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Effect of size and configuration on the magnetization of nickel dot arrays

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Abstract: We report experimental results on magnetic properties of our fabricated nickel nanodot arrays studied with magnetic force microscopy (MFM) and magneto-optical Kerr effect (MOKE). Arrays of nickel dots with different size and periodicity were fabricated by electron-beam (E-B) lithography and lift-off processes. 50 nm thick arrays (200 nm $\times$ 200 nm) of nickel dots exhibit that the magnetization occurs independently in term of the direction of applied filed, while smaller arrays (120 nm $\times$ 80 nm) with thicknesses ranging from 12 nm to 35 nm show the effect of size and configuration of arrays whose magnetic responses are different. Thinner dots in such array seem to assume single domain state with a preferential easy and hard axis in the array, but thicker dots shows a vortex type remanent magnetization. We ascribe the existence of the preferential magnetization axis to a dipolar-dipolar interaction due to small separation of single domain dots.

Keywords: Magnetic force microscopy, Nickel, Nanodot, MOKE, Magnetostatic interaction

1. INTRODUCTION

Increasing demands for higher magnetic information storage capacity have made magnetic nanotechnology an intense and competitive field of research in recent years leading to the development of nanomagnetism field of research and technology.[1] The maximum achievable storage capacity depends upon the magnetization reversal of the storage material and its stability. The size, shape and behaviour of magnetic domains as recording bits in the material are the determining factors of such magnetic memory storage devices.[2] Nanofabrication, mainly based on lithography techniques makes it possible to fabricate arrays of separated magnetic dots in comparable critical sizes in nanomagnetism.[3]

Nanostructures can be fabricated by post-lithography depositions called lift-off technique. This utilizes the height of a developed resist to break apart a subsequently deposited, much thinner, layer of material. The film deposited on top of the resist is lifted off during resist striping, leaving behind only the portions directly deposited onto the substrate. It is crucial to have a clean break-off of the film at the pattern edges of the resist. Therefore lithography process might lead to some rough and inaccurate nanostructures when the process meets technical or resolution limitation. The lithography resolution limit is ultimately determined by the radiation wavelength. Hence lithography is usually categorized by the radiation source as optical, electron-beam (e-beam), ion beam, and X-ray lithography.[3] The e-beam lithography technique uses an electron beam to expose an electron-sensitive resist. One of the main advantages of this technique is its versatility for the fabrication of arbitrary element shapes and array configurations.[4,5]

The magnetic properties of nanodots are rather difficult to study due to the small signals. In general, most researchers resort standard averaging techniques to study the magnetic properties. In recent years, it has been approved that the magnetisation reversal of such magnetic nanodot arrays can be investigated by several techniques. Magnetic force microscopy (MFM), in particular, gives a resolution below 20 nm with comparability low effort in sample preparation. It does not need ultra clean sample surface and UHV. Also, magnetic field can be applied to samples during microscopy.[6] More recently it has been demonstrated that magneto-optical Kerr effect (MOKE) can be utilized to detect magnetic response raised from a small area of magnetic nanodot arrays, revealing different magnetization modes.[7-10]

While there are several investigation results on the magnetic properties of nickel dot arrays achieved by MFM or other techniques,[11-14] but the effect of size and configuration of arrays on the magnetic properties of dots has not been extensively studied. In this paper, we aim to report our experimental results on magnetic properties of nickel nanodots arrays using MFM and MOKE methods.

2. EXPERIMENTAL DETAILS

In order to measure the magnetic properties of nickel dot arrays, we first fabricated initial marks from Ti/Au pads at the surface of an insulating Si/SiO2 substrate using optical lithography. These pads narrowed down to thin wedges separated by micron sized gaps on which we patterned arrays of nanodots. We then used electron beam lithography, model Raith Elphy plus equipped with Hitachi high resolution scanning electron microscope (HRSEM 4300S), to expose linear and grating of nano-scale dots in the poly-methyl-methacrylate (PMMA) layer directly over the gaps. Electron beam dose intensity and dose factor were chosen so that the arrays of dots could be properly obtained. We utilized different exposure and PMMA composition to make dot arrays and study the consequent structure effect on the magnetic properties. The patterned PMMA layer was developed in methyl-isobuthyl-ketone (MIBK) and isopropyl alcohol (1:3 in volume). Then thin layer of nickel was thermally evaporated at a pressure of ~2×10-6 torr. After lift-off in acetone, we obtained arrays of nickel dots aligned in the marked positions to facilitate the magnetic measurements.

