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# Magnetic Force Microscopy (MFM) Study of Remagnetization Effects in Patterned Ferromagnetic Nanodots

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**Periodic magnetic nanodot arrays were successfully produced on glass substrates by interference laser lithography and electron beam lithography methods. Magnetic force microscopy (MFM) observation was carried out on fabricated nanodot arrays. MFM tip induced magnetization effects were clearly observed in ferromagnetic elliptical nanodots varying in material and aspect ratio. Fe-Cr dots with a high aspect ratio show reversible switching of the single domain magnetization state. At the same time, Co nanomagnets with a low aspect ratio exhibit tip induced transitions between the single domain and the vortex state of magnetization. The simple nanolithography is potentially an efficient method for fabrication of patterned magnetic arrays.**

**Key words :** nanodot, magnetic force microscopy, remagnetization, domain, lithography

## 1. Introduction

Characterization and understanding of magnetic properties of ferromagnetic nanodots with well defined periodicity have been a major challenge for decades in the areas of magnetic recording media with ultra high density (up to 1 Tbit/inch) and magnetic devices. Many methods including electron beam lithography [1] and indirect lithography [2-4] have been used to fabricate nanodot arrays. Unfortunately, most methods may not be suitable for large scale device and even worse, for patterning of such a nano scale ferromagnetic dot arrays because they are multistep, time-consuming and vulnerable during the fabrication. Recently, interferometic lithography has been introduced to generate magnetic nanodot arrays by directly exposing ferromagnetic films to an interferometric laser [5].

MFM studies of magnetic configurations in such ferromagnetic nanodots and MFM tip induced transitions between the magnetic states have attracted considerable attention in recent years. Tip induced magnetization reversal effects in Co and permalloy ($Ni_{80}Fe_{20}$) dots of different shapes have been partially studied in the literatures. [6-11] In this work, we demonstrate the results of MFM measurements of single domain (SD) and single vortex (SV) states within Fe-Cr and Co nanodots and MFM tip induced effects of magnetization reversal (SD $\Leftrightarrow$ SD transitions) and remagnetization processes (SV $\Rightarrow$ SD $\Rightarrow$ SV) in these nanomagnets.

## 2. Experimental Procedure

The two types of nanodot arrays were fabricated by four-beam interference laser annealing of thin composite Fe-Cr films [6] and by electron beam lithography and subsequent ion etching of thin Co films [14].

For sample preparation, the 20 nm thick Fe-Cr films were co-sputtered onto a water-cooled glass substrate. The sputtered films were exposed to a 10 ns-pulsed-excimer laser having a wavelength of 308 nm and a flux of 0.17 J/cm$^2$. The laser beam was split into two beams of an approximately equal intensity and then recombined, generating an interference pattern and a periodic modulation of the light intensity. The interference of the four beams leads to the formation of two-dimensional arrays of modified regions having a minimum lattice periodicity equal to half of the radiation wavelength. The size and shape of the regions depend on the incident angles of the beam, on pulse duration, and on flux. With the process, elliptical Fe-Cr nanodots (800 × 280 nm) with a distance of 1 mm was successfully produced. Conventional inter-

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*Corresponding author: Tel: +82-2-958-6822, Fax: +82-2-958-6851, e-mail: presto@kist.re.kr ferometric lithography is a multistep process, involving the interference of two laser beams of wavelength which intersect on a resist-coated substrate, selective etching, and lift off [3]. The process involving the etching and subsequent cleaning raises an important issue when applying it to patterned magnetic structures. In general, achieving a sufficient degree of surface cleanliness and smoothness will be of great importance [1].

Arrays of Co nanodots were prepared by electron beam lithography followed by ion milling. Details on the procedures are well described in the previous literature [14]. The unique one to be noticed is to use fullerene consisting of $C_{60}$ molecules as a electron beam resist which acts as a patterning media as well as a robust mask for ion etching.

MFM measurements were performed in the non-contact single pass method [12] 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.

