

Magnetic Domain Structure and Imaging of Co–Pt Multilayer Thin-Film Nanostructures

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Abstract—Dots, with diameters of 100 nm and 220 nm, have been fabricated from $(\text{Co}_x\text{Pt}_{0.8-x})_{25}$ multilayer structures, where the Co thickness x was varied from 0.2 nm to 0.45 nm. The unpatterned films show perpendicular anisotropy with perpendicular coercive fields of 20 kA/m to 100 kA/m. The patterned structures show a transition from multidomain to single domain behavior as the dot dimension is reduced from 220 nm to 100 nm. The remanent hysteresis loops of the 100 nm dots were measured using magnetic force microscopy (MFM) and compared to remanent hysteresis loops of the unpatterned films. MFM line scans of the 100 nm dots were compared to calculations of the field gradients expected above uniformly magnetized dots. The calculations indicate that narrow features in the magnetic field gradients should be observed near the edges of the dots and that these samples may be of use as a magnetic imaging resolution standard.

Index Terms—CoPt, magnetic imaging reference samples, MFM, patterned media.

I. INTRODUCTION

MAGNETIC nanostructures, with perpendicular anisotropy, may have applications for patterned media and solid state magnetic memory [1]–[3]. They are also useful to test metrological tools to see if one can determine, with adequate precision, the magnetic structure and switching mechanisms in small, technologically relevant systems. In this paper we investigate the magnetic structure and switching of small CoPt multilayer dots. The magnetic structure and switching is characterized by magnetic force microscopy (MFM). The MFM line scans are compared with numerical calculations of the field gradients from uniformly magnetized dots. The numerical calculations indicate that there should be fine scale structure in the field gradients at the edge of the dots. The fine structure was not observed, either due to resolution limits of the MFM or to nonideal magnetic structure in the dots.

II. EXPERIMENT

$\text{Ta}_{2\text{ nm}}\text{Pt}_{1\text{ nm}}(\text{Co}_x\text{Pt}_{0.8-x})_{25}$ multilayers, where the Co thickness x was varied from 0.2 nm to 0.45 nm, were sputter deposited onto SiO_2 coated Si wafers. The wafers have a series of numbered fiducial frames to allow repeated identification of magnetic structures after lithographic processing, field cycles, or temperature cycles. The films were patterned using standard e-beam lithography and ion beam etching techniques to form

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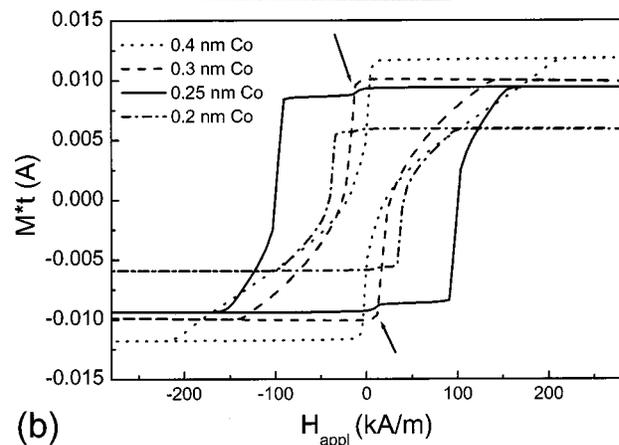
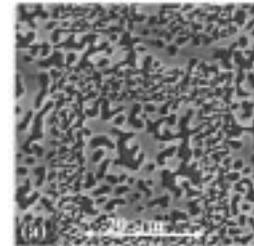


Fig. 1. (a) MFM image of as-deposited CoPt multilayer film. The fiducial frame can be seen as the region where the stripe domain widths decrease. (b) Perpendicular hysteresis loops for CoPt films with Co thicknesses varying between 0.2–0.4 nm. Arrows point to small jumps in the magnetization indicating that the system may have regions of different perpendicular anisotropy.

sets of dots with thicknesses of approximately 30 nm and varying diameters.

The MFM images were taken in lift mode by measuring the phase shift of the cantilever vibration relative to the drive signal. Commercial high coercivity tips were used. The film magnetization measurements were made using an alternating gradient magnetometer.

The magnetic structure, as measured by MFM, and the perpendicular magnetization loops of the unpatterned films are shown in Fig. 1. The films, in the demagnetized state, have stripe domains as seen in Fig. 1(a). The stripe domain periodicity varies depending on whether the film is on SiO_2 or the Au fiducial frame. Fig. 1(b) shows that the coercive field first increases as the Co layer thickness decreases but achieves a maximum value of 111 kA/m for thickness near 0.25 nm. The shape of the hysteresis curve, a sharp initial switch into a nearly demagnetized state followed by a linear region to the reverse saturation state, is similar to that observed in earlier studies [4]. MFM studies indicate that the reversal starts with

