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Research Report

EFFECT OF ION BEAM PATTERNING ON THE WRITE AND READ PERFORMANCE OF PERPENDICULAR GRANULAR RECORDING MEDIA

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Abstract-- We have used a static write-read tester to study the reading and writing of bit patterns on arrays of square bits cut with a focused ion beam into granular perpendicular recording media. We have written square-wave bit patterns on arrays of magnetically isolated islands with periods between 80-248 nm, with the recording linear density matched to this pattern period. These measurements clearly reveal the onset of single domain behavior of the islands for periods < 130 nm. We report on variations of read-back signals with this period for bits written in-phase and out-of-phase with the patterning (where bits are written in the center of the islands and lines, respectively). We also present results and analysis on the effect of patterning and phase on the transition position jitter.

***Index Terms*-- Patterned media, focused ion beam, magnetic arrays, write read performance, jitter**

Effect of ion beam patterning on the write and read performance of perpendicular granular recording media

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I. INTRODUCTION

PATTERNED media is one of many schemes proposed to overcome the thermal stability problem that arises in the traditional scaling approach to achieving higher areal density using conventional recording media [1-5]. Instead of decreasing the grain size as the bit cell size is reduced in order to maintain signal-to-noise, the media is lithographically patterned into single magnetic domain islands. In addition to requiring the islands be single domain, it is also desirable that the easy magnetization axis of the islands be aligned, and thus on a circular disk this is most easily achieved using materials with perpendicular anisotropy. It is desirable to achieve this anisotropy by interfacial or crystalline rather than shape anisotropy, since in the latter case islands with a high aspect ratio need to be used, limiting the along-track density. Islands whose anisotropy is achieved by interfacial or crystalline anisotropy have been fabricated previously, for example by physical patterning of Co/Pt multilayers [6], deposition on patterned substrates [7], ion beam modification of Co/Pt and FePt [8-11] and electron beam or focused ion beam patterning of CoCrPt [12, 13]. We present here recording results of films patterned by the latter method.

II. SAMPLES

A 30 kV Ga^+ focused ion beam (FEI 830XL) is used to pattern granular $Co_{70}Cr_{18}Pt_{12}$ with perpendicular anisotropy, as described elsewhere [14]. The media is divided into an array of uniform square islands using a pattern of crossing lines that cut trenches ~5 nm deep and ~20 nm wide into the film. Different island sizes are achieved by varying the distance between the centers of the trenches; i.e. varying the period p with fixed trench width. Arrays with periods from p=80 nm to p=248 nm and corresponding total areas between 2.5 µm x 3.2 µm and 2.5 µm x 10 µm were fabricated. The particular areal densities range from 100 Gbit/in^2 to 10 Gbit/in^2.

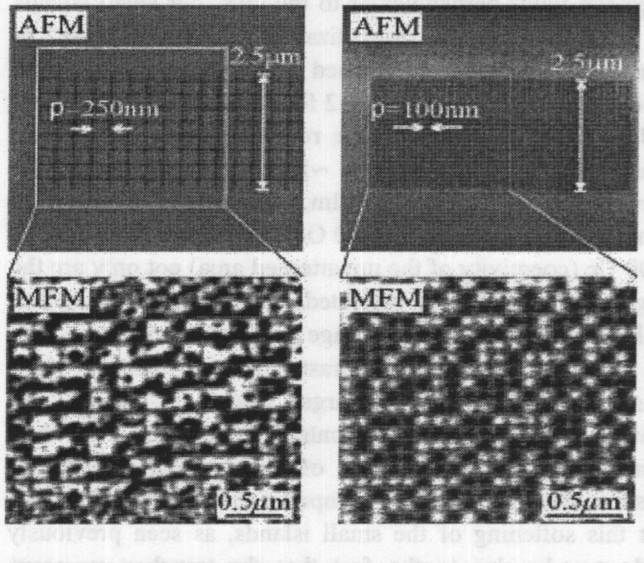

Fig. 1. AFM and MFM images of square island arrays in granular CoCrPt recording media with a perpendicular magnetic anisotropy after magnetizing in a 1200 Oe field. The island periods are p = 248 nm (left) and p = 100 nm (right).

