OSCILLATORY THICKNESS DEPENDENCE OF THE COERCIVE FIELD IN 3D ANTI-DOT ARRAYS FROM SELF-ASSEMBLY

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We present studies on magnetic anti-dot nano-structures with 3D architectures, fabricated using a self-assembly template method. We find that patterning transverse to the film plane, which is a unique feature of this method, results in novel magnetic behavior. In particular, one of the key parameters for a magnetic material, the coercive field B_c, was found to demonstrate an oscillatory dependence on film thickness.

The demand for higher magnetic recording densities is stimulating intense research activity into magnetism on sub-micrometer length scales. The main requirement for commercially viable products is an efficient and low-cost preparation process. Methods based on templates formed by the self-assembly colloidal particles have been considered for various applications such as photonic materials [1,2], microchip reactors [3] and biosensors [4]. In this work we use ordered templates for the electro-deposition of different magnetic materials. This technique offers new opportunities, which are not easily realized by standard lithographic methods, and allows us to create magnetic nano-structures with 3D architectures on a broad range of length scale, 50 – 1000 nm.

Using slow (3-5days) evaporation of a colloidal water suspension containing 1wt% of latex spheres well-ordered templates have been self-assembled on glass substrates with buffer layers of Cr (10nm) and Au (200nm) prepared by sputtering. These templates have been further used as moulds to prepare nano-porous magnetic structures by electro-deposition methods [5]. After deposition the latex spheres can be removed by dissolving in toluene. Using this method, well-ordered nano-structured 3D arrays were prepared for various magnetic materials such as cobalt, iron, nickel and soft-magnetic $Ni_{50}Fe_{50}$ alloy. An SEM image of one of the nano-structured films is given in Fig.1a. It shows that the films have excellent hexagonal order. In comparison with conventional lithographical techniques our method has a significant advantage. It also produces structuring in the direction transverse to the film plane. Cross-sectional SEM (Fig.1b) demonstrates that the transverse structuring is also well ordered.

Magnetization measurements, using a vibrating sample magnetometer (VSM), have been used to investigate the effect of the array of uniform spherical voids on the

magnetic behavior of the nano-structured films. Characteristic hysteresis loops, for the sample at room temperature and for magnetic fields (***B***) applied parallel to the film plane, are presented in Fig.2a. The nano-structuring significantly changes the magnetization loops. The loops presented in Fig.2a show that the irreversibility field, which corresponds to the merging point of increasing and decreasing field branches, monotonically increases with decreasing diameter of the spherical voids. In contrast, the coercive field B_c, shows a non-monotonic change. This can be seen in Fig 2b for Co and $Ni_{50}Fe_{50}$ structures. First, the coercivity increases by more than an order of magnitude for decreasing pore size (1000 nm ≥ d ≥ 50 nm). Note that B_c = 2.8 mT for Co films and 0.6 mT for $Ni_{50}Fe_{50}$ films deposited by a similar electrochemical route but without template. After reaching a maximum, B_c decreases for further decrease of the anti-dot diameter. We found the value of the diameter corresponding to maximum coercivity, d_{max}, to agree with the condition ½ d_{max} ≈ w_B with w_B the domain wall width for the material. Indeed, the domain wall width is w_B = 16nm for Co [7]. For $Ni_{50}Fe_{50}$, taking as a rough estimate an average value between Ni and Fe [7] we get w_B = 70nm, again in agreement with the condition ½ d_{max} ≈ w_B. This indicates the importance of domain wall pinning for such anti-dot structures.

Measurements of the dependence of B_c on the thickness of the magnetic film revealed a novel effect. Although these films have a homogeneous composition of magnetic material, as evident from the EDSRX studies, we have found that the coercive force changes periodically with film thickness. This is a clear manifestation of the periodical patterning in the direction transverse to the film and the 3D architecture of these structures. Fig.3 demonstrates that B_c shows clear oscillations and reaches a maximum for the case when the top surface of the film is near the center of a layer of close packed spherical voids. For complete spherical layers the coercive field

approaches a minimum. These observations suggest that the points where the spheres touch play an important role in domain wall pinning and hence the coercivity.

