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A method for the calibration of magnetic force microscopy tips
Calibration of magnetic force microscopy using micron size straight current wires

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A circuit with two long parallel micron size wires was fabricated by photolithography to calibrate magnetic force microscopy (MFM) tips. The tip phase shift increased as the tip scan height decreased. With the tip scan height kept constant, a linear relationship was found between the current amplitude and the phase shift of the tip at the center position of the two wires separation. The estimated magnetic moment of the tip was one order larger than its nominal value. The results imply that with better control over the fabrication process, the micron size straight wires can be used to calibrate MFM tips. © 2002 American Institute of Physics. [DOI: 10.1063/1.1456058]

Currently magnetic force microscope (MFM) is widely used in industry and research labs. Different methods have been used to calibrate the MFM tip by several groups. 1–7 However, the fabrication of the microcircuits requires the facilities for electron–beam lithography, which is very expensive and is not practical for most MFM users.

In this paper we present our work on the calibration of MFM tips by using a circuit with two long parallel straight wires on micron size, fabricated by photolithography techniques.

The standard lift-off technique was used in the fabrication of the micron size straight wires. The wires were 10/50 nm-thick Cr–Au bilayer. Patterns of different sizes were fabricated simultaneously in one run of operation. Each pattern included two long parallel wires connected at their ends. The width of the wires and the separation of the two long parallel wires both ranged from 1 to 10 μm. Figure 1(a) shows the schematic view of a microcircuit. A current supplied by a precision current source passed through the microcircuit via two wire leads. During the calibration the sense of the current in the two long wires was opposite to each other to enhance the MFM signal, where the z components of the field produced by the two wires add up, a benefit compared to using one single current carrying line. The MFM tip scanned transverse to the current direction. The atomic force image and magnetic force image of the wires were measured simultaneously using a commercial magnetic force microscopy by Digital Instruments, operated in the tapping mode. The MFM tip used was the standard commercial MESP tip from Digital Instruments, i.e., with 50 nm-thick Co alloy coated on the silicon probe. The tip was magnetized along the tip long axis, z, before the measurement.

It must be pointed out that not all of the microcircuits in the wafers were fabricated successfully. Only those parts with well-defined shape were selected to use for the calibration of the MFM tip. Thus a comparison of the results from different circuits is not available.

Generally, in the calibration of the MFM tip, the tip should be close to the wires so that a strong signal and a high signal-to-noise ratio can be obtained. However, when the MFM tip is close enough to the current wires the magnetic field produced by the tip can possibly affect the current distribution in the wires. On the other hand, the magnetic field produced by the current can also possibly alter the magnetic moment of the tip. To calibrate the MFM tip these effects should be minimized. Thus an optimized separation between the tip and the wires should be used in the experiment.

First we consider the magnetic field produced by the MFM tip at the location of the wires. For simplicity, we treat the MFM tip as a dipole with the moment of m polarized along the z axis. Then the field produced by the tip at the location of the wires is

\[
H_{\text{dipole}} = \frac{1}{4 \pi \mu_0} \left( \frac{3(m \cdot R)R}{R^5} - \frac{m}{R^3} \right),
\]

where \( \mu_0 \) is the permeability in the vacuum and R is the vector from the tip to the location of the wires. m is about 10^{-13} emu. For a rough estimation, assume m and R being in the same direction. Taking the effect of the topography of the wires into account, when the separation between the tip and the wires is 100 nm, according to (1), the magnetic field at the location of the wires due to the tip will be about 100 Oe. Its effect on the current distribution in the wires is negligible. Second, we consider the magnetic field at the tip location due to the current.

Figure 1(b) illustrates the cross section view for the wires. w and h are defined as the width and the height of each wire, separately. s is defined as the separation of the two long wires. The coordinate system is defined as shown in the figure. Since the sense of the current in the two wires is opposite to each other, the x component of the fields from the wires.
two wires cancels out. We only need to consider the \( z \)-component of the fields.

The \( z \)-component of the field due to one wire is

\[
H_z = \frac{j}{2\pi} \int^{h/2}_{-h/2} dz' \int^{w/2}_{-w/2} dx' \frac{x' - x_0}{(x' - x_0)^2 + (z' - z_0)^2},
\]

where \( j \) is the current density, \( \mathbf{r}' = (x', z') \) is the vector from the center point of the wire to another point in the wire, \( \mathbf{r}_0 = (x_0, z_0) \) is the vector from the center point of the wire to the tip location. The integral is over the whole area of the cross section of the wire. In (2), a uniform distribution of the current in the wire was assumed.

