Magnetization Reversal in a Network of Dipolar Coupled Dots

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(Received Nov. 6, 2000; Accepted Nov. 23, 2000)

Abstract- We report the physical realization of periodic networks of micromagnetic dots, coupled by both the exchange and dipolar interactions. A series of samples with different ratios of exchange to dipolar coupling ρ , were patterned using a focused Ga^+ ion beam (FIB). The parameter ρ can be controlled by varying the Ga^+ ion beam fluence. Both static and dynamic studies reveal a transition between exchange and dipolar coupled states as Ga^+ fluence is increased.

Key words : magneto-optical recording, thin film, nanostructures, irradiation, magnetic patterning, Co/Pt

1. Introduction

Current high density magnetic and magneto-optical recording media are composed of nanometer size grains more or less coupled by exchange interaction. In such systems, it is difficult to give a realistic account of the magnetization reversal process, since their local properties are highly non uniform [1,2]. Grain size and shape vary across the film, so that efficiency of exchange and dipolar coupling at grain boundaries is not well quantified. In future, patterned media consisting of arrays of well defined, sub-micron magnetic elements are likely to become important. As bit dimensions are reduced dipolar interactions become increasingly important.

The aim of our study is to investigate the influence of dipolar coupling on magnetic reversal processes in ultra thin, dot arrays with perpendicular magnetic anisotropy. As in a previous work [3], focused Ga^+ ion beam irradiation has been used to pattern arrays of dots coupled by both exchange and dipolar interactions. Tuning of the beam fluence gives a degree of control over the relative strengths of exchange and dipolar coupling.

The virgin media consisted of highly uniform Pt(3.4nm)/Co(1.4nm)/Pt(4.5nm) layers, epitaxially grown using magnetron sputtering on a transparent $\text{Al}_2\text{O}_3(0001)$ single crystal substrate. The as-grown film exhibits a very square hysteresis loop (Fig. 2), indicating a strong perpendicular, uniaxial anisotropy. In fact, the samples can be considered as 2D Ising model system with two stable 'up' or 'down' magnetization states [4]. Magnetization reversal is dominated by easy domain wall propagation following rare nucleation events. At room

temperature, the nucleation field is found to be much greater than the domain wall propagation field. Hence although the magnetization reversal has been initiated by nucleation, coercivity is defined by the domain wall propagation field H_p . The high quality of the grown media prevents a large dispersion of coercive field across the sample (width of its distribution : $\Delta H_p = 20$ Oe).

2. FIB Patterning Technique

We have previously reported the possibility to fabricate well defined magnetic dot arrays, with nanometer resolution, by the Focused Ion Beam (FIB) technique [3]. Uniform ion bombardment of the film at low dose ($D < 10^{14}$ ions / cm^2) causes intermixing of the Co/Pt interfaces and nearly no etching. As a consequence, the local exchange and anisotropy are reduced, which leads to important changes of the magnetic properties in the irradiated region. By adjusting the beam fluence it is possible to tune the magnetic properties (e.g. Curie temperature, coercive field) of the film [5]. For $D > 2 \times 10^{15}$ ions / cm^2 the film even becomes paramagnetic at room temperature. At low Ga^+ ion beam fluence ($D < 10^{14}$ ions / cm^2), the media is not etched and, optically the film remains almost unchanged. This makes the technique particularly favorable for designing magnetic or magneto-optic recording media where medium planarity is crucial. At higher doses, the film becomes etched by FIB (for example a rough estimate of the etching depth by TRIM Monte-Carlo calculations [6] is 0.7 nm for $D = 10^{15}$ ions / cm^2) and for $D > 7 \times 10^{15}$ ions / cm^2 , the Co layer is even destroyed.

Arrays of $2 \mu\text{m} \times 2 \mu\text{m}$ square dots were directly patterned onto the continuous ferromagnetic film by sweeping the FIB in two orthogonal directions. The irradiated lines have a gaussian like profile, as illustrated in Fig 1. At moderate lineic fluences (estimated $D > 0.1$ nC/cm), the centre of the lines become paramagnetic at room temperature, leading to the cancellation of the exchange interaction between dots, while the long range dipolar interaction is less affected. For $d < 0.1$ nC/cm, the ratio of exchange to dipole coupling ρ , can be precisely controlled by varying the irradiation dose. In this manner a series of samples with several values of ρ were fabricated.

Fig 1 Schematic view of FIB magnetic lines separating the magnetic dots. At the center of the line the fluence is large enough to render the Co layer paramagnetic (dark gray). At the edges of the line the dose is weaker and the material becomes magnetically softer than the dots (light gray).

Another feature of the patterning technique is that the coercive field of the film along the edges of the dots is attenuated as the ion dose tails off away from the centre of the line. In counterpart the interior of the dot retains the magnetic properties of the as-grown film. Consequently, magnetization reversal is initiated at the soft dot borders at low magnetic fields. Hence, when the switching field, H_s , is reached a rapid reversal can take place in the interior of the dots by domain wall propagation. One will take advantage of the weak dispersion of the propagation field in the interior of the dots to reveal the effects of the dipolar interaction on the system.

3. Experimental Results

We use high resolution (0.3 μm) magneto-optical microscopy to study both the local magnetism of individual dots or the entire array, for a range of samples patterned using different irradiation fluences. Figure 2 shows hysteresis loops obtained from magneto-optical Faraday measurements for the as-grown film and a FIB array of dots separated by paramagnetic lines. Both hysteresis loops show close coercive fields while the reversal slope is weaker for the FIB array. This is characteristic of a system of dipolar coupled dots. In this case magnetization reversal inside the dots takes place by domain wall motion when the local switching field $H_s = H_p + H_d$ where H_d is the dipolar field which can be either positive or negative depending on the local environment of each dot.

