Deconvolution of Magnetic Force Images by Fourier Analysis

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***Abstract* – A novel technique is presented which allows the "true" magnetic charge distribution of a sample to be obtained from a raw MFM image by deconvolution. The formation of magnetic force microscopy (MFM) images can be considered as a convolution of the tip response function and the divergence of the sample magnetization. The key element in this method is the tip response function which contains the information about the magnetic and geometric properties of the tip. This tip response function is obtained by imaging the flux emanating from the end of an ultra narrow single domain nickel strip which approximates a "point" magnetic charge. An MFM image of recorded bits obtained with the same tip is deconvolved utilizing Fourier transformation methods. By this means, the deconvolved image becomes tip independent and it is possible to achieve spatial resolutions as small as the width of the Ni strip which can be 10 nm wide.**

I. INTRODUCTION

The rapid growth in the field of Magnetic Force Microscopy (MFM) has been attributed to its potential for obtaining high spatial resolution magnetic images of the surface fields. However, applications for MFM have been limited because MFM images contain an intermixure of magnetic information about the properties of the MFM tip as well as of the sample. This is inherent to magnetic force microscopy since these images are formed by measuring the interaction between a sharp magnetic tip and the surface fields which arise from the divergence of the sample magnetization (magnetic charge). The tip dependence translates into MFM images which vary significantly when different tips are used even though the same sample is imaged[4][6]. In the past, numeric calculations of the interaction between the tip and the sample field has been the only means to interpret MFM images[1][2][3][4]. Unfortunately, these calculations require *a priori* knowledge of the tip geometry and its magnetic properties, which are difficult if not impossible to obtain.

In this paper, a new experimental method is presented which allows tip dependent MFM images to be deconvolved into a mapping of the "true" magnetic charge distribution of the sample. Conceptually, the MFM image can be considered as being formed point by point by a convolution of a tip response function with the magnetic charge distribution of the sample. The tip response function is the transfer function of this linear system (MFM), which contains specific information about the magnetization orientation, the shape, and size of the active magnetic region in the tip which interacts with the sample field. If an isolated point magnetic charge is realized, the tip response function for the specific MFM tip can be exactly obtained by imaging this point source. The experimental tip response function is obtained by imaging the flux emanating from the end of a nanoscale single domain nickel strip. The effect of the finite size of the Ni strip used as the point charge source becomes negligible if the width of the Ni strip is smaller than the system resolution. The maximum Ni strip width, w_c, was evaluated numerically for a given set of imaging conditions. Arrays of Ni strips were fabricated by electron beam lithography with widths $w < w_c$. Next, an MFM image of recorded transitions are obtained under the same imaging conditions as the tip response function. The image of the recorded transitions are deconvolved utilizing Fourier transform methods which results in a mapping of the magnetic charge distribution of the sample that is independent of the specific tip used and imaging mode .

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II. METHOD

MFM images are formed point by point by a convolution of a tip response function $a(x,y,z_o)$ with the magnetic charge distribution of the sample $\rho(x,y)$. The convolution integral representing the MFM image $c(x,y,z_o)$ can be written as,

$$c(x,y,z_o)=\int_{y'}\int_{x'} a(x-x',y-y',z_o)\,\rho(x',y')\,dx'dy' \qquad (1)$$

averaged over the sample thickness t (assuming the tip-sample spacing $z_o >> t$). The coordinates x,y,z_o give the tip position, while x',y' are the coordinates in the sample plane. In Fourier space, (1) becomes,

$$C(k_x,k_y)=A^*(k_x,k_y)\cdot P(k_x,k_y) \qquad (2)$$

where $P(k_x,k_y)$, and $A(k_x,k_y)$ are the Fourier transformation of $\rho(x,y)$ and $a(x,y,z_o)$ respectively, and k_x, k_y are the wave numbers in the x,y directions. If the tip response function is known, then the unknown magnetic charge distribution can be obtained,

$$\rho(x,y) = \mathcal{F}^{-1}\left[\frac{C(k_x,k_y)}{A^*(k_x,k_y)}\right]. \qquad (3)$$

The tip response function is obtained by imaging the ends of an ultra-narrow single domain nickel strip. The step discontinuity of the magnetization at the end of the strip approximates a "point" magnetic charge.

