Magnetic Imaging Reference Sample

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Abstract—**We propose a reference sample for magnetic imaging. We have chosen a thin-film magnetic hard disk as a representative sample because the domains are very stable magnetically and thermally. This type of sample is also of fundamental interest to the disk drive industry, currently the largest user of magnetic force microscopy. Disk samples are prepared by writing a special magnetic pattern consisting of various transition spacings designed to explore certain aspects of magnetic imaging. Disks are then cut into coupons, cleaned and patterned with a reference grid of numbered 20 µm x 20 µm Au frames. These frames allow easy navigation around the sample. We believe a sample of this type can help define limits, expectations and claims of resolution, as well as instrument sensitivity and ease of operation.**

I. INTRODUCTION

We propose a magnetic imaging reference sample to help further the quantitative aspect of magnetic imaging techniques. Available magnetic imaging techniques include scanning electron microscopy with polarization analysis (SEMPA), scanning near-field optical microscopy (SNOM), Kerr microscopy, Lorentz microscopy, ferrofluid decoration, and magnetic force microscopy (MFM) [1,2]. In particular, MFM has high resolution and is easier to use in development and production. We therefore focus on MFM in this paper. However, we believe this reference sample will have general application to other imaging techniques.

A reference sample should be useful for determining several important quantities in MFM [3]. These include the magnetization polarity of the MFM tip, relative spatial resolution, and relative magnetic sensitivity. Presently, MFM is a relative measurement. MFM images are dependent on the specific magnetic tip, the type of sample, and the force detection scheme. For example, the thickness of the magnetic coating on the MFM tip can affect the resolution of the images and the sensitivity of the instrument [4]. Also magnetically soft tip coatings give considerably different images than magnetically hard tip coatings [5].

Currently, most MFM users have a favorite sample which they measure from time to time to affirm confidence in their measurements. These samples are either shipped with the instrument or acquired by the MFM user. These samples usually vary greatly, examples include VCR tapes, hard disk drive components (media and heads), floppy disks, and many naturally occurring magnetic samples. Most of these samples do not include complete magnetic characterization. Many MFM images of these samples are published as supporting evidence for new concepts [4,6,7,8].

A reference sample that can be used to calibrate instrumentation and operating techniques would be an invaluable first step toward quantitative interpretation of MFM. We propose a reference sample using a commercial magnetic hard disk. We chose a hard disk for the following reasons: (1) The magnetic domains are very stable. Magnetic storage media have been designed to retain magnetization and resist corrosion for many years. (2) The temperature required to alter the magnetization is higher than temperatures to which the sample would probably be exposed. (3) Magnetic storage media can be nondestructively imaged with MFM. (4) Magnetic storage media also have been extensively studied providing a large resource of background information. (5) Current spin-stand technology insures the repeatability of the pattern written to the disk. There should only be slight variation in the shape of the magnetic pattern recorded on the surface of the disk, and as long as the disks are from the same batch there should only be slight variation from disk to disk. (6) We can write specific patterns on the disk to study different aspects of MFM. (7) The magnetic layer on the disk is designed to support very sharp transitions. The characteristic length of these transitions is comparable to the current resolution of MFM.

Several approaches to development of a reference sample are currently being considered by other researchers. These include micro-lithographically patterned wires, which develop a small magnetic field when a current is passed through them [9]. These wires allow for accurate field calculations, but the field strength is very low. These samples are excellent for measuring sensitivity, however, magnetic fields this low do not simulate fields developed by samples of current interest. Also, the current achievable line width is slightly less than one micrometer, which limits the magnetic feature size on the reference sample. Another possibility is fabricating a planarized film with magnetic islands imbedded in a non-magnetic matrix. This type of sample could have sharp transitions at the interfaces between magnetic and non-magnetic materials depending on the accuracy of the fabrication processes. Lithographically patterned magnetic particles which sit on top of a non-magnetic substrate have been fabricated by several researchers [10,11,12,13]. Unfortunately, with the current achievable line width, the applied pattern spacing is limited compared with a disk

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sample which can have transition spacing less than 500 nm. In addition, because the magnetic features correspond to topographic features they can be difficult to separate.

Another problem in quantifying MFM is that the magnetization of the tip is extremely difficult to measure due to its small size. The MFM measurement itself can have a large effect on the measured value. The sample magnetization can be altered by the tip, or the tip magnetization can be altered by the sample; both can cause effects that make the images difficult to interpret. Further, if the sample fields are close to the coercivity of the tip, the image is a convolution of hard and soft tip magnetization. Also quantifying MFM analytically is difficult. The tip magnetization is practically impossible to calculate, due to the variation in tip geometry. Researchers have addressed these problems with various techniques [14,15,16,17,18].