## 3. Results and Discussion

### 3.1. MFM induced magnetization reversal in Fe-Cr nanodots

Patterned arrays of ferromagnetic nanodots were fabricated by four-beam interference laser annealing of thin (10-20 nm) composite Fe-Cr films. Fig. 1(a) shows topography image of a patterned Fe-Cr layer. As seen from this picture, the laser modified areas correspond to elliptical-shape dots with approximate size of 800 × 280 nm (aspect ratio 3:1). As-deposited films were nonmagnetic (i.e. nonferromagnetic) at room temperature, but upon annealing by laser the patterned array of nanodots 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 [13], the ground state of magnetization of these Fe-Cr dots corresponds to the single domain configuration.

Fig. 1(b) depicts a MFM image of a Fe-Cr nanodots 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 dots. In the first group the dots change the direction of magnetization to opposite during tip scanning (Fig. 1(c)). The dots from another group change their single domain orientation twice during scanning (Fig. 1(d)). And the third group contains dots, which do not change their magnetization. When using the MFM tip with high magnetic moment, we observed practically all dots in the array switch under the impact of the probe magnetic field (Fig. 2(a)). Absence of the magnetization reversal effects in some dots is a consequence of the sample surface non-uniformity. Analysis of the MFM images shows that switching of dot occurs only when the MFM tip is positioned over the white magnetic pole of the dot (the same as the magnetic pole of the tip apex). Single act of the SD ⇒ SD transition in the Fe-Cr particle is shown in Figs. 2 (b) and 2(c).

A series of experiments on the control of tip induced magnetization reversal process in Fe-Cr nanodots were performed. Fig. 3 shows successive stages of controlled process of magnetic moment switching in Fe-Cr nanodots. The SD ⇒ SD transitions were initiated by scanning over the pole of the dot at a small height in single pass mode.

First, one dot is switched (Fig. 3(a)), then another (Fig. 3(b)), subsequently third one is done (Fig. 3(c)). After that, the second dot was switched to the initial state (Fig. 3(d)). All these MFM pictures were taken in the single

