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Optimizing the NIST Magnetic Imaging Reference Sample†

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***Abstract*—We have further developed the NIST magnetic imaging reference sample to include a magnetic pattern which can indicate the magnetic polarity of a magnetic force microscope tip. Several samples cut from the same disk were measured with a single tip. We have also measured a single transition with several tips. Both measurements have shown the variability in images taken with different tips and different instrument configuration which underscores the need for a well calibrated sample.**

I. Introduction

Magnetic force microscopy (MFM) is becoming widely used as an analytical tool in the disk drive industry. Presently, MFM images can vary greatly due to variations in tip geometry, magnetic materials used to coat the tip, and instrument configuration. Having a well characterized, widely distributed sample provides much-needed information about variations of tip magnetization and imaging technique[1]. Our magnetic imaging reference sample (MIRS) is based on a thin-film magnetic recording disk[2]. In this paper we show the progress made in optimizing this sample for practical use. We also show comparisons between tips measuring the same transition, and samples measured by the same tip.

II. Experimental

We have replaced the previous disk with a smoother, laser-textured disk. This disk provides less topographic influence on the MFM images. The nominal magnetic parameters of the disk are $M_r t = 9.0 \times 10^{-3}$A (0.9 memu/cm^2) and $H_c = 175 \times 10^3$A/m (2200 Oe). The disk has a surface texture of 15 nm peak-to-valley as measured by the atomic force microscope. The disk was prepared in the following manner. We first wrote the magnetic data with a thin-film inductive head on a conventional spin-stand. We then lithographically deposited Au into an array of patterns across the whole surface of the disk. The pattern consists of the sample identification and 100 numbered 20 µm square frames. The frames within the pattern are used to locate specific magnetic features. These frames provide landmarks for optical microscope location of previously imaged areas, which is very useful since the magnetic fields are invisible. The lubrication was removed with a fluorocarbon and ethanol bath and the carbon overcoat was removed by an oxygen plasma. The disk was finally cut into 8 mm coupons.

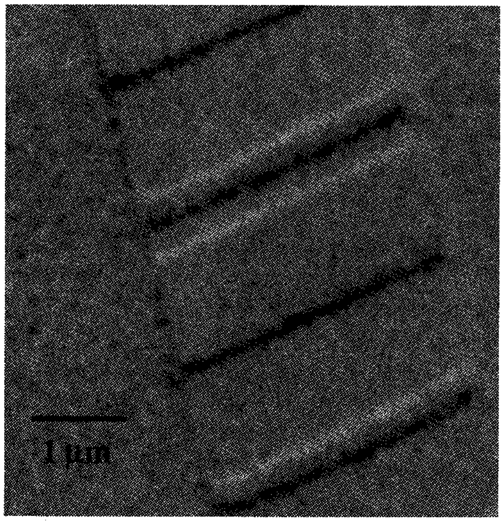

Fig. 1. MFM image of the magnetic pattern written on the disk. The light and dark bars indicate the written transitions. A tri-bit, seen just above center is two light bars closely flanking a dark bar.

We have written a new pattern which can show the polarity of the tip perpendicular to the sample surface (the Z direction). In all MFM detection schemes the tip is mounted on the end of a cantilever that is deflected or oscillated perpendicular to the plane of the sample surface. This means the tip is mostly sensitive to the Z component of the stray field gradient. In order to determine the tip's polarity we have written a repeating pattern containing two sets of three closely spaced transitions "tri-bits" separated by an isolated transition. These tri-bits are written with the same polarity. One can be seen in Fig. 1.

The complete repeating pattern consists of an isolated transition followed by a tri-bit, an isolated transition, a second tri-bit, an isolated transition, two closely spaced transitions, and last another isolated transition. This completes the repeating pattern. This repetition is very practical, since the sample can be imaged anywhere to determine the tip's polarity. This pattern also provides various transition spacings which can test effects on the

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MFM image such as intersymbol interference between tip fields and sample fields.

III. RESULTS

In order to determine the magnetization of the sample, and most important the magnetization within the tri-bits, we image this sample with scanning electron microscopy with polarization analysis (SEMPA)[3]. Figure 2 shows an image from the earlier sample taken with SEMPA. The arrow in the figure shows the magnetization direction in the light area. This magnetization is between two isolated transitions. To the right of the center of the image is a narrow light area next to a narrow dark area. This light and dark area form a tri-bit. It shows the magnetization within the tri-bit, allowing us to determine the sign of the magnetic field gradient emanating from these transitions. With the SEMPA information the polarity of the MFM tip can be deduced directly from the MFM image of the tri-bit.