Fig.1 shows atomic force microscopy (AFM) and magnetic force microscopy (MFM) images of two typical islands arrays with periods of p=248 nm and p=100 nm. These images have been taken in the remanent state after saturating the sample in a direction perpendicular to its surface and subsequently exposing it to an opposite magnetic field of 1200 Oe. It is seen that the islands are magnetically separated [14]. While the large islands are clearly split into multiple

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domains, we find that arrays with p<130 nm have single-domains islands. In either case, the area of dark contrast roughly equals the area of bright contrast, indicating that the field of 1200 Oe is close to the remanent coercivity of the patterned arrays.

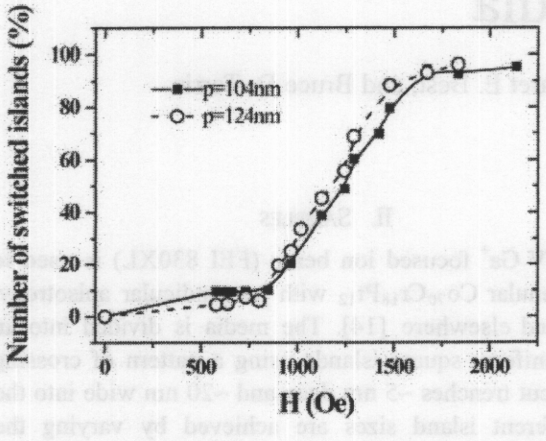

Fig. 2. Remanent magnetization curve for two single-domain island arrays, obtained from MFM images. The indicated field was applied up to the values indicated after saturation in the reverse direction.

To precisely measure the remanent coercivity of single-domain islands arrays, MFM-images have been taken in the remanent state after exposing the samples to various magnetic fields perpendicular to the disk. For small islands, an indication of the magnetization can be obtained by counting the number of switched islands for a given applied field. Results are shown in Fig.2 for island periods of 104 nm and 124 nm, respectively. The remanent coercivity of both island arrays is found to be ~1200 Oe. In contrast, the coercivity of the unpatterned film, as measured by polar Kerr rotation, is approximately 3000 Oe. We find that at a field of 3000 Oe (coercivity of the unpatterned area) not only are the single-domain islands saturated, but also the smallest multidomain islands in the range from p=166 nm to p=203 nm show a homogeneous contrast, indicating that they have all switched. In contrast, the largest islands (p=248 nm) still exhibit an inhomogeneous contrast, suggesting that their coercivity is higher than that of the smallest islands and closer to the coercivity of the unpatterned area. We speculate that this softening of the small islands, as seen previously [12], may be due to the fact that the trenches represent nucleation centers. MFM images of larger islands magnetized in intermediate fields show switched domains grow outwards from the cuts, consistent with this interpretation.

III. WRITING AND READING

To evaluate the recording properties of magnetic media without the need for flying a write/read head, static write read testers have been previously used, both on continuous [15, 16] as well as on patterned media [17]. This tester consists of a conventional magnetic recording head, mounted on a flexible stainless-steel suspension, placed in contact with the sample. Fig.3(a) shows schematically how the write/read head is moved back and forth in x-direction on the sample. Since the width of the write and read elements are comparable to the width of the island arrays (2.5 µm), only single columns of islands, and not single islands, can be addressed.

