

An Ultra-high Resolution Single-domain Magnetic Force Microscope Tip Fabricated Using Nanolithography

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Abstract - An ultra-high resolution MFM tip is proposed and demonstrated. The tip consists of a ~30 nm thick ferromagnetic film coated on a non-magnetic pillar that has a diameter of 150 nm, a length over 1.5 μm and a sharp end of a 10 nm radius. The pillar was fabricated on the apex of a commercial scanning force microscope tip using electron beam lithography. The ferromagnetic films were coated only on one side of the pillar but not on the rest of the tip. Therefore, the tip has a trough shape and a tapered end with a tip radius of ~10 nm. The ferromagnetic trough is single-domain because of its nanoscale size and shape anisotropy. Compared to conventional Ni wire tips, the new tips have a much smaller magnetic charge distribution at the end of the tip, thus offering better imaging resolution. Furthermore, they have a lower stray field, thus making them well suited to measuring soft magnetic materials.

I. INTRODUCTION

The magnetic force microscope (MFM) tip is one of the most important elements in determining the resolution and sensitivity of a MFM [1-4]. Previously, sharpened Ni wires [1] and magnetically coated atomic force microscope tips [5] have been used as MFM tips. Both kinds of tips suffer from several drawbacks. First, these tips are large in area, and therefore consist of multiple magnetic domains and have a broad distribution of magnetic charge that results in poor spatial resolution. Second, the tips have a sizable magnetic charge that can alter the magnetic properties of the magnetic material under inspection. To avoid such interference, the tip has to be kept rather far away from the sample surface, drastically reducing the MFM's sensitivity.

Here we propose and demonstrate a new, ultra-small, single-domain MFM tip that has very small distribution and magnitude of magnetic charges, and therefore offers a resolution many times greater than other MFM tips.

II. TIP STRUCTURES

The novel MFM tip consists of a thin, narrow, but rather long magnetic spike on a nonmagnetic conventional scanning force microscope (SFM) tip.[6] The width and thickness of the magnetic spike are typically a few nanometers and its length is about 1 μm . The dimensions of the magnetic spike are so chosen that the spike is a single magnetic domain and therefore the tip is referred as single-domain spike (SMS) tip. The MFM tip has two important advantages. First, due to the single-domain and sharpness of the tip, the magnetic charge is concentrated in a very small area at the end of the tip therefore it offers higher resolution. Second, due to the small magnetic charge, it is less likely to alter the magnetic

properties of the sample.

In this paper we present one embodiment of such a SMS tip, its fabrication technology, and evaluate its performance. The SMS tip consists of a long non-magnetic spike of nanoscale diameter and a ferromagnetic film that covers only part of the pillar but not the rest of the tip. Therefore, the ferromagnetic portion of the SMS tip has a trough shape with a 10 nm end radius.

III. TIP FABRICATION

The SMS tip fabrication process consists of two main steps (Fig. 1). (1) The non-magnetic pillar was fabricated by

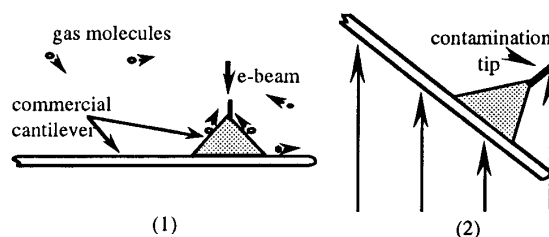


Fig. 1. Schematic of the fabrication process.

contamination electron beam lithography on top of the pyramid of a commercial scanning force microscope (SFM) tip. (2) Ferromagnetic materials, such as nickel or cobalt, were coated on one side of the pillar. In the first step, SFM cantilevers were first sputter coated with 20 nm of gold to prevent charging during the electron beam contamination lithography and to facilitate subsequent focusing on the apex. The tips were then mounted and inserted into an electron beam lithography system with a diffusion pump vacuum system and a tungsten filament gun. A contamination pillar was then grown on the apex by exposing the tip in spot mode for a specified length of time. Growth is due to electron beam assisted molecular deposition onto the cantilever surface. The deposited material was not intentionally introduced, but originates primarily from the background of the lithography system's vacuum chamber and from the sample surface itself. Similar contamination deposits have been shown to be mainly composed of carbon and oxygen.[7]

The tip growth process was investigated and optimized to produce long but narrow pillars with small tip radii that are desirable for high resolution MFM tips. We found that the accelerating voltage and beam current were the most significant parameters in the growth process. It was found that the growth rate would increase with increase of accelerating voltage or decrease of beam current. Figure 2 shows the tip length versus the exposure time at three

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different accelerating potentials 15, 25, and 35 kV, but for the same beam current of 10 pA. The growth rate for 35 kV was