The effect of the finite size of the Ni strip means that the experimental tip response function $\hat{a}(x,y,z_o)$ is itself a convolution of the ideal tip response function $a(x,y,z_o)$ over the width of the strip w. This is described by,

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$$\hat{a}(x,y,z_o)=\frac{q_m}{w}\int_{-\frac{w}{2}}^{\frac{w}{2}} a(x-x',y,z_o)\partial x', \tag{4}$$

where q_m/w *(poles/unit length)* is the line charge density arising from the step discontinuity of the magnetization at the ends of the Ni strip. If the variation of the ideal point response $a(x,y,z_o)$ is small over the width w of the Ni strip, then the finite sized tip response function is a good approximation. Under these conditions, (4) reduces to

$$\hat{a}(x,y,z_o)\approx\frac{q_m}{w}a(x,y,z_o)w \tag{5}$$

$$\approx q_m a(x,y,z_o) \tag{6}$$

To assess the maximum Ni strip width, defined as w_c, a nominal error function $E(w)$ was evaluated numerically for a varying strip width w at a given tip sample separation z_o. This function provides a measure of the difference between the tip response due to the finite size "point" source $\hat{a}(x,y,z_o)$ to the ideal point tip response function $a(x,y,z_o)$.

$$E(w)\Big|_{z_o}=\sum_{x,y}\left\|\frac{(a_{x,y}-\hat{a}_{x,y}(w))}{(a_{x,y}+\hat{a}_{x,y}(w))}\right\|. \tag{7}$$

$\hat{a}_{x,y}(w)$ and $a_{x,y}$ represent the discrete form of the continuous response functions, $\hat{a}(x,y,z_o)$ and $a(x,y,z_o)$ respectively. A 2% difference in the response functions are the criterion used to define w_c. The 2% criterion is an estimate of the noise introduced by the instrument and distortions introduced during the image acquisition. Figure 1 displays $E(w)$ for two sets of curve: one for the force gradient map proportional to $\delta H/\delta z$ of the sample field, the second curve is proportional to $\delta^2 H/\delta^2 z$. The first and second derivative dependence represent the force gradient response due to a monopole and dipole type tip respectively [4][5]. The tip was modeled as a point with its magnetization normal to the sample plane, at a tip sample separation of 100 nm. Under these conditions, the required Ni strip width w_c is approximately 50 nm. Emphasis should be placed on the effects of two parameters on the nominal error function $E(w)$: the tip sample separation z_o and the active magnetic volume of the MFM tip. An increase in these parameters cause a decrease in the spatial resolution, thus relaxing the constraint on the size of the Ni strip width w_c. The experimental MFM images obtained for this analysis were acquired at a tip-sample separation of 200 nm. At this distance, the Ni width w_c becomes approximately 70 nm. In addition, if the finite tip volume is included in the calculation, then a value of approximately 100 nm is found.

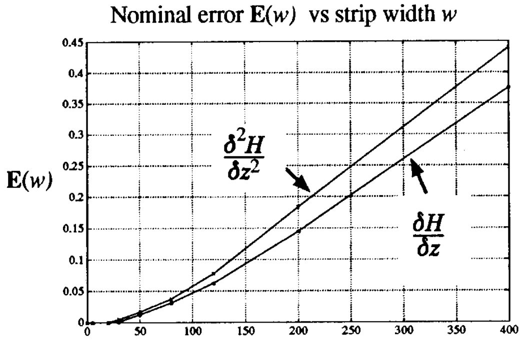

Fig. 1 Nominal error E(w) versus strip width w. Calculations include the modeled response due to a monopole and dipole type tip represented by the first and second derivative dependence.

III. Results and Discussion

The MFM system used in this experiment was developed by the authors. It implements a fiber-optic interferometer detection system very similar to the one used in [7]. The probes used are electrochemically etched Ni wires bent into a tip/cantilever configuration.

In this experiment, arrays of ultra-narrow nickel strips were fabricated on a Si substrate using electron-beam lithography and lift-off techniques [8]. Each Ni strip used for obtaining the tip response function $\hat{a}(x,y,z_o)$ is about 1 µm long, 90 nm wide and 20 nm thick. The deconvolved image using this Ni array should have a spatial resolution of of at least 90 nm. Figure 2 displays an AFM image of an array of Ni strips. If the width of the Ni strip can be further decreased, higher spatial resolutions can be achieved, provided that the MFM imaging condition is optimized to take advantage of the smaller point charge. Recently, arrays as narrow as 10 nm have been fabricated[10]. Therefore, using these small width arrays, 10 nm maybe the ultimate spatial resolution limit that can be achieved from deconvolved MFM images.

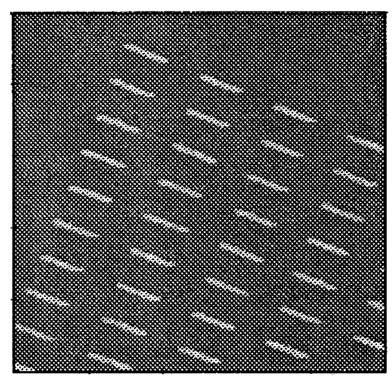

Fig. 2. 10 µm by 10 µm AFM image of nanoscale nickel strip array elements used to acquire the experimental tip response function. Each array element is 1 µm long by 90 nm by 20 nm thick.

