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Effects of Interdot Dipole Coupling in Mesoscopic Epitaxial Fe(100) Dot Arrays

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***Abstract*—The domain structure and the coercivity of epitaxial Fe(100) circular dot arrays of different diameters and separations have been studied using magnetic force microscopy (MFM) and focused magneto-optical Kerr effect (MOKE). The MFM images of the 1 μm diameter single domain dot arrays show direct evidence of strong interdot dipole coupling when the separation is reduced down to 0.1 μm. The coercivity of the dots is also found to be dependent on the separation, indicating the effect of the interdot dipole coupling on the magnetization reversal process.**

***Index Terms*—Fe dot arrays, interdot coupling, magnetic storage media, micromagnetism.**

I. INTRODUCTION

MAGNETIC properties of small magnetic articles in bulk-like materials have been studied since early 1960s [1]. The critical size of single domains, the dipole interaction between particles etc. have been extensively studied particularly in magnetic receding media. Micro/nano scale magnetic dots and wires, patterned from two dimensional thin film, with well defined shapes and sizes, owning to the advance in nanofabrication techniques, are of great interest recently due to their potential applications in high density magnetic storage media and spin electronic devices such as magnetic random access memory. While the domain structure and magnetization reversal in both the polycrystalline [2]–[6] and epitaxial [7]–[14] dots and wires continue to attract attention, the effect of the dipole coupling between dots and wires in well defined arrays is now an important topic as well [12], [15]–[18]. Hillebrands *et al.* [15], [16] studied the static and spin wave properties of the Permalloy dot arrays using Brillouin light scattering and found evidence of interdot coupling in arrays with a separation of 0.1 μm. Grimsditch *et al.* [17], on the other hand, found that the large in-plane anisotropies in submicron Fe dot arrays is due to the shape anisotropy of individual dots rather than interdot coupling. We have recently carried out a study of micromagnetism in epitaxial Fe(100) circular dot arrays of different diameters and separations grown on GaAs(100) by molecular beam epitaxy and patterned by e-beam lithography. The competition between the magnetic anisotropy, demagnetization fields, and exchange interaction in isolated bcc Fe dots was found to lead to a first transition from a single domain to a multidomain state around 10 μm, followed by a second transition from the multidomain to single domain state upon reducing the dot diameter [12]. In this paper, we further report the effects of interdot dipole coupling on the magnetic domain structure and the coercivity in dot arrays of various separations. This study of such a model system is highly relevant to the understanding of the effects of dipole interactions between particles in high-density magnetic storage media.

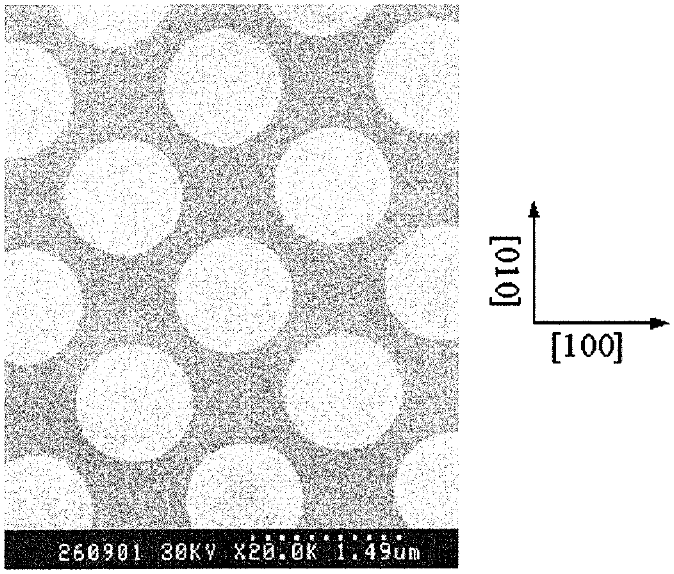

Fig. 1. A scanning electron microscopy picture of the 1 μm diameter and 0.5 μm separation dot array.

II. SAMPLE FABRICATION AND MEASUREMENTS

The starting magnetic material is a high quality epitaxial bcc Fe film of 140 monolayers (ML) thick grown by molecular beam epitaxy on GaAs(100) substrates at room temperature. The GaAs substrate has a half-micron epilayer protected by an As capping layer. The As capping layer is desorbed prior to the Fe growth by annealing. The film was then capped with a 4 nm thick Au layer to prevent oxidation before removal from the growth chamber. The Fe dot arrays were fabricated using electron-beam lithography (JEOL JBX5D2U) operated at 50 KeV and ion beam etching with an intermediate metallic mask of Al made by a lift-off process. The diameter d of the circular dots was varied from 50 μm to 0.1 μm, and the separation s varied from $2d$ to $0.5d$. The square dot arrays