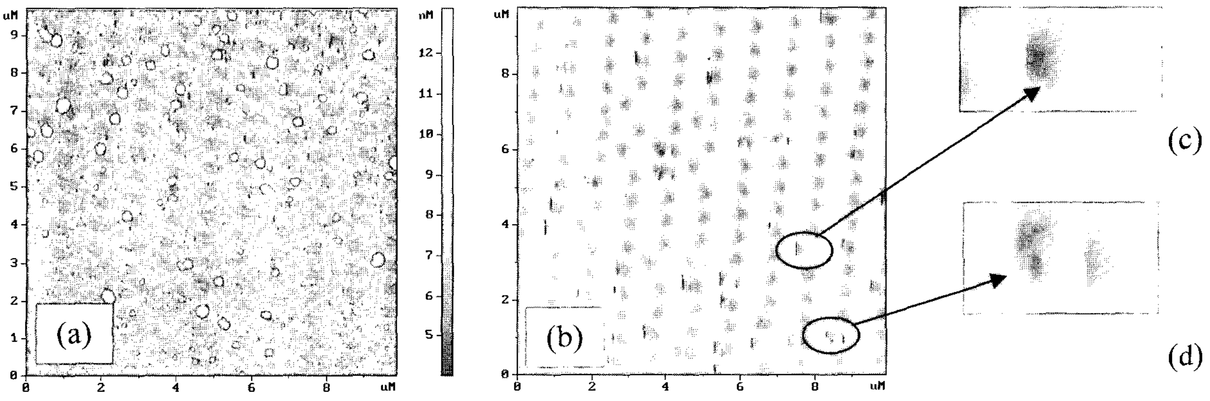

**Fig. 1.** AFM and MFM images of Fe-Cr nanodots array.

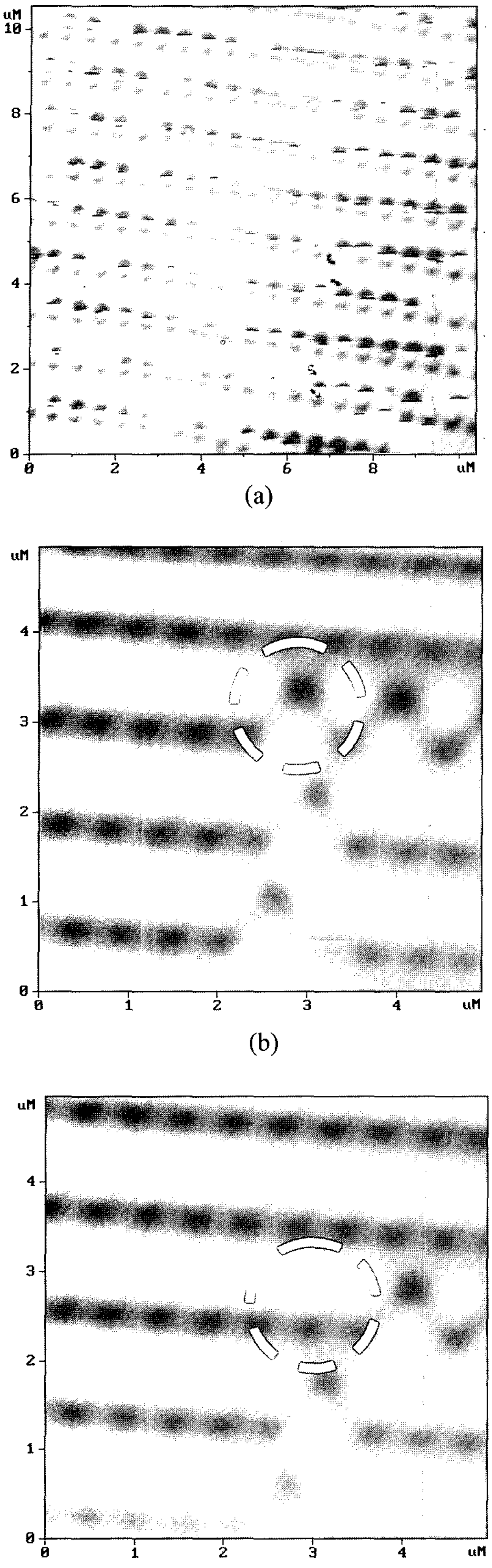

**Fig. 2.** Magnetization reversal effects in Fe-Cr nanodots.

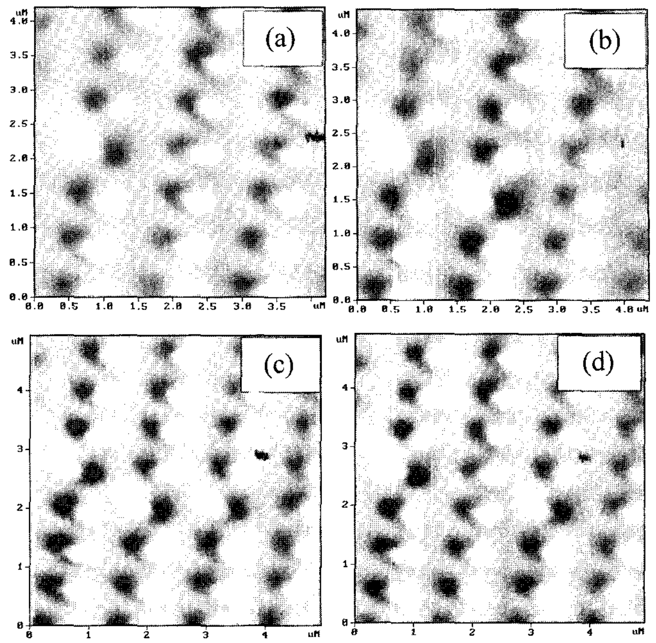

**Fig. 3.** Continuous stages of tip induced magnetization reversal process in Fe-Cr nanodots.

pass mode.

### 3.2. MFM induced single domain – vortex transitions in Co nanodots

Elliptical Co dots with different values of aspect ratio and thickness were fabricated by E-beam lithography process and subsequent ion etching technique of Co thin (25 nm) films [14]. Our MFM measurements showed that SD and SV states could be realized in elliptical Co dots depending on correlation between the thickness and lateral dimensions of the dots. Fig. 4 shows AFM and corresponding MFM images of the same place on sample surface.