MFM was used to study the magnetic response of the fabricated structures using an Asylum research MFP3D instrument in dynamic lift mode. We used two different high quality magnetic cantilevers with integrated tips and spring constants between 1 and 2 N/m supplied by Asylum Research. The resonance frequencies were found to be 55-90 kHz. One of the cantilevers called Standard is Si coated with a single layer of 50 nm CoCr served as a magnetic thin-film coating for the tips with 300-450 Oe coercivity. The other one called Low coercivity has 30 nm permalloy coating with a coercivity of less than 10 Oe. Magnetic force gradients were measured by detecting phase shifts in the cantilever oscillation due to attractive or repulsive forces acting on the ferromagnetic MFM tip. In some cases, we magnetized samples using an external electromagnet before studying the samples. In all experiments MFM tip was magnetized in the z direction or perpendicular to the plane of the substrate prior to the measurement.

The magnetization curves of the dot arrays were measured by magneto-optics Kerr effect[8], at 300K and for different angles of the magnetic field in the plane of the dots in respect to the mark angles.

3. RESULTS AND DISCUSSION

We first fabricated larger arrays of square nickel dots. Figure 1(a) illustrates a typical three dimensional atomic force microscopy (AFM) image representing the topography of 200 nm × 200 nm grating of nickel square dots. AFM image shows that the fabricated dots are of good quality. The thickness (or height) of the dots in the grating is 50 nm. We measured the magnetization of these dots using MOKE magnetometry.[8] Figure 1 (b) shows the average magnetization curves of the arrays in different configurations, when the external field is applied in the plane of dots along different directions. Superimposed curves do not reveal any considerable change between magnetization reversal of the array in different configurations. Hence, there is no detectable easy or hard axis of magnetization of the large array of nickel dots and each single dot is likely magnetized in its independent status. In order to investigate the effect of array configuration, we also fabricated a linear array of 200 nm $\times$ 200 nm grating of nickel square dots and examined the domain structure of both arrays with MFM. Figure 2 (a) shows AFM image representing the topography of the nickel 200 nm dots in a linear array. In the absence of an applied field, there is no preferential direction of magnetization across the array. Upon application of an external field (H ~ 1.0 KOe externally before MFM) nearly all the dots seem to rotate from in-plane to out of plane configuration across each single dot. MFM images of magnetised Ni dots show that white areas disappear and dark area form. Figure 2(b) shows the growth of domains whose magnetizations are parallel to the applied field. Since the image presents the remanence state, just after turning off the external field, the process of domain expansion should be continuing with increasing field, indicating constant magnetization inside, and strong bright/dark contrast on the ends, representing the concentration of magnetic poles along the magnetised direction. We observed the same behaviour for grating of nickel dots. [15]