Fig 2 Faraday hysteresis loops for the as-grown film and for an array $2\text{ }\mu\text{m} \times 2\text{ }\mu\text{m}$ of square dots patterned using a FIB line dose of 0.5 nC/cm

At low field, dipolar interactions aid dot reversal and many dots switch before nucleation in the continuous film. However, once the total magnetization of the system reaches zero, dipolar interactions resist magnetization reversal. Further evidence can be derived from hysteresis loops of individual dots in the system. These are found to be very square indicating propagation controlled reversal [3]. In addition the switching field H_s , of individual dots depends upon the spin configuration of the neighbouring dots and has a much higher dispersion ($\Delta H_s = 80\text{ Oe}$), than that of the propagation field within the dots alone ($\Delta H_p = 20\text{ Oe}$).

In order to probe the equilibrium magnetic ground state of the system of dots, we performed an isothermal, slow demagnetization by applying a perpendicular magnetic field with alternating decreasing amplitude [3]. The results of this experiment performed on arrays irradiated at four different doses, are shown in Fig 3. For low dose arrays (Fig 3a) the blob like magnetic domain pattern (typical dimensions of 10 μm) is indistinguishable from that exhibited by the continuous film. At high doses (Fig 3d) the dot array adopts a broadly checkerboard pattern with narrow regions of frustration formed at the boundaries between misaligned checkerboards. This is in strong agreement with expected results for an array of dipolar coupled 2D Ising dots [3].

For a critical dose of 0.1 nC/cm (Fig. 3b), the competition between exchange and dipolar coupling produces an irregular stripe domain state. This is the signature of a transition between the exchange and dipolar dominated behaviours, as already predicted by simulation for $p = 0.37$ [6]. Note that this transition appears sharp. Collective behaviour similar to that found at the highest dose is already established at a dose which is only twice the critical dose (Fig. 3c). The observed domain structures are consistent with those predicted by simulation, but performed on an hexagonal lattice [1].

Fig 3: Demagnetized state for irradiated arrays of $2\ \mu\text{m} \times 2\ \mu\text{m}$ dots for different fluences of Ga^+ ions. (a) 0.005nC/cm , (b) $0.1\ \text{nC/cm}$, (c) 0.25nC/cm , (d) $5.0\ \text{nC/cm}$. At low doses the magnetic domain pattern is indistinguishable from that of the continuous film, while for high doses the dots take on a partial checkerboard ordering with regions of frustration.

One can gain some quantitative notion of the degree of ordering of the demagnetized dot arrays by defining an order parameter N_1 , which is the average over all the dots of nearest-neighbours (immediately top, bottom, left and right) with opposite spin orientation. The number N_2 , of next-nearest-neighbours (at either corner) with the same spin orientation can be also estimated. As the system becomes more checkerboard like, both numbers should approach four. Results for arrays fabricated with five different lineic doses are given in Table 1.

FIB fluence (nC/cm)	Reversed nearest neighbours, N_1	Aligned next nearest neighbours, N_2
0.1	1.659	1.652
0.25	2.146	1.763
0.5	2.9093	2.5574
2.5	2.924	2.538
5	2.909	2.557

Table 1: Statistical analysis of the experimental demagnetized state for a series of $2\ \mu\text{m} \times 2\ \mu\text{m}$ dot arrays, fabricated using different fluences of Ga^+ ions.

We find that the degree of order of the demagnetized state is increased with FIB fluence as a consequence of the enhancement of ρ . In agreement with simulations [3], perfect checkerboard alignment is not achieved due to the random nature of the switching of the first dots. Large checkerboard regions may grow from a small number of 'seed' dots with low H_p , but frustration occurs when misaligned checkerboards meet up. Thus, the values of N_1 and N_2 tend rapidly towards limits around 2.9 and 2.56.

Finally, the magnetization reversal dynamics of the dot arrays under a constant applied magnetic field, (i.e. magnetic after-effects) have been studied (Fig 4). Once again we note that the low dose arrays behave very much like the continuous film with magnetization reversal taking place by easy domain wall propagation. In the high dose arrays, where the exchange interaction between dots has been broken, the reversal in each dot is controlled by the dipolar interactions. In this case, many dots start to switch after short time, t . However as discussed above, once half the dots have switched, the reversal becomes very slow. Analysis of the reversal curves for the dipolar coupled dot arrays indicate power law like dynamic behaviour, in agreement with recent simulations [7].

(a) Low Dose (0.001 nC/cm), $H=255$ Oe

(b) Intermediate Dose (0.01 nC/cm), $H=263$ Oe

(c) High Dose (0.50 nC/cm), $H=263$ Oe

Fig 4: Magnetic aftereffect (the time elapsed after reversing the field is indicated) under a constant field H for Pt/Co(1.4nm/Pt) patterned arrays of $2\ \mu\text{m} \times 2\ \mu\text{m}$ square dots : (a) For the low dose, magnetization reversal takes place by a rather uniform domain wall motion and is indistinguishable from the continuous film, (b) At intermediate doses, there is a transition from continuous to discrete behaviour. (c) At high doses, exchange coupling is destroyed and magnetization reversal is dominated by dipolar coupling between dots.

4. Conclusion

In this paper we have reported on the first studies of the static and dynamic behaviour of magnetic dot arrays with perpendicular anisotropy, in the presence of both exchange and dipolar interactions. Due to the uniformity of initial structural and magnetic properties, it was possible to study the transition between the exchange and dipolar dominated regimes. In such a simple case, the limitations due to dipolar effects on perpendicular recording have been emphasised.

Acknowledgment This work was carried out under the ISARD collaboration (Université d'Orsay) and the SUBMAGDEV European TMR network which provided funding for R.H.

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