Presence of domain boundaries can be seen from the MFM images. They were obtained with a Digital Instruments 3000 scanning probe microscope using lift-mode with a fly height of 100 nm and a standard low-moment ferromagnetic tip. Results are shown in Fig. 4 for a 100 nm thick Co film with d = 700 nm in the remanent state. These images reveal ordered, rhombic magnetic patterns associated with the hole array. Magnetic structures for 2D hole arrays were calculated using micromagnetic modelling with the OOMMF software suite [8]. The large number of computational cells (~10^8) required for 3D case to explain the $B_c(t_f)$ data appears above present computing powers. Therefore we have employed a simplified approach. Using the values of $B_c(D/d)$ found from the 2D numerical simulations we consider our system as a multilayer with properties averaged in the plane direction. By a Monte-Carlo method we calculate $B_c(t_f)$ for this stack of exchange coupled layers. As can be seen from Fig.5 the results of the numerical simulations reproduce our experimental behaviour. Note that for simplicity we have chosen the period in the perpendicular direction to be d in this model; the period of the $B_c(t_f)$ oscillations reflects this.

We can qualitatively understand the results of our experiment assuming that domain wall pinning is the main mechanism for the coercive properties. In this case the narrow constrictions between the spherical voids are dominant pinning sites. The number of effective pinning sites changes periodically with the film thickness t_f. Using this, we can describe the observed behavior using a simple model of domain wall pinning. In this model we assume a flat domain wall and take its energy E_b to be proportional to the volume of the domain wall. From the dependence of E_b on domain

wall position we calculate the coercive field B_c [7]. As can be seen from Fig.5 model results also reproduce well experimental observation of the $B_c(t_f)$ oscillations.

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FIGURE CAPTIONS

Fig.1. SEM image of structured Ni film prepared using 0.5 μm polystyrene spheres (a) and cross-sectional view for a thick film after cleaving (b).

Fig.2. Magnetization curves obtained by VSM for nano-structured and plain $Ni_{50}Fe_{50}$ films with different pore diameters (a). The dependence of coercive force on pore diameter for $Ni_{50}Fe_{50}$ and Co films (b). The Co films with very small pore sizes (d < 20 nm) were prepared using soft templates [6].

Fig.3. Coercive field for $Ni_{50}Fe_{50}$ films with different thickness prepared using 550nm and 750nm spheres. For clarity, in the case of 750nm the B_c values are divided by factor 2. The dashed lines show the positions of sphere centers for each layer in a close packed structure.

Fig.4. MFM image for a Co anti-dot film with d = 700 nm and t_f = 100 nm.

Fig.5. Model dependences of the coercive field for $Ni_{50}Fe_{50}$ films with d = 0.5μm from the homogeneous-layer micromagnetic model and from the domain wall pinning model (with d/w_B = 25).