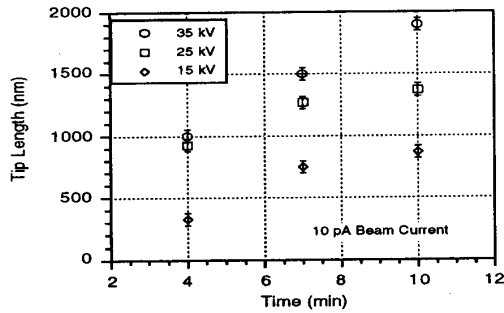


Fig. 2. Tip length with respect to exposure time for a beam current of 10 pA and an accelerating potential of 15, 25, and 35 kV.

found to be the highest (0.1 $\mu\text{m}/\text{min}$. after the initial transient). For a given accelerating voltage, the growth rate becomes relatively constant after an initial transient. Figure 3 shows the resulting tip length versus the beam current at 25 kV for 7 min. exposure time.

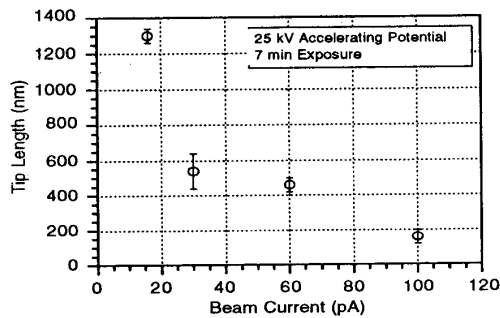


Fig. 3. Characterization of tip length with respect to beam current for a 7 minute exposure with a 25 kV beam.

We also found that the accelerating voltage and beam current affect the tip radius. In fact, higher accelerating voltage or smaller beam current gave smaller average pillar radius. This is mainly because (a) a higher accelerating voltage or a smaller beam current gives smaller beam diameter and (b) a higher voltage reduces the electron back scattering that broadens the effective beam diameter. The average pillar tip radius was observed to decrease from 30 nm to 19 nm as the accelerating voltage increased from 15 to 35 kV.

Based on the study of pillar growth conditions, the pillars used for making SMS tips were grown with a beam current of 10 pA, an accelerating potential of 35 kV, and a growth time ranging from 7 to 10 min. The 10 pA beam current can maximize the growth rate while maintaining sufficient signal to readily focus the beam on the SFM tip apex. A 35 kV accelerating potential, the highest for our e-beam system, gives the small tip radius and high growth rates.

After growing the non-magnetic contamination pillar, the magnetic spike was formed by evaporating nickel or cobalt from an angle as illustrated in figure 1. The angle is selected

so that only the pillar but not the pyramid of the tip is coated with ferromagnetic material. Figure 4 shows a completed MFM tip with a nanoscale nickel magnetic sensor at the tip. The nickel spike, which is trough shaped with a tapered end, is 30 nm thick, ~150 nm wide, and has an average diameter of about 150 nm and a 10 nm tip radius. The non-magnetic contamination pillar is approximately 1.9 μm long, and has an average diameter of about 150 nm. As shown, the tip after fabrication is slightly bent due to intrinsic tensile stress in evaporated nickel. We found that the tip can be straightened by evaporating a nonmagnetic film from the opposite side of the pillar.

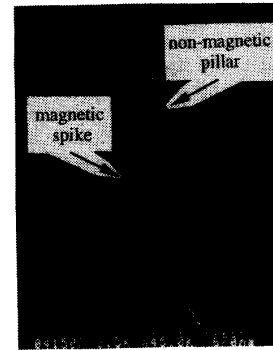


Fig. 4. Completed SMS tip with a nanoscale nickel magnetic sensor at the tip. The Ni spike, which is trough shaped with a tapered end, is 30 nm thick, ~150 nm wide, and has a 10 nm tip radius. The non-magnetic contamination pillar is ~150 nm wide and 1.9 μm long. Intrinsic stress in evaporated Ni bends the tip.

IV. ANALYSIS OF TIP PERFORMANCE

Calculations were performed to evaluate the performance of the SMS tips. The response of the SMS tip to a magnetic dipole was compared to a standard Ni wire tip (Fig. 5). The

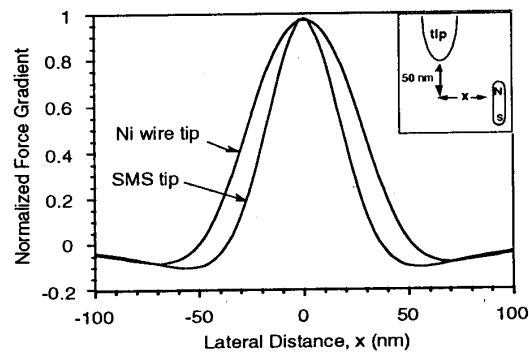


Fig. 5. Response to a magnetic dipole for the SMS tip and a standard Ni wire tip. The FWHM responses are 40 and 60 nm for the SMS and Ni wire tips respectively.

full width at half maximum (FWHM) response for the SMS tip is 40 nm whereas the FWHM response for a standard Ni wire tip is 60 nm. The calculation was performed at a tip-to-sample spacing of 50 nm. It also assumes the SMS tip to be rectangular with a thickness of 15 nm, width of 80 nm and a tip length of 1 μm , and the Ni wire tip to be cylindrical with

a radius of 35 nm and a length of 1 μm . If a sharp tip end is assumed, the SMS tip's resolution should be even better than that indicated in Fig. 5.