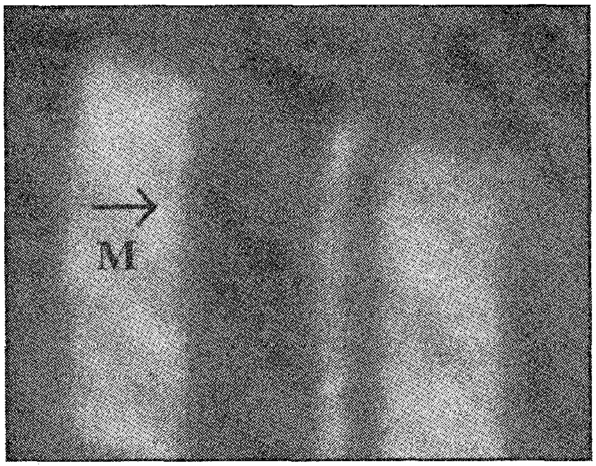

Fig. 2. SEMPA image of the magnetic imaging reference sample. The arrow indicates the magnetization direction in the light area.

The imaging technique used for the MFM images in this paper detects the change in phase of a vibrating cantilever as it is scanned 10 nm above the surface of the sample. The phase is measured between the input to the cantilever piezocrystal and the output of the detector[4]. The tips were similarly magnetized with a small permanent magnet except where noted. To compare image consistency between samples, five different samples cut from one disk were imaged with the same commercially available CoCr coated tip[5]. Fig. 3 shows the results. This phase change was measured by averaging across the track and plotting the difference between a peak and trough. As can be seen, there is approximately a 1° variation among four of the samples. The difference of sample 2 is attributed to instrument setup. The set point was adjusted slightly to obtain similar image resolution[6]. Feed back parameters and MFM scan height were unchanged. We know the disk magnetization pattern does not vary that much since the variation of peak height around the disk as measured by the spin stand is less than 10%.

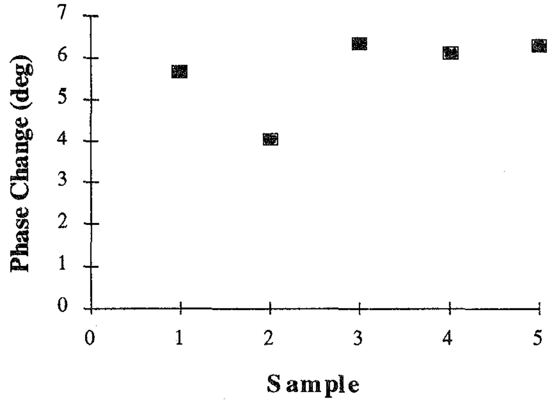

Fig. 3. One tip was used to image five different samples taken from a single disk. The maximum phase change of the tip, as measured on the MFM image between a similar peak and trough, is plotted for each sample.

We have used sample number 1 for determining the relative sensitivity of five commercially available CoCr coated tips. The tips were from the same box and used consecutively as supplied. Fig. 4 is a plot of phase change that was measured as described for the previous experiment. For this experiment the control parameters for the tips were optimized for the first tip and then all succeeding tips were operated with the same parameters. As seen in Fig. 4, the phase change for first three tips varies less than 1°. However, there was a noticeable variation in resolution of the images, as evidenced by an apparent defocusing of the media noise. The last two tips varied considerably as can be seen in the figure. Resolution varied as well, although, not in proportion to phase change. Fig. 3 and Fig. 4 both demonstrate the variability of MFM imaging. The disk magnetization does not vary as much as the MFM measurements, underscoring the need for a consistent, calibrated sample.

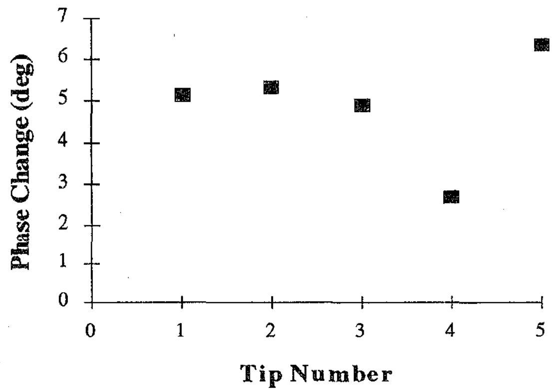

Fig. 4. Five tips were used to image the same area on one sample. The maximum phase change of the tip, as measured on the MFM image between the same peak and trough, is plotted for each tip.

