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# Magnetic Force Microscopy of Single-Domain Cobalt Dots Patterned Using Interference Lithography

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**Abstract** — We have fabricated arrays of Co dots having diameters of 100 nm and 70 nm using interference lithography. The density of these arrays is  $7.2 \times 10^9/\text{in}^2$ . Magnetic force microscopy measurements indicate that the Co dots are single-domain with moments that can be controlled to point either in-plane or out-of-plane. Interference lithography is a process that is easily scaled to large areas and is potentially capable of high throughput. Large, uniform arrays of single-domain structures are potentially useful for high-density, low-noise data storage.

## INTRODUCTION

It is anticipated that an alternate form of magnetic media will be required for very high-density data storage. The packing density of thin-film recording media is fundamentally limited by the jaggedness of domain walls which gives rise to noise in the readback signal [1]. In principle, a storage technology based on single magnetic domain particles can overcome this limitation and allow for much higher storage densities [2]-[4]. A single-domain particle can be magnetized in two discrete states with equal but opposite magnetic moments. An array of such particles could be used to record binary information with each particle storing one bit of information.

Recently, several groups have investigated the magnetic properties of small, lithographically defined magnetic structures and considered the possibility of their use for data storage [2]-[4]. New *et al.* fabricated arrays of 150 nm by 200 nm islands patterned from 20 nm thick Co films [2], [3]. They used electron beam lithography to define the islands and a dry etch process to transfer the pattern. Magnetic force microscopy (MFM) indicates that the islands are single-domain with moments that are in-plane [3]. Using electron beam lithography and electroplating, Krauss *et al.* fabricated arrays of 50 nm diameter Ni pillars with densities as high as  $6.5 \times 10^{10}/\text{in}^2$  [4]. These particles exhibit single-domain behavior with moments that are out-of-plane.

One of the main challenges in developing a storage technology based on single-domain particles is finding a

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viable and cost-effective process for fabricating high-density arrays of magnetic structures. Three key fabrication requirements must be satisfied. (1) The particles must be sufficiently small to inhibit multiple domain formation. This requires that the particles be approximately 100 nm or less in diameter. (2) The size and shape of the particles must be uniform over large areas. (3) The arrays must be produced inexpensively and with a process that can be easily scaled to meet the demands of high-volume manufacturing.

In this paper, we report on the use of interference lithography to fabricate high-density arrays of single-domain Co dots. Interference lithography provides a relatively inexpensive way to generate periodic structures over large areas. It has been used in a variety of applications including the fabrication of x-ray and extreme ultra-violet gratings [5], ultra-violet polarizers and filters [6], and, more recently, field emission arrays for flat panel displays [7]-[9]. Importantly, interference lithography is capable of defining structures with dimensions of 100 nm [5]-[10]. Here, we present MFM analysis of the fabricated Co arrays. These measurements demonstrate we can control the dimensions of the structures to permit easy-axis magnetization either in-plane or out-of-plane.

#### FABRICATION

Interference lithography is carried out by combining two beams of coherent radiation at a specified angle at the exposure plane. Interference of the two beams produces a sinusoidal intensity pattern with a period given by  $\lambda/[2 \sin(\theta)]$  where  $\lambda$  is the wavelength and  $\theta$  is the recombination half-angle. If the beam intensities are matched, the modulation transfer function of the intensity pattern is 1 and independent of the period. This has the important consequence that deep submicron period gratings can be produced with a near i-line coherent source. (We use the 351 nm line of an Ar ion laser.) Another advantage is that the depth-of-focus of the interference pattern is virtually infinite on the scale of semiconductor processing [10] due to the long coherence length of the lasers typically used. Furthermore, the exposure area can be scaled to areas as large as 50 cm  $\times$  50 cm [9] which makes interference lithography attractive for high-throughput applications.

The details of the dot fabrication process are described elsewhere [9]. Briefly, a resist coated Si wafer is exposed to the interference pattern. It is subsequently exposed a second time after being rotated 90° with respect to the first pattern. Development of the exposed layer produces a 2-dimensional array of resist holes or pedestals. Co dots are defined by thermally evaporating a thin layer of Co through the holes and subsequently using a lift-off process. No intermediate film is deposited between the Co and Si. The dots are centered on a 300 nm square grid which

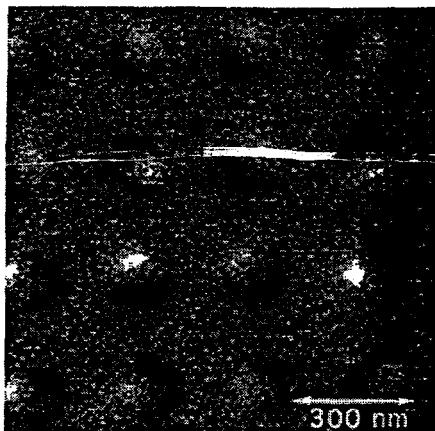


Fig. 1. MFM image of an array of type I Co dots which are 100 nm in diameter and 40 nm tall. The dipole signature of these dots indicates the moments are in-plane.

corresponds to a density of  $7.2 \times 10^9/\text{in}^2$ . Their diameter is controlled by varying the exposure dose.