Smaller dots in closer separation reveal more interesting magnetization features. We fabricated 120 nm $\times$ 80 nm grating of nickel square dots with different heights (or thickness). Figure 3 (a) shows the topography and line profile of 120 nm nickel nanodots with 12 nm thickness. The corresponding average magnetization curves of such array in different configurations are shown in Figure 3 (b). The main feature of the hysteresis loops is the existence of preferential easy and hard axes for different configurations. Indeed, there seems an easy axis along $\theta = 0^0$ as we see a squared loop along this direction of the application of external field. The magnetic domain features of this array are different from what we see for larger grating (Figs. 1 and 2). Figure 4 presents MFM images of 120 nm $\times$ 80 nm grating of nickel square dots with 12 nm thickness taken by the two different magnetic tips. In Figure 4 (a) the MFM image is studied using the standard magnetic tip having a coercivity of about that of dots measured by MOKE, while Figure 4 (b) is the MFM image obtained with the low coercivity tip which does not interrupt the magnetic state of small dots. The MFM measurements were performed in the dynamic mode with a phase detection system. Resonance frequency shifts towards higher frequencies led to a bright contrast in the phase detection. Therefore, a repulsive interaction between tip and sample is represented by bright contrast and an attractive interaction by dark contrast.[16] The sample was magnetized along ($\theta = 0^0$) direction prior to the MFM measurement. The magnetization direction of the dots are not exactly aligned in the direction of the applied field, while bright contrast on the right hand side and black contrast on the left hand side are deviated for all dots in the array. Repeating the same experiment with a low coercivity tip led to a magnetic contrast that is characterized by a repulsive interaction above the center of a dot and an attraction interaction at both ends with same deviating angle for all dots. The remanent state of Ni dots can be described as single domain state[16], while the preferential magnetic state seen by MOKE and MFM measurements implies that a magnetic coupling occurs between adjacent dots in the array. Indeed, it has been shown that a magnetic anisotropy in thin dot arrays is induced by a magnetostatic coupling energy.[17-19] P. Castrucci *et al* have carried out micromagnetic simulations including an uniaxial anisotropy along the long side of an array of permalloy dots. It was then verified that the anisotropy field is quite effective that makes the simulations and experimental results quite similar.[19] The change of magnetization easy axis seen in our results may be explained in terms of the magnetostatic inter-dot interaction which gives an additional energy contribution to be overcome by the external field during the static magnetization rotation. Another feature observed in our study is the remanent vortex state in thicker nickel nanodots. An array of 120 nm $\times$ 80 nm Ni dots with 35 nm thickness was fabricated and examined by MFM. Figure 5 shows AFM, line profile and the corresponding MFM image of such array of Ni dots. Sample was magnetized perpendicular to the plane of the dot. The vortex is at the center of the disk in remanence. The vortex-type remanent magnetization distribution is energetically favorable for the disks with weak magnetocrystalline anisotropy. The evolution of this state in nickel dots is expected to be stabilized when the disk size is above a critical value which determines the single state.[20,21] It has been theoretically mentioned that such magnetization reversal of a dot in a vortex state takes place via nucleation, displacement and annihilation of a single magnetic vortex, when the magnetic field applied in the direction perpendicular to the cylinder axis.[22]

4. CONCLUSIONS

In conclusion, MFM and MOKE are complementary techniques giving precise information on average and local magnetic properties of the dot arrays. In particular, MFM technique is able to show the magnetic domain state corresponding to each single dot and to the array. The latter provided makes average information above the whole array of dots. We observe that size and configuration play an important role in magnetic properties of nickel dot arrays. The smallest nickel dots in our study fabricated in arrays with the closest separation seem to be in single domain state and exhibit a magnetostatic interaction with adjacent dots giving rise to a preferential magnetization direction observed by MOKE. While thicker dots in the same array gives a vortex-type remanent magnetic state. Larger dots in greater separation do not reveal any dependence of magnetization on the configuration of applied field.

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Figure 1- (a) Three dimensional AFM image of 200 nm $\times$ 200 nm grating of nickel square dots and (b) average magnetization curves measured by MOKE magnetometry in different configurations. Onset shows the direction of applied magnetic field in respect to the array configuration.