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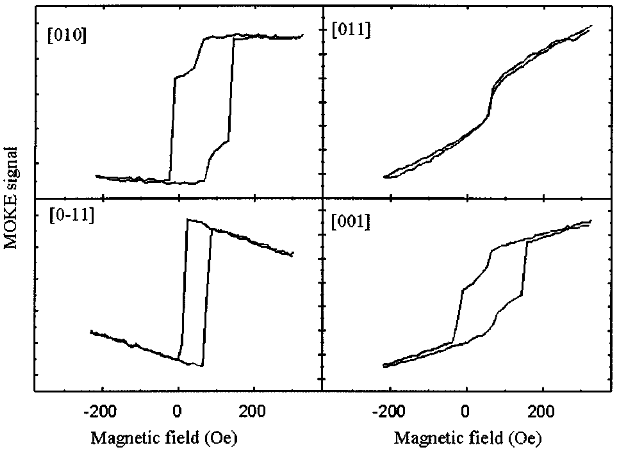

Fig. 2. MOKE hysteresis loops of an isolated 50 μm dot with the magnetic field applied along four major axes.

have total sizes of about 200–500 μm. Fig. 1 shows a scanning electron microscopy picture of the 1 μm diameter and 0.5 μm separation dot array, confirming that the dots have well defined shape and sharp edges.

The magnetic anisotropy of an isolated 50 μm dot was characterized as a reference using focused magneto-optical Kerr effect (MOKE) microscopy with a lateral resolution of about 2 μm. The MOKE loops shown in Fig. 2 reveal that the global magnetic easy axis is along the [0–11] direction due to the presence of a strong uniaxial magnetic anisotropy (UMA). Although it is surprising that the UMA persists to such a large thickness, large variations in UMA strength have been reported previously [19]–[21]. The domain structures were studied using magnetic force microscopy (MFM) with a commercial Si tip coated with CoCr.

III. Effect of Interdot Dipole Coupling on Domain Structures

Our previous work [12] has revealed two transitions in the domain structure with reducing size for isolated dots. A single domain state is observed for the large dots (about 20 to 50 μm), which is stabilized by the magnetic anisotropy, while the single domain state appears again in small dots (around 1 μm) due to the exchange interaction. In the single domain state, the magnetic configuration can be characterized by a single "giant" spin corresponding to the total moment of the dot. We have also shown that the single domain states in the large dot arrays collapse into multi-domain states due to the local dipolar coupling between dots via the edges when the separation is reduced down to half the diameter. While the domain structure of the large single domain dots are seen to be strongly affected when the separation is reduced, the interdot coupling in the small single domain dots can be expected to be important only for very small separations. Fig. 3 shows the domain structures of the 1 μm dot arrays of different separations in the demagnetized state (as grown). The MFM image of the 1 μm separation array in Fig. 3(a) shows dark and bright contrast across the individual dot. This indicates that the dots are in the single domain state with the spin aligned along the global magnetic easy axis. The MFM image of the 0.5 μm separation array in Fig. 3(b) shows a similar pattern to that of Fig. 3(a), but with relatively weak contrast. However, the image of the 0.1 μm separation array in Fig. 3(c) shows distinctively different patterns. The spins of different dots are now correlated and form a large domain around the right-hand bottom corner of the image. We would like to point out that the dots in the 0.1 μm separation array are not physically connected, as confirmed by line scans across the sample as shown in Fig. 3(d). The formation of the large domain extending across several dots is thus clear evidence of the interdot dipole coupling, which in this case arises for smaller separations than for the larger diameter dots studied previously [12].