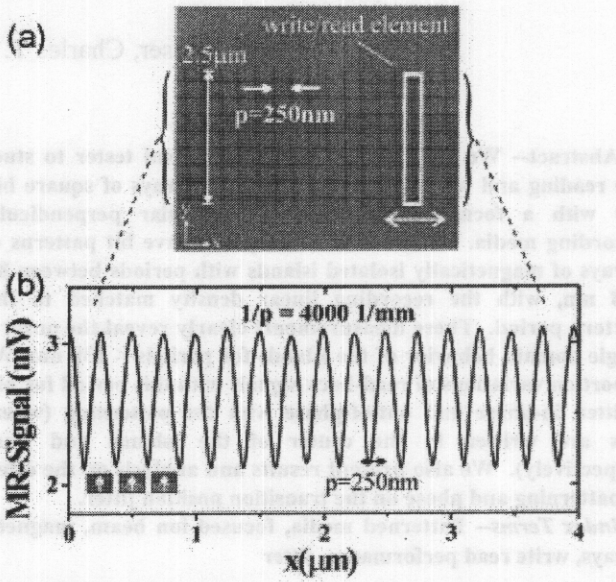

Fig 3. (a) AFM image of an island array (p=250 nm). The write/read element and its scan direction are schematically indicated. (b) Read-back signal of the dc-erased array.

Fig.3(b) shows the read-back signal after all islands have been magnetized in one direction by applying a uniform static write field (dc-erase). This experiment is used to adjust the y-position of the write/read element, since a maximum read-back amplitude is only achieved when the write/read element is exactly positioned above the pattern. Skew and tilt angles are minimized using additional lines cut by FIB on the sample. The dc-erase measurement also allows the precise determination of the actual island period p and corresponding linear density 1/p, which in this case 1/p ~4000 mm^{-1}.

Fig.4 shows MFM images of three island arrays with periods of 248 nm, 124 nm and 80 nm, corresponding to linear island densities of 4040 mm^{-1}, 8050 mm^{-1}, and 12190 mm^{-1}. In each array a square wave bit pattern has been written with a linear density (fc/mm) that matches the respective island density. The square-wave bit pattern has been written in-phase with the islands; i.e. adjacent columns are magnetized in opposite directions using the write head. The head field is reversed as it passes over the trenches, so that the transitions between up and down bits occur at the trenches between the islands. The MFM images clearly reveal the corresponding alternating contrast of the island columns. Note, that in the single-domain regime most of the columns are not perfectly magnetized, which is in part due to the finite switching field distribution of the islands (Fig.2). In Fig.4 the magneto-resistive read-back signal is plotted together with the MFM signal averaged over the entire column length. The two signals are in excellent agreement, even for the smallest islands. The amplitude of the read-back signal clearly decreases with island size. This decrease is mostly due to the roll-off curve of this head/media combination. However, an additional reduction in amplitude results from the fact that with decreasing island size, a larger fraction of the bit's magnetic material is removed, as the trench width remains constant while the islands are made smaller [18].

