approximately equivalent to remanent magnetization and the coercivity field for this array was near 500 G. As shown by the magneto-optical measurements and micromagnetic modeling [10], the ground state of magnetization of these Fe-Cr particles corresponds to the single domain configuration.

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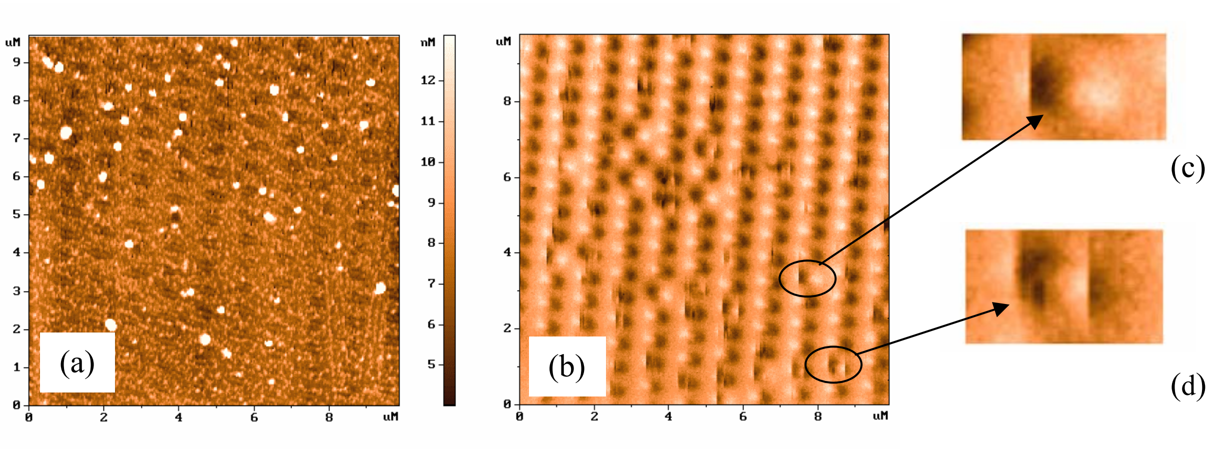


Fig. 1. AFM and MFM images of Fe-Cr nanoparticles array.

Fig. 1(b) depicts a MFM image of a Fe-Cr nanoparticles array (two-pass tapping/lift mode is used; fast scan direction is from left to right). It is readily seen, that this magnetic image contains peculiarities related with the tip induced magnetization reversal effects. One can single out three groups of particles. In the first group the particles change the direction of magnetization to opposite during tip scanning (fig. 1(c)). The particles from another group change their single domain orientation twice during scanning (fig. 1(d)). And the third group contains particles, which do not change their magnetization. When using the MFM tip with high magnetic moment, we observed practically all particles in the array switch under the impact of the probe magnetic field (fig. 2(a)). Absence of the magnetization reversal effects in some particles is a consequence of the sample surface nonuniformity. Analysis of the MFM images shows that switching of particle occurs only when the MFM tip is positioned over the white magnetic pole of the particle (the same as the magnetic pole of the tip apex). Single act of the SD $\Rightarrow$ SD transition in the Fe-Cr particle is shown in fig. 2(b,c).

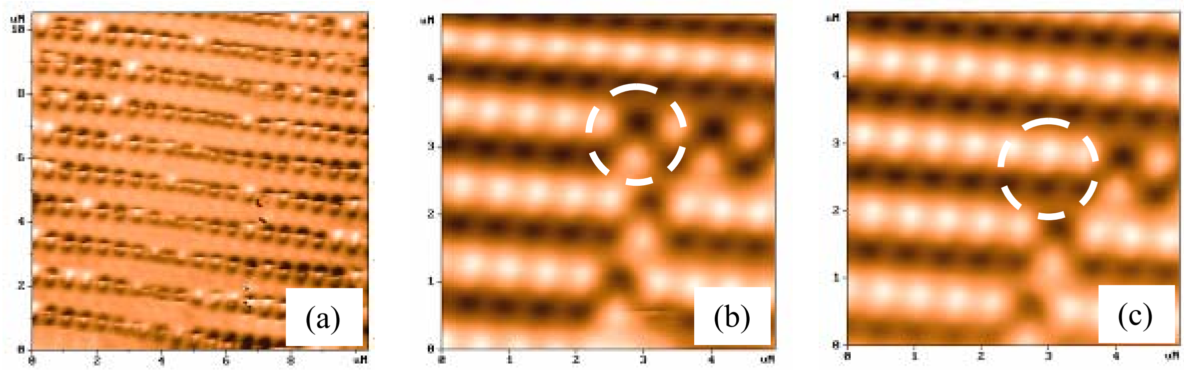


Fig. 2. Magnetization reversal effects in Fe-Cr nanoparticles.

A series of experiments on tip induced controlled magnetization reversal in Fe-Cr nanoparticles have been performed. Fig. 3 shows successive stages of controlled process of magnetic moment switching in Fe-Cr particles. The SD $\Rightarrow$ SD transitions were initiated by scanning over the like pole of the particle at a small height in single pass mode.