The ground state in these dots was shown to correspond to SV. During scanning of this array in the two-pass technique, we observed 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. It is noted that the SV $\Rightarrow$ SD transition occurs during scanning in the central part of the dot (scanning along the long axis of the dot). If the MFM probe moves near the edge of the dot, a reverse transition from single domain to vortex state (SD $\Rightarrow$ SV) occurs. Such effects could be used for switching of vorticity direction within a Co dot. An elementary act of the magnetic vortex sign reversal is shown in Fig. 5. Remagnetization effects were also found in Co dots with lateral dimensions of 0.5 × 1 $\mu$m. It was revealed that the

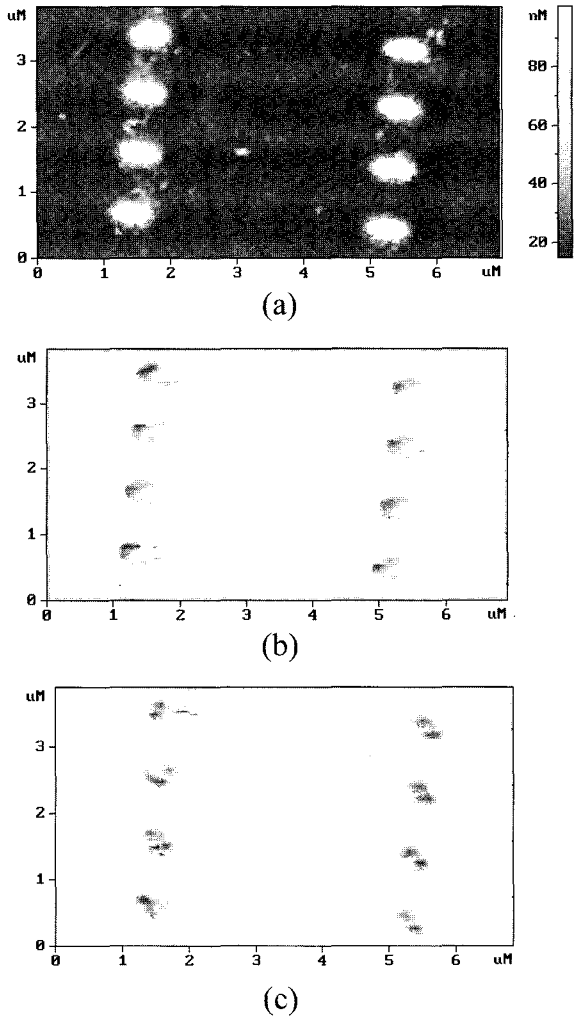

**Fig. 4.** AFM (a) and corresponding MFM images (b, c) of Co dots array.

magnetic multi-vortex state is more favorable for these dots.

## 4. Conclusion

In conclusion, high periodicity array of ferromagnetic nanodots was successfully produced using both laser interferometric lithography and e-beam lithography. MFM experiments show that the magnetic field of the MFM cantilever can easily change the magnetic configuration within ferromagnetic nanodots. Tip induced single domain to single domain (SD ⇒ SD) reversible magnetization reversal effects were observed in Fe-Cr nanodots. In Co dots a reversible transition SV ⇒ SD ⇒ SV was observed to occur with change of the vorticity direction. The character of the remagnetization processes largely depends on dot geometry (aspect ratio), the magnetic moment of the tip and the lift height during scanning. The above mentioned remagnetization effects probably could be used in high-density memory technologies.