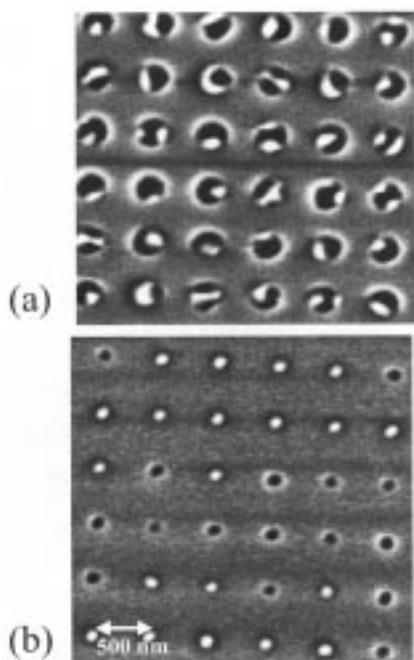


Fig. 2. (a) MFM images of demagnetized 220 nm $(\text{Co}_{0.25}\text{nm Pt}_{0.8}\text{nm})_{25}$ dots, (b) MFM images of demagnetized 100 nm $(\text{Co}_{0.25}\text{nm Pt}_{0.8}\text{nm})_{25}$ dots. The images a use a gray scale in which the black to white variation corresponds to a 3° phase shift.

an abrupt switch to the stripe domain state followed by a stage of gradual domain growth.

The in-plane hysteresis measurements (not shown) exhibit open loops with a nonzero value of the remanent magnetization, typically $M_1/M_s = 0.1$. The deviation of the in-plane magnetization loops from ideal hard axis loops indicates that the system is more complicated than one in which there is a uniform perpendicular anisotropy. The structure seen in the in-plane loops, as well as the fine scale structure seen in the perpendicular loops, near 0 and -30 kA/m, indicate the system may be a composite of two or more coupled systems with different perpendicular anisotropies. The saturation field measured from the in-plane hysteresis loops can be used to estimate the perpendicular anisotropy. For these samples, the perpendicular anisotropy energy varies from $2.0 \times 10^6 \text{ J/M}^3$ to $3.0 \times 10^6 \text{ J/m}^3$.

Fig. 2 shows the MFM images of 220 nm and 100 nm patterned dots in a demagnetized state. MFM clearly shows multidomain structure in the 220 nm dots whereas no fine structure is seen in the 100 nm dots. The 100 nm dots seem to be single domain within the resolution of the MFM. Fine structure and nonuniform magnetization on length scales below the resolution of the MFM are likely, given the complexity of the multilayer system.

The remanent hysteresis loop of the 100 nm dots was measured by analyzing the MFM images of a set of 100 dots after application of a perpendicular field opposite to the initial magnetization direction of the dots. The dot magnetization is defined as the normalized difference in the number of black and white dots. The remanent hysteresis curves for the 100 nm dots and the unpatterned film are shown in Fig. 3. The switching field for the dots is considerably larger than that for the film. This is expected

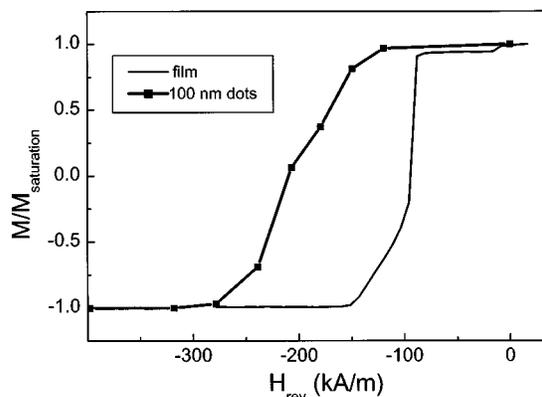


Fig. 3. Remanent hysteresis curves of 100 nm $(\text{Co}_{0.25}\text{nm Pt}_{0.8}\text{nm})_{25}$ dots and unpatterned film.

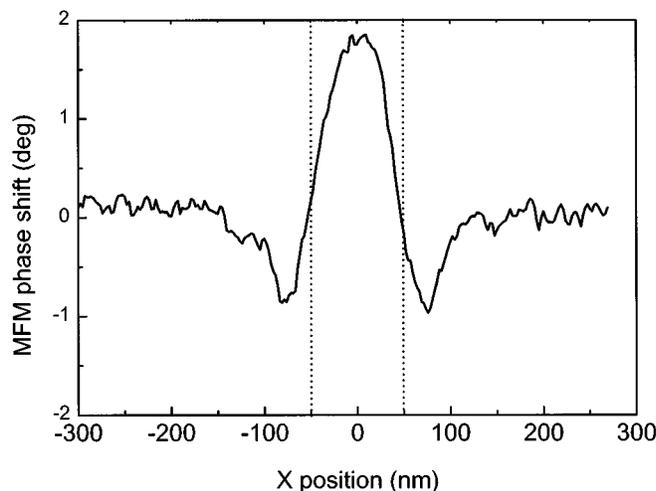


Fig. 4. MFM line scan across a 100 nm dot. The broken lines indicate the physical extent of the dot.

since the perpendicular demagnetizing field, which assists in the reversal process, is less for the dots than it is for the film. The change in the perpendicular demagnetizing factor, ΔN_{ZZ} , going from a bulk film to a 100 nm dot is $\Delta N_{ZZ} = 0.149$, which corresponds to a decrease in the demagnetizing field in the dots of 212 kA/m. The change in demagnetizing field is roughly the same size as the observed increase in the coercivity, approximately 150 kA/m.