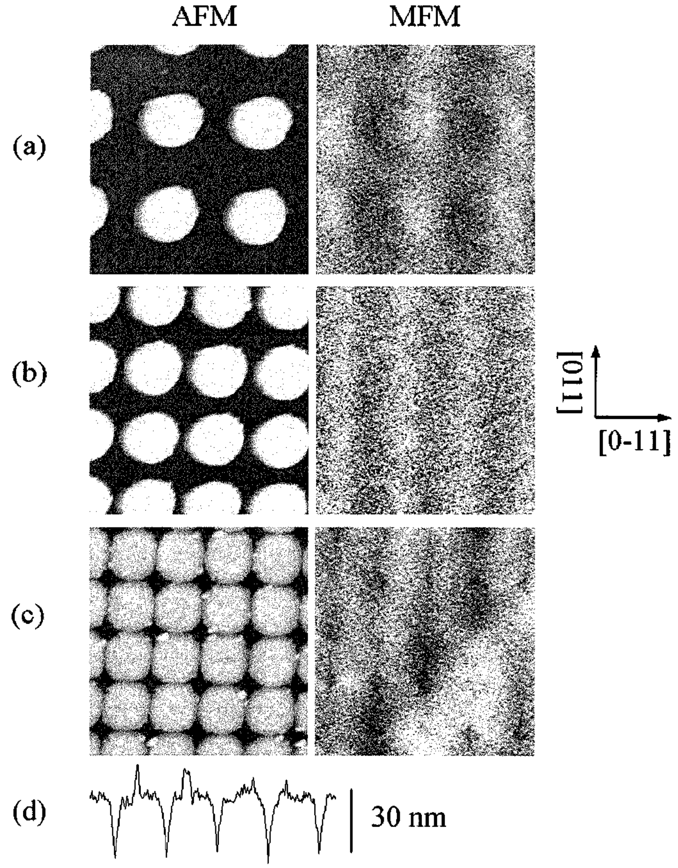

Fig. 3. AFM and MFM images of 1 μm dot arrays of three different separations: (a) 1 μm, (b) 0.5 μm, and (c) 0.1 μm, and (d) line scan across the 0.1 μm dot array in (c) showing clearly that the dots are not connected.

IV. Effect of Interdot Coupling on Coercivities

The coercivity of an individual dot in the array has been measured using focused MOKE. An optical beam with a diameter of about 2 μm was focused on the center of dot for the measurements. We have so far measured the dot arrays with a diameter larger than 2 μm. Fig. 4 shows the coercivities of two sets of dot arrays with $s = 2d$ and $s = 0.5d$ as a function of the diameter with the magnetic field applied along the global easy axis. There are two important features: 1) the coercivity is enhanced in both arrays with decreasing diameter, and 2) the coercivity is much smaller in the dot array with $s = 0.5d$ than those with $s = 2d$. The increase of the coercivity with the decrease of dot diameter in the $s = 2d$ dot arrays suggests that coherent domain rotation

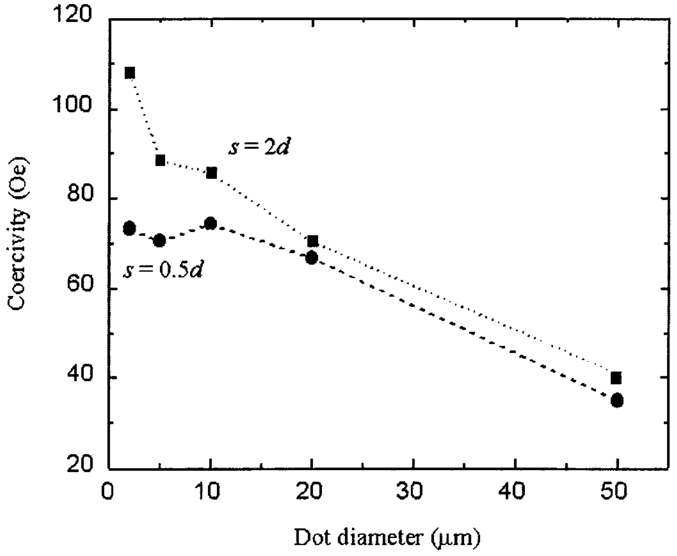

Fig. 4. Coercivities of two sets of dot arrays with $s = 2d$ and $s = 0.5d$ as a function of the diameter with the magnetic field applied along the global easy axis.

becomes more important in the magnetization reversal process. This is similar to the enhanced coercivity observed in ultrathin epitaxial Fe dots upon reduction of the thickness [11]. The decrease of the coercivities in the $s = 0.5d$ array as compared with those of the $s = 2d$ arrays can be readily understood: the coercivity of the dot arrays can be expected to approach that of the continuous films when the separation becomes sufficiently small. A further experimental study and micromagnetic simulations are needed to get deeper insight into the separation dependence of the coercivity. However, the significantly different coercivities observed for these two different separations demonstrate that the interdot dipole coupling plays an important role in the magnetic reversal process.

V. CONCLUSION

Epitaxial Fe(100) circular dot arrays of different diameters and separations grown on GaAs(100) by molecular beam epitaxy have been patterned by e-beam lithography, and studied using magnetic force microscopy and focused magneto-optical Kerr effect. Evidence of the effects of the interdot dipole coupling on both the domain structure and the coercivity was found. The domain structure of the 1 μm diameter dot arrays show the effect of strong interdot coupling only when the separation is reduced down to around 0.1 μm. The coercivity of the large dot arrays (with diameter larger than 2 μm) was found be dependent on their separations. While both the $s = 2d$ and $s = 0.5d$ arrays show enhanced coercivities, the coercivity is decreased in $s = 0.5d$ arrays as compared with that of $s = 2d$ arrays. This further indicates the effect of interdot coupling on the magnetization reversal process, and illustrates that both the dot diameter and separation are crucial parameters.

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