Two types of samples are fabricated for this study. In the first type (referred to as type I), the nominal dot diameter is 100 nm and the Co thickness is 40 nm. In the second type (type II), the nominal dot diameter is reduced to 70 nm while the Co thickness is increased to 120 nm. A characteristic of this process is that type-II dots are shaped like cones. Cones are formed because the diameter of the holes decrease during deposition due to condensation of Co on the periphery of the holes. Consequently, as the deposition continues, cone shaped dots grow at the bottom of the holes. The tips of the cones are formed as the apertures close. The average height of the type II dots is 100 nm as measured with an atomic force microscope (AFM). It follows from the above argument that type-I Co dots are shaped like truncated cones with a height of 40 nm.

#### MAGNETIC FORCE MICROSCOPY

MFM measurements are performed on a Nanoscope Dimension 5000 AFM. All MFM images are phase images acquired using Digital Instruments' patented LiftMode [11] technique. Fig. 1 shows an MFM image of an array of type I Co dots. The characteristic dipole-like shape of the dots indicates that each dot is uniformly magnetized in a direction parallel to the substrate. This result is consistent with recent studies by New *et al.* [3] which show that patterned Co particles smaller than 200 nm are single-domain.

It is clear from Fig. 1 that the in-plane moments of these dots are not preferentially aligned. This is expected since they are circularly symmetric in the plane and therefore do not possess a strong azimuthal shape anisotropy. Dots with an elliptical shape can be fabricated with this process by varying the relative exposure dose for the two orthogonal interference exposures.

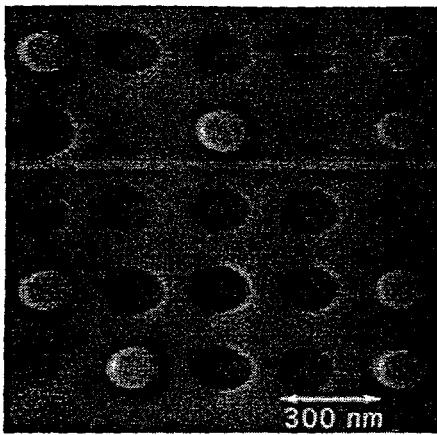


Fig. 2. MFM image of an array of type II Co dots which are 70 nm in diameter and 100 nm tall. The symmetry of the images shows that the moments are out-of-plane.

By varying the aspect ratio of the dots out of the plane, we are able to control the direction of magnetization. In Fig. 2 is an MFM image of type II Co dots which are taller and narrower than type I dots. The images of the dots are primarily azimuthally symmetric and either dark—indicating a negative force gradient—or light—indicating a positive force gradient. We interpret these images to show that the Co dots are single-domain and magnetized in a direction which is normal to the plane of the substrate. We find that over 95 % of the type II Co dots are magnetized in an out-of-plane direction.

Figs. 3(a) and 3(b) show MFM images of type II Co dots after application of a strong magnetic field along the surface normal in a direction parallel and anti-parallel to the tip moment respectively. From these images we learn that dark dots correspond to moments which are parallel to the tip moment while light dots correspond to dots which are anti-parallel. A slightly larger percentage of dots are magnetized parallel to the tip in Fig. 3(a) compared those that are anti-parallel in Fig. 3(b). This is attributed to a weak but discernible tendency for anti-parallel moments to flip during scanning to a parallel configuration. As an example, in the lower right corner of Fig. 3(b) are two dots which flipped as the MFM tip passed over them. (The image was scanned from top to bottom.) Fabricating dots with a stronger shape anisotropy should minimize this effect.

#### CONCLUSIONS

We have fabricated arrays of Co dots with diameters of 100 nm and smaller with an areal density of  $7.2 \times 10^9/\text{in}^2$  using laser interference lithography. MFM analysis of the dots indicates that they are single-domain with moments that can be controlled to point either in-plane or out-of-plane. While a fabrication process based on lift-off has been used here, it should be possible to couple other fabrication schemes such as dry etching and electroplating

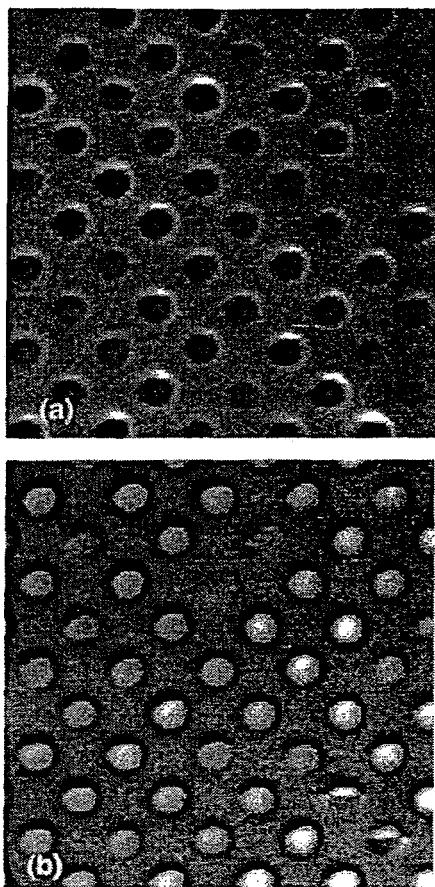


Fig. 4. MFM images of an array of type II Co dots after application of a strong magnetic field along the surface normal in a direction (a) parallel and (b) anti-parallel to the MFM tip moment.

with interference lithography to pattern arrays of small magnetic structures with a wide variety of 3-dimensional shapes. The distinct advantages of using interference lithography over other lithographic techniques are that high-density arrays of nanometer scale structures can be produced over large areas, in a relatively inexpensive way, and with potentially large throughput.

#### ACKNOWLEDGMENT

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