In contrast to previous MFM calibration techniques we propose to develop a reference sample that will be as completely characterized and as uniform from sample to sample, as currently possible. The disk drive industry can produce extremely uniform heads and media. This will allow us to reproduce large numbers of very consistent reference samples. To characterize these samples we plan to use SEMPA on a small subset of these samples to accurately map the magnetization. Using the SEMPA images and the magnetic parameters of the disk coating, we will model the magnetization and the stray fields from the sample using micromagnetic modeling techniques. We then have a theoretical field profile above the sample. These samples will then be used to test the rest of the samples for uniformity by using MFM. These samples can be distributed, including the characterization data, to any MFM or other magnetic imaging technique user. Images taken at NIST of specific areas on a sample will be included with the reference sample when it is distributed to compare with images acquired by the final user. This cross-referencing between SEMPA, theory, and MFM can provide a good representation of the real magnetization of the reference sample, which can then be used to calibrate and compare various MFM imaging techniques.

Magnetic features on this scale are very difficult to return to time after time, since the details of the magnetic field patterns are not optically visible. There is no suitable nondestructive method of locating the previously imaged positions, although with MFM and extreme persistence it is possible to locate these areas by incrementally scanning the sample surface. To provide a simple method to locate specific magnetic features, we propose to pattern the disk with small frames, which will be used as markers to navigate around the sample.

These frames will allow a comparison of MFM images taken with various tip coatings or taken with different force detection techniques. This can lead to a better understanding of the actual magnetization of the tip. The resolution or sensitivity of one tip compared to another can easily be measured by relocating the same transition and comparing the signal from the tip. This allows individual users to have consistency of units (cantilever frequency shifts or deflection) in their measurements. If one of these samples is exchanged a comparison of data taken from the same location by different MFM users permits discussion about instrumentation without requiring exhaustive understanding of their individual sample or debating operator technique.

II. Experimental

We chose a typical thin-film magnetic hard disk for this imaging reference sample that is representative of current disk drive technology. The nominal magnetic parameters of the disk are $M_r t$ = 0.1 A (130 G·μm) and H_c = 175 kA/m (2200 Oe). The disk has a surface texture of 30 nm peak-to-valley and a 20 nm thick carbon/lubrication overcoat. The recording head used to write the disk was a proximity recording head with gap width of 180 nm and a gap length of 5 μm. The peak-to-peak writing current applied to the head was 10 mA and the head-to-disk spacing was comparable to the carbon/lubrication overcoat.

The disk was prepared in the following manner. A magnetic pattern consisting of alternating data tracks and unwritten tracks was written on the disk. The data tracks were written with a repetitive bit pattern to demonstrate several transition spacings. This pattern consists of two isolated transitions, followed by two transitions close together (di-bit), then another two isolated transitions, and finally three transitions close together (tri-bit). Because of the odd number of transitions imposed by the tri-bit, the pattern is then repeated with opposite polarity. The spacing in these images for the isolated transitions was 1.5 μm apart, 350 nm for the di-bit and 350 nm for the tri-bit. The write frequency was kept constant so the bit spacing varies proportionally to the radius of the disk. The transition spacing varies only about 3 percent over 1 mm.

The disk was cut into 12.5 mm coupons which are easily mounted in most magnetic force microscopes. The lubrication was removed with a fluorocarbon and ethanol bath, and the carbon overcoat was subsequently removed by reactive 80% Ar/ 20% O ion beam etching. This treatment did not appear to affect the magnetic layer. Measurements of $M_r t$ taken using a vibrating sample magnetometer before and after the etching did not change by more than a few percent (see Fig. 1). MFM images taken before and after the etching were also unaffected. We then lithographically patterned 100 numbered 20 μm square frames which are used to locate specific magnetic features. The frames are 30 nm thick, thermally deposited Au. This thickness is comparable to the disk surface roughness.