First, one particle is switched (fig. 3(a)), then another (fig. 3(b)), then third one (fig. 3(c)). After that, the second particle is switched to the initial state (fig. 3(d)). All these MFM pictures were taken in the single pass mode.

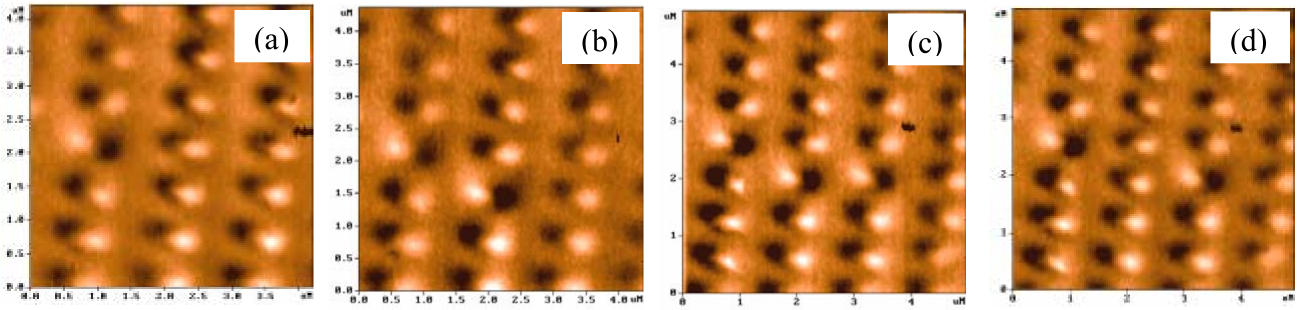
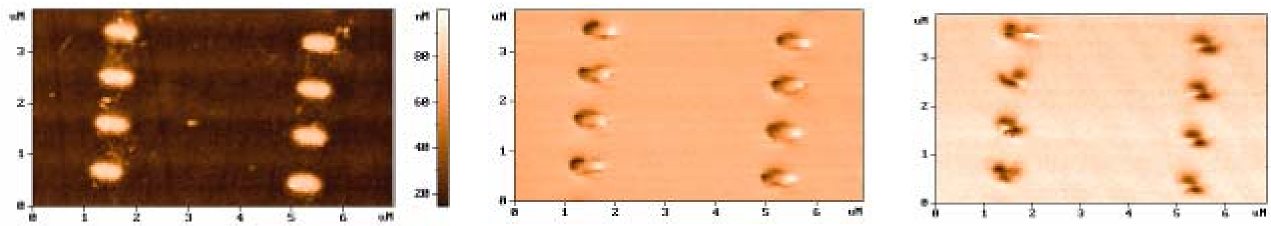


Fig. 3. Stages of tip induced magnetization reversal process in Fe-Cr nanoparticles.

MFM induced single domain – vortex transitions in Co nanoparticles

Elliptical Co particles with different values of aspect ratio and thickness were fabricated by E-beam lithography process and subsequent ion etching technique of Co thin (25nm) films [8]. Our MFM measurements show, that SD and SV states can be realized in elliptical Co particles depending on correlation between the thickness and lateral dimensions of the particles. Fig. 4 shows AFM and corresponding MFM images of the same place on sample surface.



(a) (b) (c)

Fig. 4. AFM and corresponding MFM images of Co particles array.

As shown, the ground state in these particles corresponds to SV. During scanning of this array in the two-pass technique, we observed effects of transitions between the vortex and single domain states. As seen in fig. 4(b), these phenomena are accompanied by an abrupt increase in the MFM signal. Note that the SV ⇒ SD transition occurs during scanning in the central part of the particle (scanning along the long axis of the particle). If the MFM probe moves near the edge of the particle, a reverse transition from single domain to vortex state (SV ⇒ SD) occurs. Such effects could be used for switching of vorticity direction within a Co particle. An elementary act of the magnetic vortex sign reversal is shown in fig. 5.