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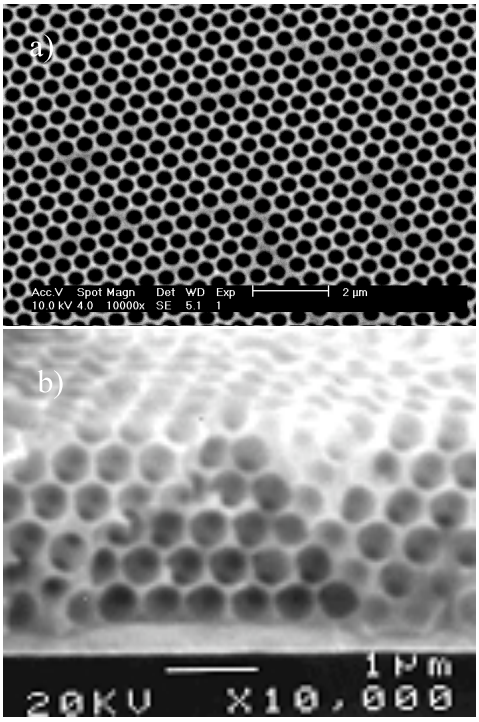
a)
Acc.V Spot Magn Det WD Exp
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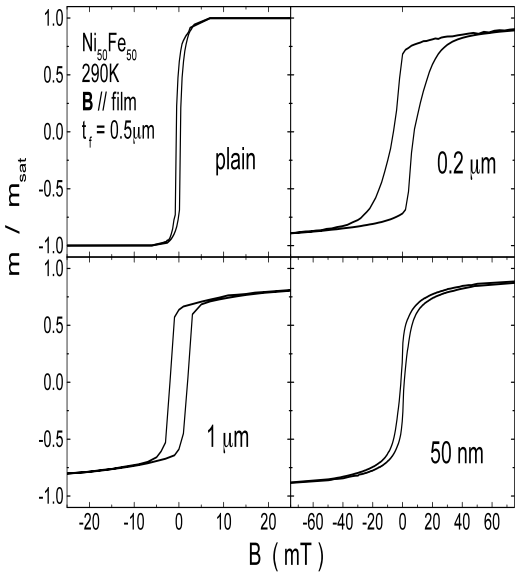
2 µm
b)
1 µm
20KV X10,000

Fig.1

a) b)


Ni50Fe50
290K
B // film
tf = 0.5μm
plain
0.2 μm
1 μm
50 nm
m / msat
B (mT)

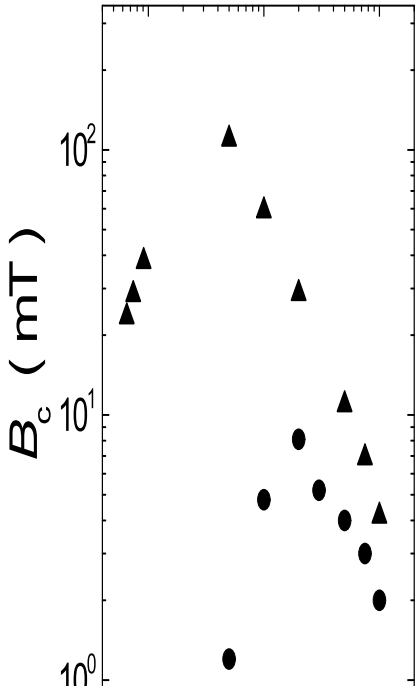

Bc (mT)