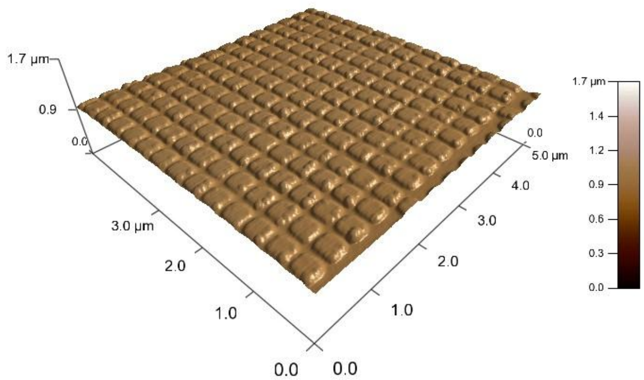
Figure 2- (a) AFM and (b) MFM images of 200 nm $\times$ 200 nm linear array of nickel square dots

Figure 3- (a) Top panel: AFM image of 120 nm $\times$ 80 nm grating of nickel square dots, bottom panel: line profile of the dots representing the thickness, (b) average magnetization curves measured by MOKE magnetometry in different configurations. Onset shows the direction of applied magnetic field in respect to the array configuration.

Figure 4- MFM image of 120 nm $\times$ 80 nm grating of nickel square dots taken with (a) standard magnetic tip and (b) low coercivity magnetic tip.

Figure 5- (a) Top panel: AFM image of 120 nm $\times$ 80 nm grating of nickel square dots, bottom panel: line profile of the dots representing the thickness. (b) MFM image taken after magnetizing sample perpendicular to the dot.

Figure 1, F. Nasirpouri et al.



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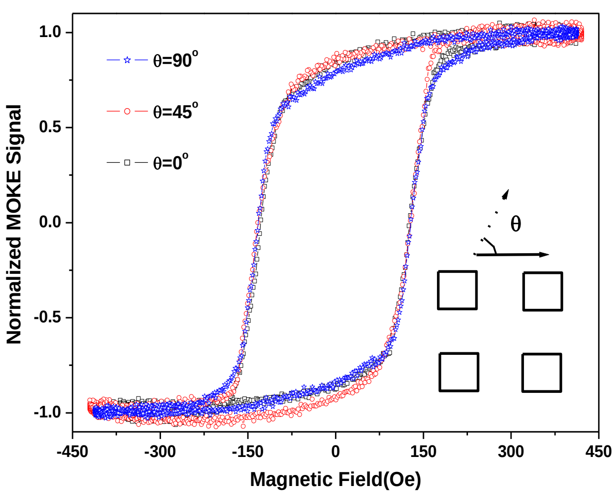

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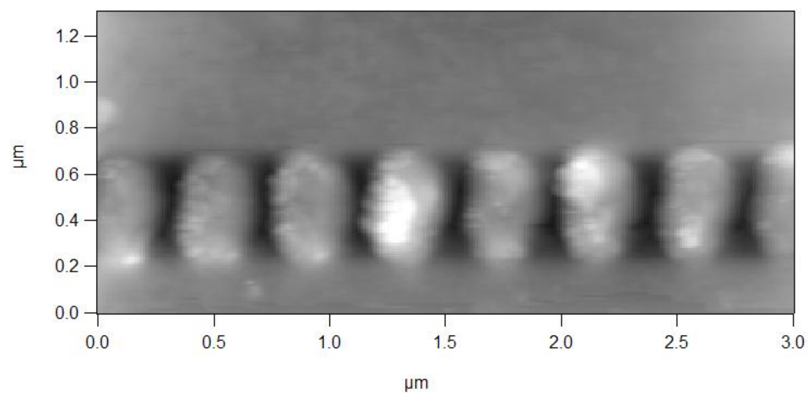
Figure 2, F. Nasirpouri et al.



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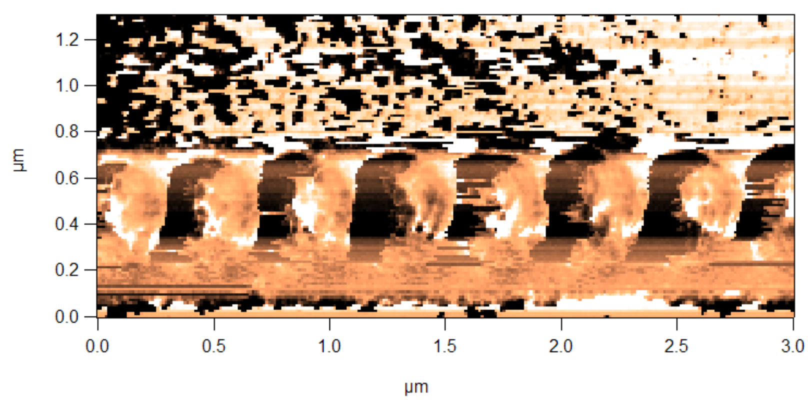