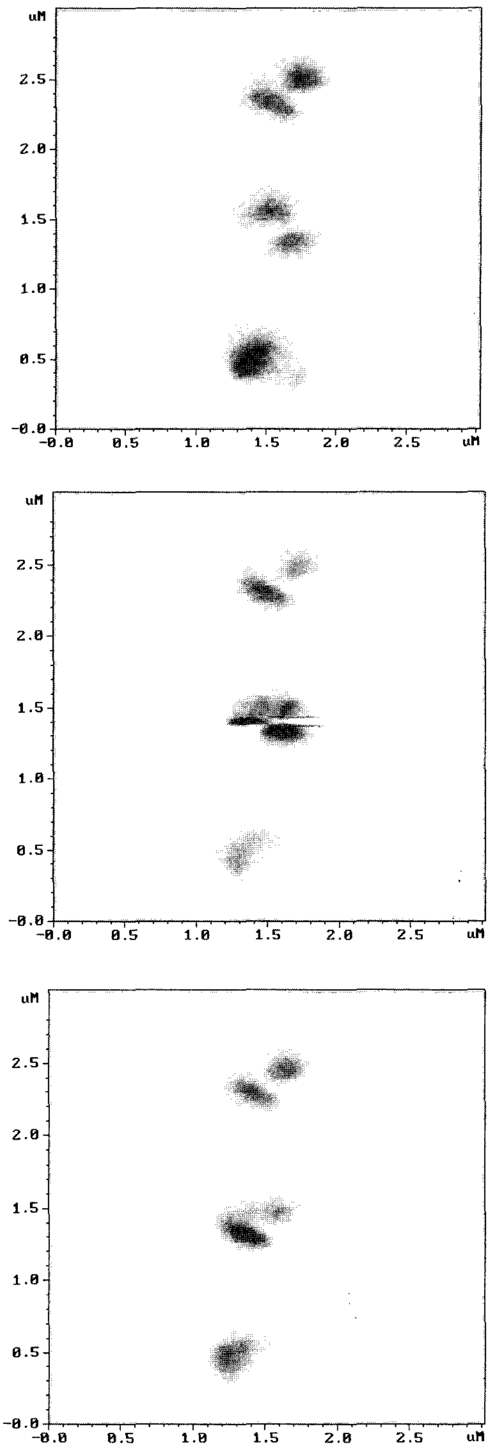

**Fig. 5.** Switching of vorticity direction within Co dot (middle dot). Three consecutive scans from the same place.

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## References

[1] B. D. Terris. L. Folks, D. Weller, J. E. E. Baglin, A. J. Kellock, H. Rothuizen, and P. Vettiger, Appl. Phys. Lett. **75**, 403 (1999).

[2] S. Y. Chou, M. Wei, P. R. Krauss, and P. B. Fisher, J. Vac. Sci. Technol. B **12**, 3695 (1994).

[3] T. A. Savas, M. Farhoud, H. I. Smith, M. Hwang, and C. A. Ross, J. Appl. Phys. **85**, 6160 (1999).

[4] A. Fernandes, P. J. Bedrossian, S. L. Baker, S. P. Vernon, and D. R. Kania, IEEE Trans. Magn. **32**, 4472 (1996).

[5] M. Zheng, M. Yu, Y. Liu, R. Skomski, S. H. Liou, D. J. Sellmyer, V. N. Petryakov, Y. K. Verevkin, N. I. Polushkin, and N. N. Salashchenko, Appl. Phys. Lett. **79**, 2606 (2001).

[6] M. Kleiber, F. Kümmerlen, M. Löhndorf, A. Wadas, D. Weiss, R. Wiesendanger, Phys. Rev. B **58**, 5563 (2002).

[7] X. Zhu, P. Grütter, V. Metlushko, and B. Ilic, J. Appl. Phys. **91**, 7340 (2002).

[8] X. Zhu, P. Grütter, V. Metlushko, and B. Ilic, Phys. Rev. B **66**, 024423 (2002).

[9] A. Fernandez, M. R. Gibbons, M. R. Wall, and C. J. Cerjan, J. Magn. Magn. Mater. **190**, 71 (1998).

[10] A. Fernandez, and C. J. Cerjan, J. Appl. Phys. **87**, 3, 1395 (2000).

[11] T. Okuno, K. Shigeto, T. Ono, K. Mibu, and T. Shinjo, J. Magn. Magn. Mater. **240**, (2002).

[12] N. I. Polushkin, B. A. Gribkov, and V. L. Mironov, Book of abstracts international conference "Micro- and nano electronics-2003", Zvenigorod, October 6-10, 2003, p. O1-21.

[13] http://math.nist.gov/oommf.

[14] A. A. Fraerman, S. A. Gusev, L. A. Mazo, I. M. Nefedov, Yu. N. Nozdrin, I. R. Karetnikova, M. V. Sapozhnikov, I. A. Shereshevsky, and L. V. Sukchodoev, Phys. Rev. B **65**, 064424-1 (2002).