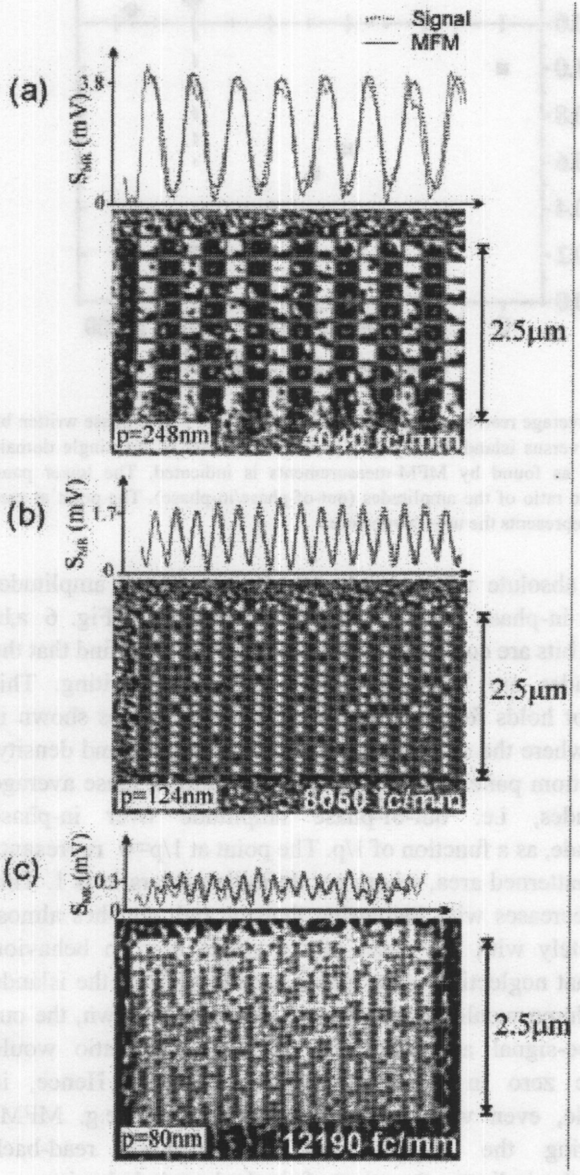

Fig 4. MFM images of in-phase written island arrays of various island size. The linear densities of the written bit-patterns are denoted in the lower right image corners. The particular MFM signals averaged over the column length and the corresponding read-back signals are plotted above the respective image.

Since we find that the effective coercivity of the islands decreases with decreasing island size, different write currents must be used to optimize the writing of bit patterns. In order to find the optimal write current for a given island size, the write current was varied to maximize the read-back amplitude. At too low currents, only small damped read-back signals are acquired, because the write field is not sufficient to completely magnetize the addressed bit cell. At currents that are too high, the read-back amplitude again is reduced. To illustrate this, the upper part of Fig.5(a) shows the read-back amplitude for bits that have been written in-phase at 4930 fc/mm using a write current of 6 mA and 10 mA, respectively. The homogeneity and the amplitude of the read-back signal are clearly reduced for the higher write current. This reduction may be due to the fact that at write fields that are much higher than the coercivity, the trailing edge of the write head starts to erase bit patterns that have been previously written by the leading edge.

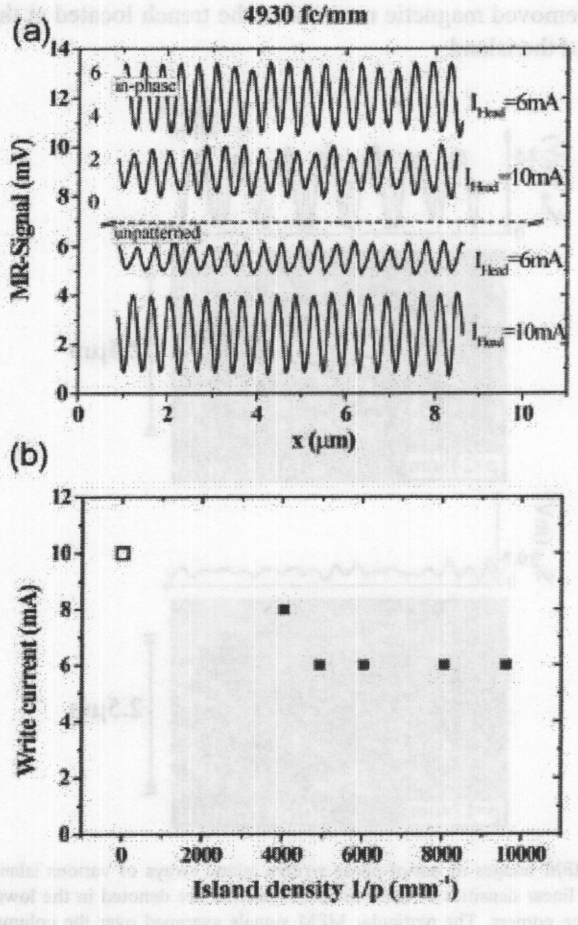

Fig 5. (a) Read-back signal for a square wave bit pattern that has been written with two different currents at a linear density of 4930 fc/mm in the patterned area (in-phase) and in the unpatterned area. (b) Optimized write current versus island density. The open square represents the unpatterned area.

The lower part of Fig.5(a) shows that when using the same write currents to write the same bit pattern in the unpatterned region, the ratio of the amplitudes is inverted. Since here the coercivity is higher and a current of 6 mA is no longer sufficient to completely reverse the sample's magnetization, leading to a damped read-back signal. In Fig.5(b) the optimized write currents for all investigated arrays and the unpatterned region are shown. The currents are plotted versus the island density 1/p, where a density 1/p=0 (open square) represents the unpatterned area. (The optimal write current in the unpatterned region is almost independent of linear density in this regime.) The trend of requiring lower write currents with decreasing island size parallels the results of the MFM and Kerr coercivity measurements.