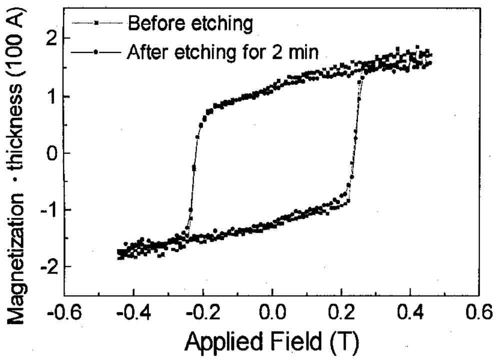

Fig. 1 Hysteresis loop of a disk coupon from a vibrating sample magnetometer taken before and after removing the coatings from the magnetic layer. Magnetic film was on both sides of the coupon, so the magnitude of the loop is doubled.

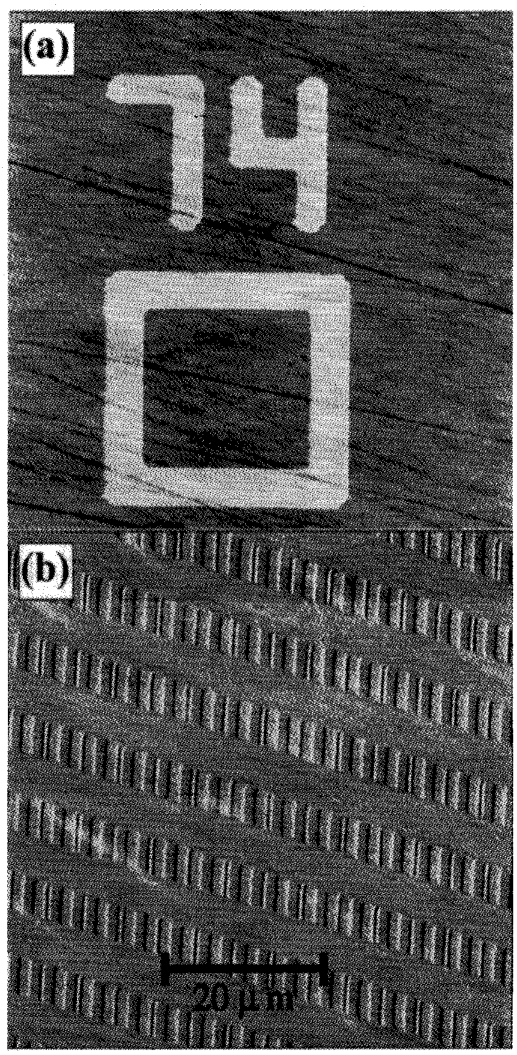

Fig. 2. 65 µm x 65 µm atomic force microscope image (a) of frame number 74 and the corresponding magnetic force microscope image (b).

III. RESULTS

Fig. 2 is a 65 µm x 65 µm combination AFM/MFM image of the proposed magnetic imaging sample using a phase-locked force derivative detection scheme with a commercial CoCr-coated Si AFM tip [19]. This type of MFM alternates, line by line, between MFM and AFM, which minimizes the effect of AFM topography on the MFM image.

Fig 2(a) shows an AFM image of frame number 74. The texture on the surface was created by an oscillating polishing technique that is concentric with the disk. This texture transmits through the 30 nm thick Au frame. We think that a very flat substrate would probably provide less topographic influence on the MFM image, but this texture could be beneficial, demonstrating the instrument's ability to separate magnetic and topographic signals. This is important since magnetic samples can have large topographic features relative to the tip sample spacing.

The corresponding MFM image, Fig. 2(b), shows the alternating unwritten tracks and data tracks. The magnetic fields from the transitions in the data tracks can be clearly seen above the Au frame, although there is a slight loss in both resolution and magnitude of the MFM signal. The unwritten tracks are dc erased, having the majority of magnetization oriented in one direction with very small magnetic gradients.

Fig. 3 is a smaller scan taken inside the frame. All of the various transitions can be seen in this image. One tri-bit can be seen in the lower right corner of the image as two light bars enclosing a dark bar. The opposite polarity tri-bit can be seen at the center left edge as two dark bars flanking a light bar. If, by using SEMPA, we can determine the magnetization of these tri-bits then we can infer from the images an up or down magnetic moment of the tip,

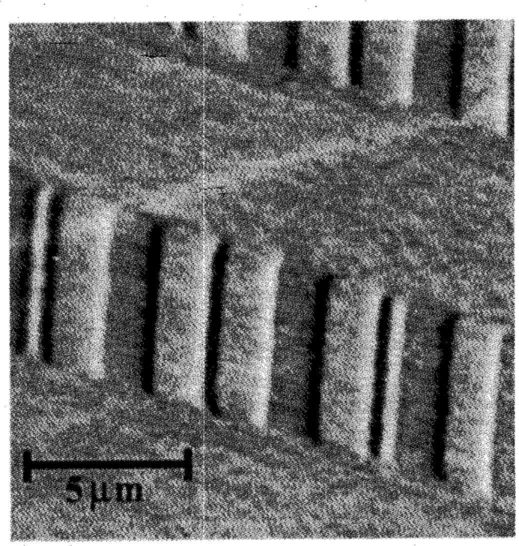

Fig. 3. A 14 µm x 14 µm magnetic force microscopy image inside square number 74 showing the various transition spacings in the data tracks and the dc erased unwritten tracks.