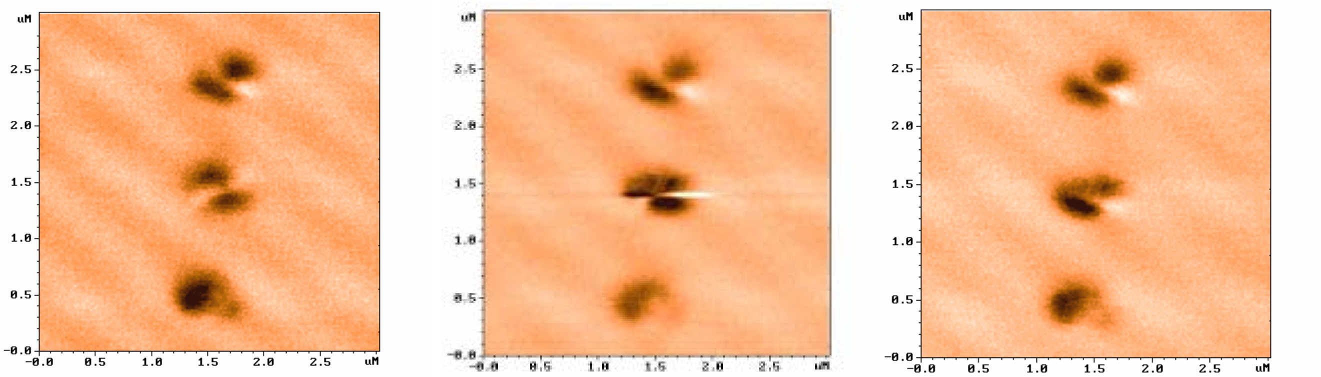
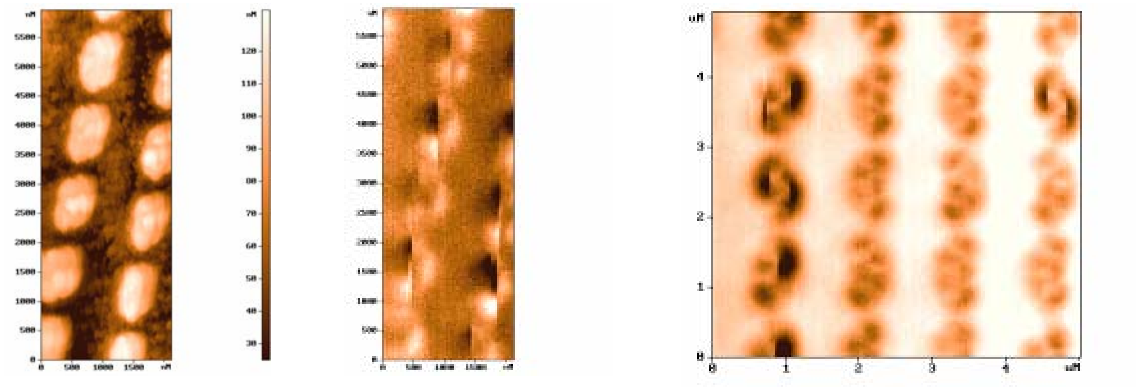


Fig. 5. Switching of vorticity direction within Co particle (central particle). Three consecutive scans from the same place.

Remagnetization effects were also found in Co particles with lateral dimensions of 0.5 × 1μm. It was revealed, that the magnetic multi-vortex state is more favorable for these particles. For example, fig. 6 depicts MFM images which show remagnetization from the single domain to multi-vortex state (fig. 6(b)) and the tip induced restructuring of the multi-vortex magnetic state (fig. 6(c))



(a) (b) (c)

Fig. 6. Tip induced remagnetization effects in Co particles.

Conclusion

In conclusion, our MFM experiments show, that the magnetic field of the MFM cantilever can easily change the magnetic configuration within ferromagnetic nanoparticles. Tip induced single domain to single domain (SD ⇒ SD) reversible magnetization reversal effects were observed in Fe-Cr particles. In Co particles a reversible transition SV ⇒ SD ⇒ SV was observed to occur with change of the vorticity direction. For larger Co particles, tip induced effects of single domain to multi-vortex state transitions and restructuring of the multi-vortex state were observed. As our investigations show, the character of the remagnetization processes largely depends on a particle geometry (thickness and aspect ratio), the magnetic moment of the tip and the lift height during scanning. The above mentioned remagnetization effects could be used in high-density memory technologies.

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1. M.Kleiber, F.Kümmerlen, M.Löhndorf, A.Wadas, D.Weiss, R.Wiesendanger – Phys. Rev. B, v. 58, № 9, p. 5563 (2002).
2. X.Zhu, P.Grütter, V.Metlushko, B.Ilic – J. Appl. Phys., v. 91, № 10, p. 7340 (2002).
3. X.Zhu, P.Grütter, V.Metlushko, B.Ilic – Phys. Rev. B, v. 66, p. 024423 (2002).
4. A.Fernandez, M.R.Gibbons, M.R.Wall, C.J.Cerjan – J. Magn. Magn. Mater., v. 190, p. 71 (1998).
5. A.Fernandez, C.J.Cerjan - J. Appl. Phys., v. 87, № 3, p. 1395 (2000).
6. T.Okuno, K.Shigeto, T.Ono, K.Mibu, T.Shinjo - J. Magn. Magn. Mater., v. 240, p. 1 (2002).
7. A.M. Alexeev, Yu.V.Verevkin, N.V.Vostokov, V.N.Petrjakov, N.I.Polushkin, A.F.Popkov, N.N.Salashchenko – JETP letters, 73, 214 (2001) (in russian).
8. A.A.Fraerman, S.A.Gusev, L.A.Mazo, I.M.Nefedov, Yu.N.Nozdrin, I.R.Karetnikova, M.V.Sapozhnikov, I.A.Shereshevsky, L.V.Sukchodoev – Phys. Rev. B, v. 65, p. 064424-1 – 064424-5, (2002)
9. N.I.Polushkin, B.A.Gribkov, V.L.Mironov – Book of abstracts international conference "Micro- and nano electronics - 2003", Zvenigorod, October 6-10, 2003, p. O1-21.
10. http://math.nist.gov/oommf