Fig.2

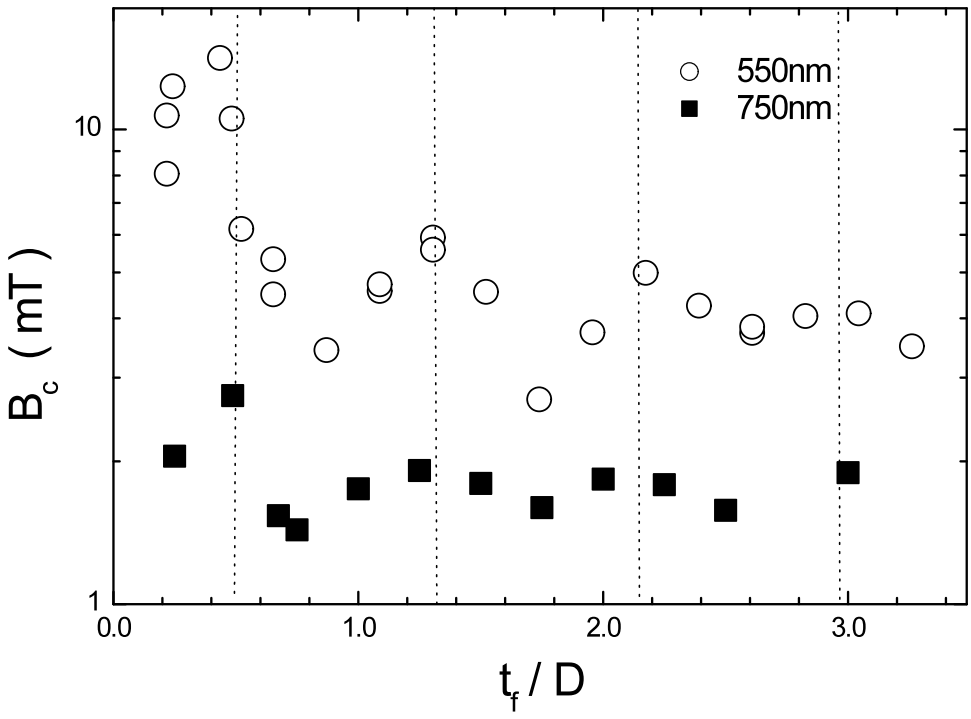


Fig.3

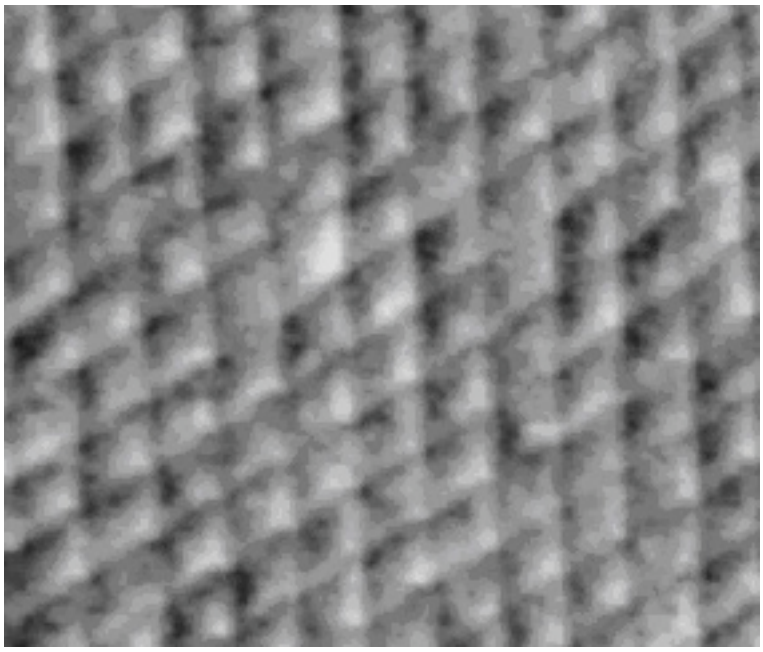


Fig.4

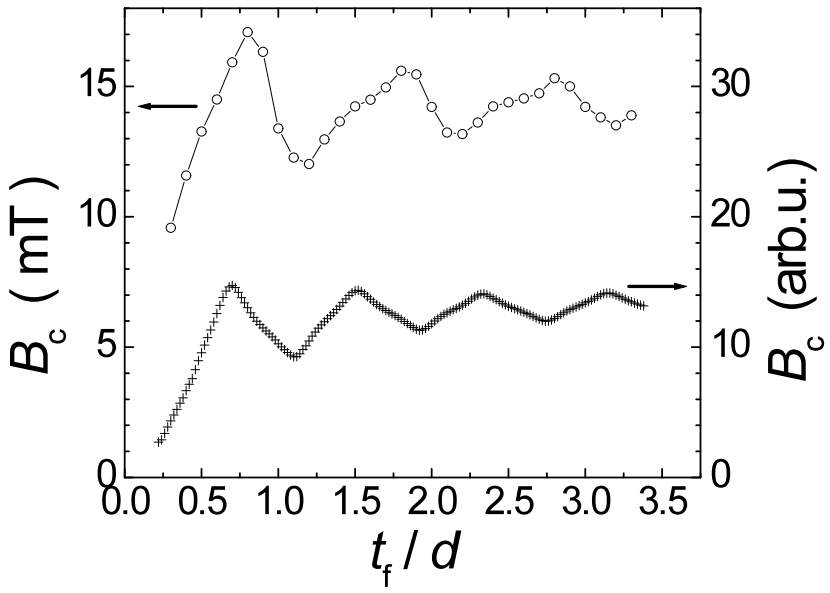


Fig.5