by assuming that the moment is primarily in the Z direction (perpendicular to the sample surface). This opposite polarity also provides a check on any asymmetric response of the tip to the sample. If the tip magnetization is disturbed more by one tri-bit polarity, the MFM image will show this asymmetry. This could be caused if the shape anisotropy of the magnetic film on the tip preferentially pins the magnetization and domain wall motion.

Another effect to the MFM image due to changes in the tip magnetization could be saturation of the tip only at areas of high field strength; this could be seen in the image by a clipping of the higher peaks and valleys. An isolated transition can be seen as a single light bar following the tri-bit on the left of the image. Isolated transitions are spaced so that there is minimal influence from other transitions. Depending on the polarity, some are light and some are dark. The di-bits are a light bar and a dark bar closely spaced. A faint vertical band on the left side of the image shows the influence of the Au frame on the tip-sample interaction. The image of media noise in this area clearly has lower resolution compared to the uncoated area, demonstrating the possibility of a distance verses resolution calibration of the MFM tip.

The details of large magnetization gradients can be difficult to see due to the large field gradients interacting with a greater portion of the tip. Fig. 4 is a close up of an isolated transition showing the strong contrast between opposing magnetization directions. In this situation a magnetically soft tip might provide more details. Measuring this sample with several different tips or techniques could provide complementary data that would help describe the sample more completely.

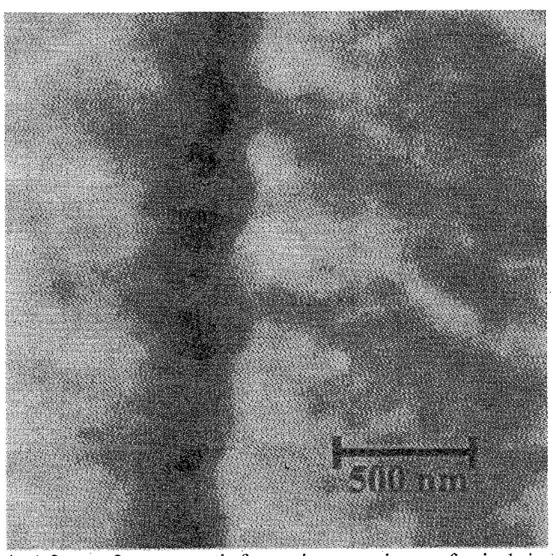

Fig. 4. A 2 μm x 2 μm magnetic force microscopy image of a single isolated transition.

The meandering character of this transition is due to the inhomogeneous nature of magnetic reversals [20]. This inhomogeneity results in media noise and can show the resolution achievable with MFM. The smaller features of the noise are about 50 nm across as measured in these images, a size similar to current commercial MFM resolution [4]. The media noise can also be seen between the tracks as a mottling of the surface.

IV. Summary

We think that there is a broad need for standard magnetic imaging reference samples. MFM has become a widely used diagnostic tool in the disk drive industry, because of its high resolution and ease of application. Disk drive technology is changing rapidly with storage densities increasing by at least fifty percent annually. This rapid change makes it important to have reference samples that are consistent throughout the community.

Finally, this is the first sample that will been characterized at the same location using SEMPA, micromagnetic modeling, and MFM. This is made possible by a grid work of lithographically patterned frames that allow accurate relocation of previously measured magnetic features. Other important features of this hard disk-based magnetic imaging reference sample are magnetic features whose scale is comparable to the current resolution of commercially available instruments and the ability to write these features on the disk, allowing emphasis on certain aspects of the MFM process. These samples can be produced in large quantities with a high level of consistency, since they do not require high-resolution fabrication techniques. This sample will help validate claims of resolution, sensitivity, and ease of instrument operation. The magnitude of the tip response compared against the magnitude provided with the sample can be a quick measure of the sensitivity. Resolution could also be determined by a quick comparison to images supplied with the reference sample. These comparisons can be accomplished using this reference sample.

V. References

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