Figure 3 shows a detailed mesh plot of the tip response obtained from imaging one end of a Ni strip. The dark and light features are the response due to the positive and negative magnetic charges located at the end of the Ni strips. The orientation of the magnetic moment of the tip in this particular case appears to be predominantly normal to the sample plane (m_z). Closer examination of the tip response shows some asymmetry in the response function due to the skewing of the

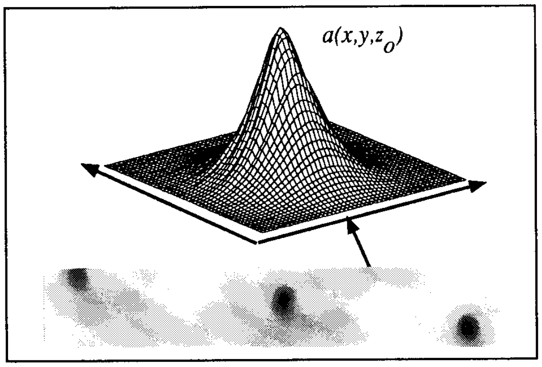

Fig. 3. 1 μm by 5 μm MFM image of nanoscale nickel strips and the detail mesh plot of the tip response function.

tip axis at approximately 10^{o} from the sample normal. However, this deconvolution method should work for any tip orientation as long as the particular tip response is used to deconvolve MFM images taken by the same tip under identical imaging conditions.

The raw MFM image to be deconvolved is taken of a longitudinal thin film recording medium with recorded transitions. The sample is a 300 Å thick CoCrTa/Cr thin film with a coercivity of 377 Oe. The recorded bit is a 1011 pattern from left to right with a 1.5 um bit length, as shown in Figure 4. The raw MFM image is obtained using identical imaging conditions as the tip response function.

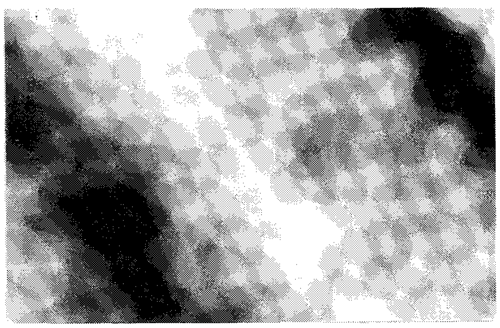

Fig. 4. Raw 3.5 μm x 5 μm MFM image of a recorded magnetic transitions on a 300 Angstrom thick CoCrTa sample.

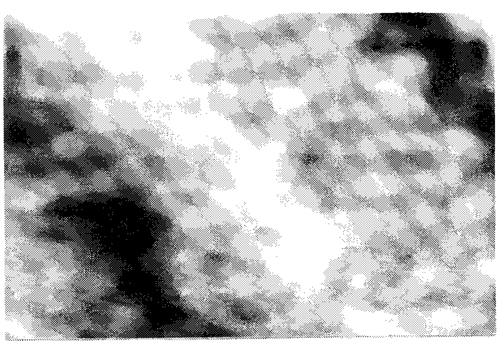

Fig. 5. 3.5 μm x 5 μm deconvolved MFM image revealing the tip independent magnetic charge patterns of the recorded sample.

This raw MFM image is deconvolved with the experimental tip response function using the algorithm described in the previous sections. Figure 5 displays the deconvolved magnetic charge image. Features which were vague and smeared in the raw image become significantly clear and distinctive. The magnetic charge distribution of the recorded transition in the sample shows intermixing of opposite charges in the transition region, which is characteristic of low coercivity thin film media.

Some faint horizontal streaks appear in the deconvolved image which are due to an enhancement of scanning distortions in the original image. Otherwise, there appears to be no significant artifacts introduced by the deconvolution process.

IV. Conclusion

A novel method for the deconvolution of magnetic force images has been presented. The tip response function necessary for the deconvolution has been successfully obtained from MFM images of nanolithographic single domain Ni strip arrays. This procedure enables the removal of the MFM tip dependence, allowing an unambiguous interpretation of magnetic force microscopy images. In addition, the deconvolved image clearly shows improved spatial resolution which is limited mainly by the width of the Ni strip. The method of deconvolution outlined in this paper appears to be a critical step toward quantitative analysis of raw MFM images.

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