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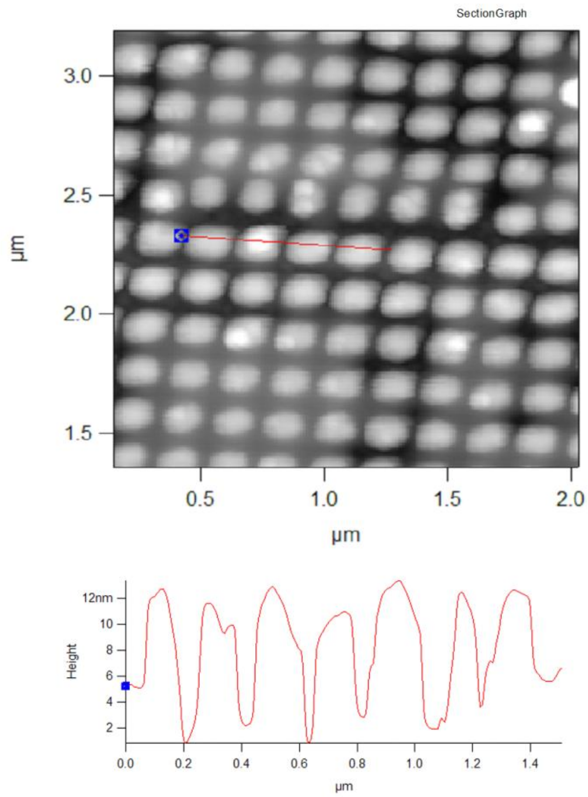

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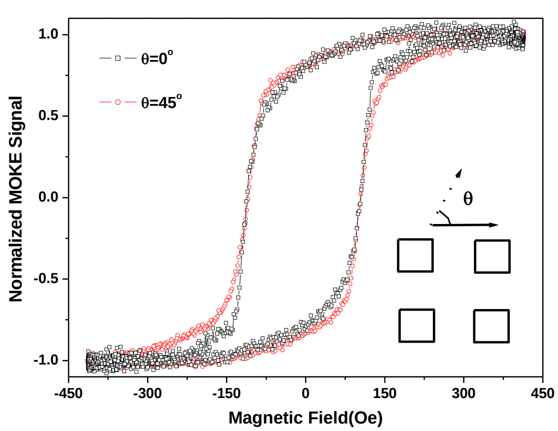

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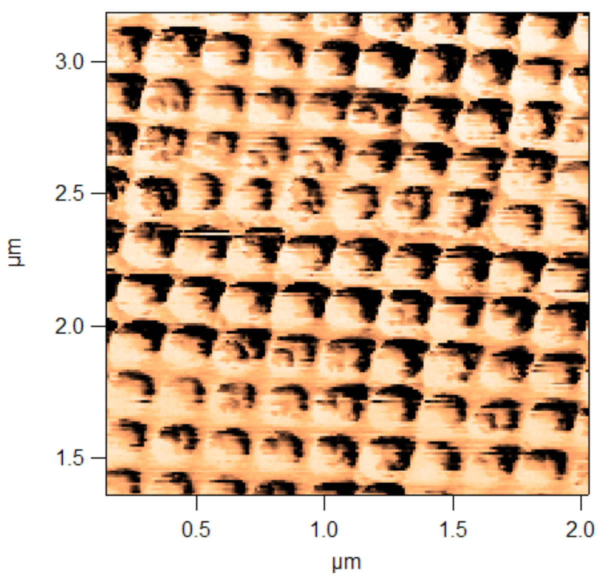
Figure 4, F. Nasirpouri et al.