In addition to writing square waves in-phase with the patterned islands it is also possible to write squares waves out-of-phase with the islands. Fig. 6 shows read-back signals for square wave bit patterns that have been written 90° out-of-phase, the write field is applied when the head is over a trench in an attempt to write bit transitions in the center of the islands. We observe that the read-back signal from the largest islands shows a slight dip in amplitude at the peaks, indicative of the removed magnetic material in the trench located at the center of the island.

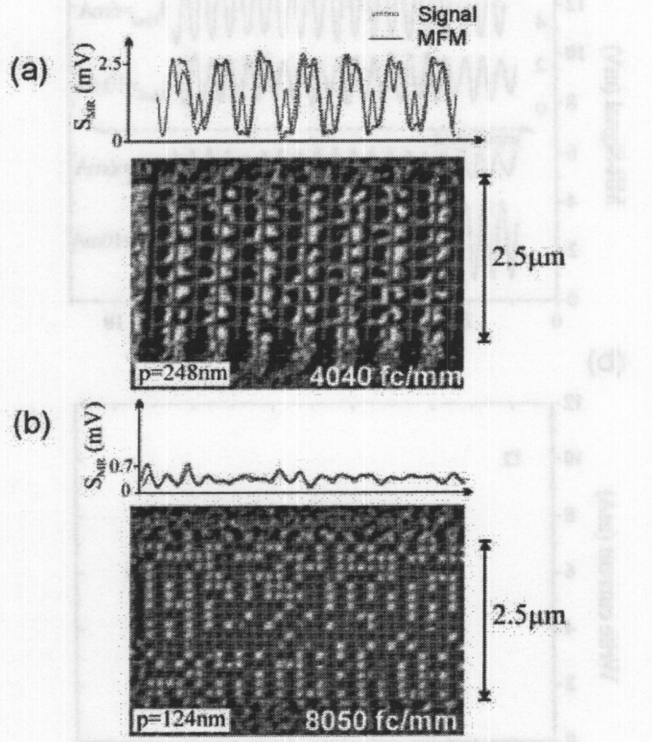

Fig 6. MFM images of out-of-phase written island arrays of various island size. The linear densities of the written bit-patterns are denoted in the lower right image corners. The particular MFM signals averaged over the column length and the corresponding read-back signals are plotted above the respective image.

This effect is clearly seen in the MFM image and waveforms of Fig 6(a), where a trench is seen in the middle of the bit and a domain wall is located in the islands. In contrast, in the small islands shown in Fig 6(b), domain walls cannot be placed in the islands and thus each island will have a 0.5 probability of being either magnetized up or down. Hence, on average the total magnetization of a single column of islands and therefore the read-back signal equals roughly zero.

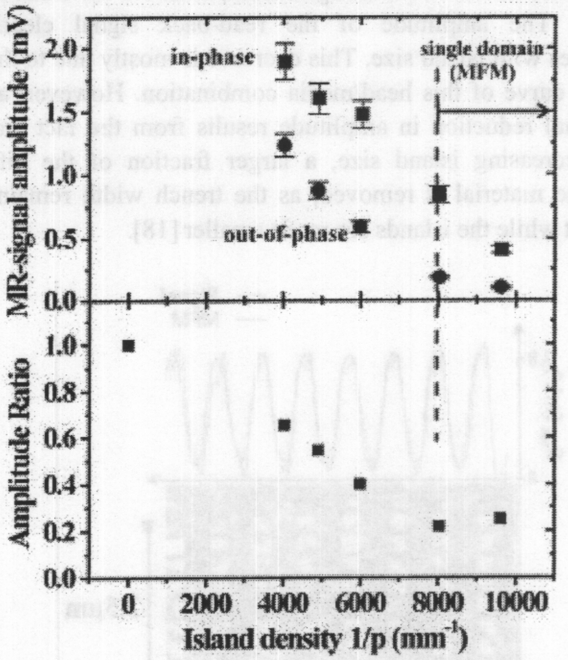

Fig 7. Average read-back amplitude for in-phase and out-of-phase written bit patterns versus island density (top panel). The onset of the single domain behavior as found by MFM-measurements is indicated. The lower panel shows the ratio of the amplitudes (out-of-phase/in-phase). The point at zero density represents the unpatterned area.