The shape of the remanent hysteresis curve for the bulk film is quite different. The reversal in the bulk film is determined by a rapid transition to a stripe domain state and a region of domain wall growth. The reversal process in the dots will be quite different since the size scale of the dots is below the natural domain size. The broad shape of the remanent reversal curve for the dots is likely due to distribution in the dot sizes and shapes.

A line scan of the MFM image taken across a 100 nm dot is shown in Fig. 4. A dip in the signal is seen at the device edges. The physical extent of the dot is also marked in the figure, and it is seen that the edge of the dot occurs where the signal, in the central peak, is approximately zero. The line scan was taken in lift mode at 20 nm above the measured topography.

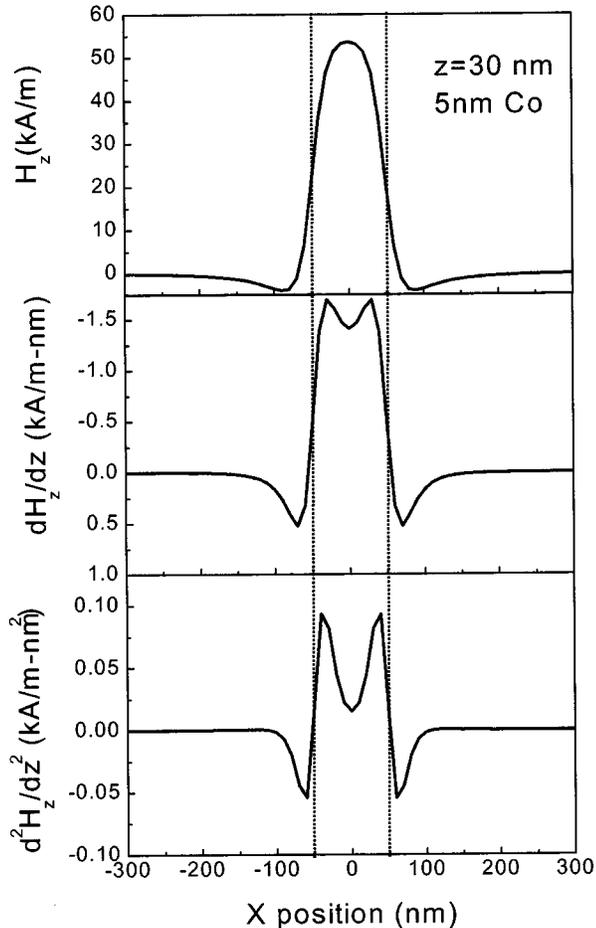


Fig. 5. Calculated perpendicular fields and field gradients 30 nm above a current ring equivalent to a 100 nm diameter dot with a moment equal to 5 nm of Co.

III. DISCUSSION

If the dot were uniformly magnetized in the perpendicular direction, then the field it would produce would be equivalent to a current ring with a diameter of 100 nm and a height of 30 nm. The perpendicular component of the magnetic field, H_z , and perpendicular field gradients, dH_z/dz and d^2H_z/dz^2 , from an ideal current ring are plotted in Fig. 5 for a height of 30 nm above the plane of the ring. In the simplest model of MFM [5], [6], the active area of the tip has a monopole and a dipole component which gives rise to an output signal which has a component proportional to $-dH_z/dz$ and a component proportional to d^2H_z/dz^2 . The ratio of these components is a function of the magnetic structure at the tip and is not well known. However, both the first and second field gradients have peak structures with characteristic widths of 20 nm. Features on this length scale are not seen in Fig. 4. It is important to note that the calculated

field values are for a fixed distance above the substrate, not a fixed distance above the topography, as in the MFM line scan. However, given the variation in the MFM tip height relative to the substrate, we still expect to see smaller features than what is observed.

The results indicate that either the MFM resolution is not sufficient or that the magnetic structure in the dot is not ideal. The resolution of our MFM is typically measured by imaging a virgin demagnetized region of fine grain magnetic recording media. The resolution is determined as the spatial frequency, in the Fourier transform of the image, at which the magnetic signal drops below the noise level. This method yields a resolution of 40 nm to 50 nm for our current setup. This resolution is consistent with the minimum observed feature in the MFM line scans of the CoPt dots. New MFM methods and tips are being developed which promise to have a resolution of 20 nm or less [7], [8], and it should soon be possible to determine whether this discrepancy is due to limited resolution or complex magnetic structure in the CoPt dot.

In conclusion, we have fabricated small, perpendicularly magnetized CoPt dots, and observed a transition from multi-domain behavior to single domain behavior as the dot diameter is reduced from 220 nm to 100 nm. Dots with dimensions of 100 nm are chemically and magnetically stable and should have features in the field gradients on size scales which are at the current resolution of MFM. These nanostructures provide a useful system to test current MFM technologies and may form a good system for future magnetic imaging reference samples.

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