The MFM imaging resolution can be further improved by reducing the tip-to-sample spacing. Figure 6 shows the FWHM response of the SMS and Ni wire tips (using the same geometry as before) to a magnetic dipole versus the tip-to-sample spacing. For tip-to-sample spacings greater than about 100 nm, the responses of the two tips are similar. At a tip-to-sample spacing of 20 nm, however, the FWHM response of the SMS tip is nearly 20 nm, whereas the Ni wire tip is still ~ 70 nm. This demonstrates that the ultimate resolution of an MFM tip is limited by its magnetic charge size. The improved resolution of the SMS tip is a direct result of the small area of the magnetic charge and illustrates the significance of single-domain and the control of the magnetic spike size.

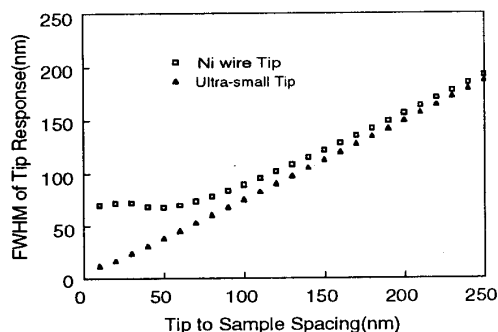


Fig. 6. FWHM response of the SMS and Ni wire tips to a magnetic dipole for different values of tip-to-sample spacing.

Another advantage of the SMS tip is the smaller stray field compared to a conventional Ni wire tip (Fig 7). The SMS tip has very small volume of magnetic material resulting in a stray field of only 150 Oe at a distance of 50 nm. In comparison, the stray field of the SMS tip is at least 10 times smaller that of Ni wire and 2 times smaller than conventionally coated tips.

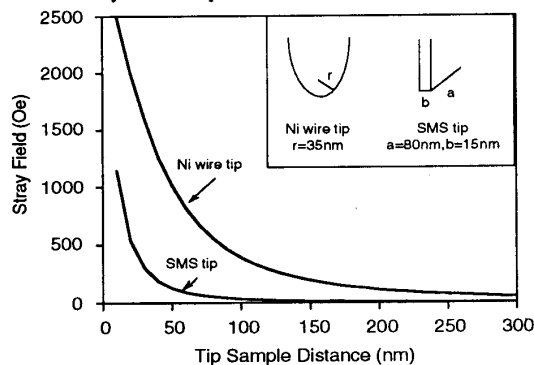


Fig. 7. Stray field of SMS and Ni wire tips.

V. MEASUREMENTS

The SMS tips were tested in a custom-built MFM operating at 300 mTorr. The cantilevers used had a resonance

frequency of 18 kHz which is much lower than that of commercial MFM tips. The SMS tips can readily achieve a magnetic image of a hard disk. To test the resolution of the tip, we fabricated special nanoscale nickel bar arrays. Each bar is 100 nm long, 20 nm wide and 10 nm thick; the separation between bars is 100 nm. Using conventional tips, neither topographic images nor magnetic force images of individual bars could be obtained. But, using an SMS tip, distinct topographic images of each individual bar can be seen, but not the magnetic image. This is because the SMS tip, due to the small magnetic charge needed for high resolution, has a smaller signal to noise ratio and is unable to detect the very small magnetic charge despite its spatial resolution. In other words, the resolution advantage of the SMS tip can not be tested with our current system unless the noise in our system is further reduced. Work in this direction is in progress.

VI. SUMMARY

We have proposed and fabricated a novel magnetic force microscope tip that consists of a ~ 30 nm thick ferromagnetic film coated on one side of a non-magnetic pillar which is ~ 150 nm wide and over 1.5 μm long. The coated ferromagnetic film has a trough shape and a tapered end with a tip radius of ~ 10 nm. Such an MFM tip has three important advantages. First, because of the nanoscale size and shape anisotropy, the magnetic tip is single-domain. Second, due to single-domain properties and the sharpness of the tip, it has magnetic charge concentrated on a very small area at the end of the tip and offers higher resolution. Third, due to the small magnetic charge, it is less likely to alter the magnetic properties of the sample. The non-magnetic pillar was fabricated by contamination electron beam lithography and the ferromagnetic needle was produced using an angle evaporation of nickel or cobalt. Analysis based on a dipole field model indicates that the SMS tip should have a resolution of ~ 20 nm. Furthermore, the tips should have a stray field less than 150 Oe at a tip to sample spacing of 50 nm, making the tips well suited for measuring soft magnetic material. Experimental investigation of the SMS tip is still in progress.

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