The absolute values of the average read-back amplitudes for the in-phase (Fig. 4 a,b) and out-of-phase (Fig. 6 a,b) written bits are compared and shown in Fig 7. We find that the amplitudes are lower for the out-of-phase writing. This behavior holds for all investigated island arrays as shown in Fig.7, where the amplitudes are plotted versus island density. The bottom panel of Fig. 7 shows the ratio of these average amplitudes, i.e. out-of-phase amplitude over in-phase amplitude, as a function of 1/p. The point at 1/p=0 represents the unpatterned area, where per definition the ratio is 1. This ratio decreases with increasing density and vanishes almost completely with the onset of the single domain behavior. Note that neglecting noise and if exactly 50% of the islands in a column would be magnetized either up or down, the out of-phase-signal and therefore the amplitude ratio would become zero in the single domain regime. Hence, in principle, even without further measurement (e.g. MFM) comparing the in-phase and out-of-phase read-back amplitudes indicates the onset of single domain behavior.

IV. JITTER COMPARISON

One of the advantages to patterned media, in addition to improved thermal stability, is reduced jitter [12]. Ideally, to measure jitter one would need write and read heads with the cross track width as small as the island width. However, a lower bound on the reduction, as explained below, can be made using the wide head we have used to read and write. The read-back amplitudes from the 2.5 μm wide columns have been analyzed for transition position jitter, as described elsewhere[19] and compared to signals from the same linear density in the unpatterned regions. Transitions were written at densities of 8000 fc/mm and 9600 fc/mm in the unpatterned regions as well as in-phase and out-of-phase to the corresponding patterned arrays. At both linear densities, the in-phase jitter was reduced compared to the unpatterned region, from 3.3±0.3 nm to 2.0±0.2 nm at 8000 fc/mm and from 3.0±0.3 to 1.6±0.2 nm at 9600 fc/mm. In contrast, the jitter for the out-of-phase written bits is one order of magnitude larger, 18±2 nm at 8000 fc/mm and 25±3 fc/mm at 9600 fc/mm. This large increase in jitter for out-of-phase writing is not surprising, as it is not possible to write a transition in these small islands.

As noted above, this jitter estimate is not a true measure of the improvement expected from patterned media. The jitter measured by averaging across the 2.5 μm width of the array is dominated by the non-perfect writing of an entire column at once. If single islands could be individually addressed, we would expect a decrease in the patterned region jitter limited by the lithography jitter. In contrast to this, averaging across the large track width reduces the jitter in the unpatterned region. If the track width were reduced to the width of an island, for example to 125 nm, the unpatterned jitter would be expected to increase by $(2.5/0.125)^{0.5}$ ~4.5 [20, 21]. Thus, the patterned jitter is overestimated, the unpatterned jitter underestimated, and the ratio would be greatly increased if single islands could be addressed.

V. SUMMARY AND CONCLUSIONS

Granular perpendicular recording media has been patterned with a focused ion beam to form arrays of magnetically separated square islands with periods ranging from 80 nm to 248 nm. Using a static write/read tester, square wave bit patterns were written in the unpatterned area and in the patterned regions both in-phase as well as out-of-phase with the islands. We have found that read-back amplitudes depend strongly on the write phase, vanishing for writing out-of phase on the single-domain islands. In principle, the onset of single domain behavior can be obtained from these writing experiments. Transition-position jitter for the in-phase signal is reduced from that of the unpatterned region, while the out-of phase written bits show a dramatically increased jitter. This poor writing in the out-of-phase islands demonstrates the need to synchronize the head write field to the pattern.

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