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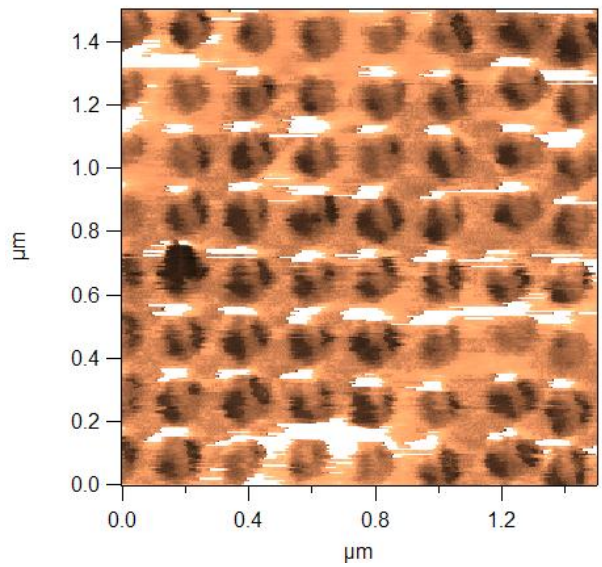

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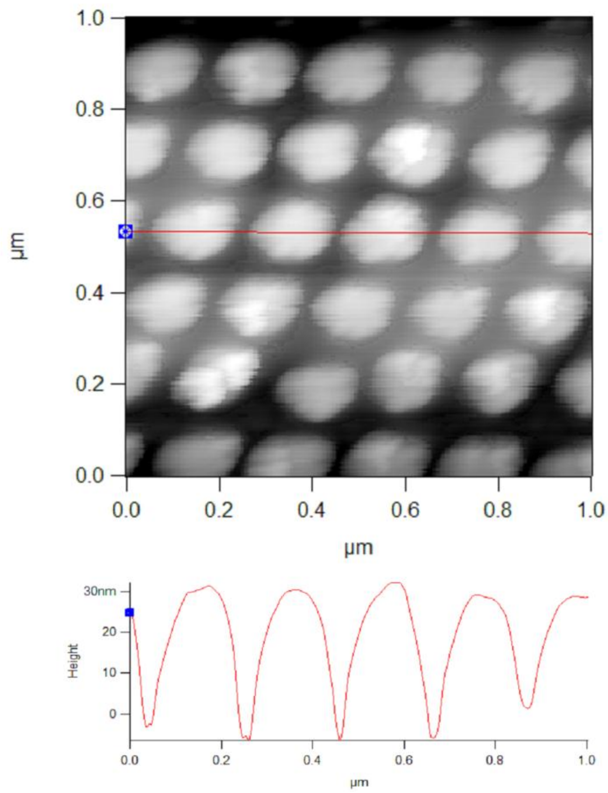
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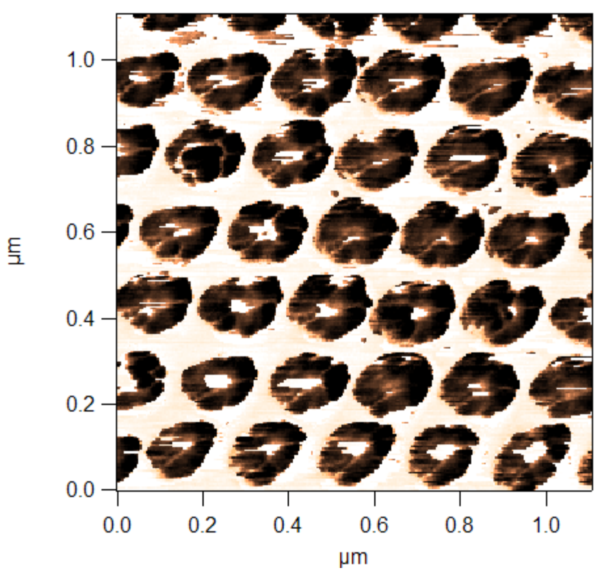
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