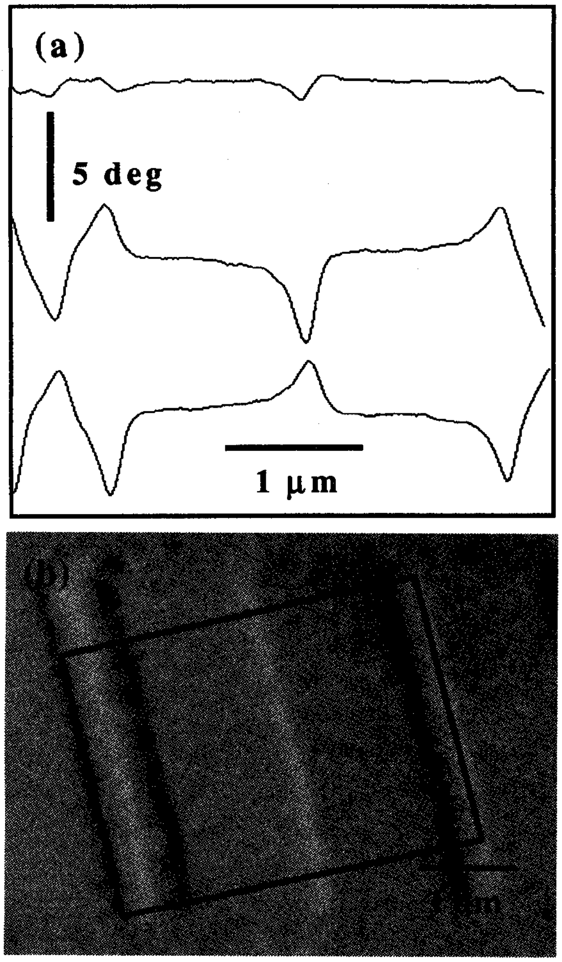

Fig. 5. (a) Averaged cross sections of MFM images taken with different tip magnetization. Top curve: tip magnetized parallel to sample. Middle curve tip magnetized perpendicular to sample. Bottom curve: tip also magnetized perpendicular to sample but opposite to the middle curve tip. (b) The square indicates where the image was averaged for the curves in (a). For this image the tip magnetization points into the page.

Fig. 5a shows the effect on the image as the tip magnetization is rotated[7]. The curves in Fig. 5a are averages of cross sections taken parallel to the track, within the box in Fig. 5b. The data were averaged to minimize variation both from the sample and the instrument. The top curve is taken with a tip magnetized parallel to the sample surface and perpendicular to the 1μm scale bar. The middle curve is from a tip magnetized perpendicular to the sample surface and the bottom is from a tip also magnetized perpendicular to the sample surface but of opposite polarity to the middle curve.

Comparing the top curve to the lower two, it is clear that the isolated transition in the center of the curve deflects the cantilever. This indicates that the tip has remnant magnetization which is perpendicular to the sample surface. This is to be expected since the anisotropy imposed by the long narrow shape of the tip could prevent the smooth rotation of the magnetization.

When the height of the peaks is compared to the depth of the troughs, on the two lower curves in Fig. 5a, it can be seen that on average the repulsion is not as large as the attraction. In other words the peaks are not as high as the troughs are low. This occurs regardless of the tip magnetization. This is caused by an increase in force on the tip while scanning an attractive area. During the MFM scan there is no active control of tip-to-sample distance. So when the tip encounters an attractive area it is drawn closer and the field strength increases. This increases the tip deflection. Alternatively, when the tip is repulsed the field strength decreases thus decreasing the tip deflection. We have used a similar tip in dc mode (force detection) and seen the tip deflect about 2 nm, which is sufficient for these changes. However, this effect has only been explored for this type of MFM.

IV. SUMMARY

We have improved the reference sample by changing to a smoother laser-textured disk which minimizes topographic effects. The magnetic pattern written to the disk has also been changed to enable a quick measure of the polarity of the MFM tip. We have demonstrated the usefulness of this sample by comparing a number of tips and shown their variability. We have also seen how the magnetization direction of the tip can affect the image and how the signal is increased when scanning an attractive area. We are currently working to solve some lithography problems of the Au pattern associated with the lubrication or carbon layer on the disk. We are also developing software to present magnetic field profiles at various heights from the sample surface. This software will use the SEMPA images and micromagnetic modeling to determine how MFM images relate to the magnetization. Also we are preparing a set of samples for a round-robin comparison of techniques, tips, and procedures.

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