In our experiment, the height of the wire \( h \) was about 0.05 \( \mu \)m and the maximum applied current through the wires was 20 mA. When the tip scan height is 100 nm, according to (2), for a wire of 3 \( \mu \)m wide and with the applied current of 20 mA, the magnetic field produced by the wire at the tip location is about 50 Oe. This is much smaller than the coercivity of the standard MESP tip, 400 Oe. The field due to the current will not have a significant effect on the moment of the tip.

The above analysis suggests that with a tip scan height of 100 nm and an applied current of 20 mA in the wires, the interaction between the tip and the current is not so strong as to affect either the tip moment or the current distribution in the wires. In the experiment, we chose the tip scan height varying from 0 nm to 1 \( \mu \)m and the applied current in the wires varying from 0 to 20 mA.

On the basis that both the MFM tip moment and the current distribution in the wires are not affected by the tip–current interaction, it is possible to calibrate the MFM tip by using the microcircuit. For simplicity, we use a model only including a monopole and a dipole to describe the MFM tip. When the frequency that drives the MFM tip is kept constant, the phase shift in the tip vibration due to the force between the sample stray field and the MFM tip can be expressed as

\[
\Delta \Phi = \frac{Q}{k} \left[ q \frac{\partial H_z}{\partial z} + m_x \frac{\partial^2 H_x}{\partial z^2} + m_y \frac{\partial^2 H_y}{\partial z^2} + m_z \frac{\partial^2 H_z}{\partial z^2} \right],
\]

where \( Q \) is the quality factor of the MFM tip cantilever resonance, \( k \) is the spring constant of cantilever, \( q \) is the effective magnetic charge of the MFM tip, \( m_s (s = x, y, z) \) is the effective moment of the tip, and \( H_z \) is the vertical component of the sample stray field. It was shown previously by Kong et al. that the contributions from the second term and from the third term in (3) was negligible.\(^6,^7\) In the following, we will only consider the terms with \( H_z \).

From (2) and (3), we can obtain the expression for the phase shift of the tip vibration due to the field from the two wires. A special case is at the locations of \( x = 0 \),

\[
\Delta \Phi = \frac{jQ}{k} \left( \frac{q}{2\pi} \ln \left( \frac{w + s/2 + h/2}{w + s/2} \right) + \ln \left( \frac{w + s/2 + h/2}{w + s/2} \right) - \ln \left( \frac{w + s/2 + h/2}{w + s/2} \right) \right)
\]

where \( \mathbf{r}_0 = (x_0, z_0) \) is the vector from the center point of the wire to the tip location. The integral is over the whole area of the cross section of the wire. In (2), a uniform distribution of the current in the wire was assumed.
where \( r=(x,y) \) refers to the vector from the center point of the two wires separation to the MFM tip location. Assuming that the current distribution is uniform and that the tip magnetic moment is not affected by the current, one immediate implication from (4) is that the phase shift be proportional to the current density.

From (4) we can estimate the tip effective magnetic moment \( m_z \), and the effective magnetic charge \( q \). The quality factor \( Q \) can be determined by measuring the tip’s resonance frequency, \( f_0 \), and the full bandwidth, \( \Delta f_0 \), at 0.707 of the maximum amplitude:

\[
Q = \frac{f_0}{\Delta f_0}.
\]

Figure 2 is the phase shift of the tip vibration at \( x=0 \), \( \Delta \Phi \), as a function of the applied current. The current wire width was 3 \( \mu \)m and the separation of the two wires was 6 \( \mu \)m (center to center). The tip scan height was kept constant, 100 nm. \( \Delta \Phi \) correlates linearly with the current, in good agreement with (4). The results confirmed that both the tip moment and the current distribution in the wires were not affected by the tip–current interaction, so that we can use (4) to estimate the moment and the effective charge of the tip.

Figure 3 is the phase shift at \( x=0 \), \( \Delta \Phi \), as a function of the scan height. The applied current in the wires was kept constant, 20 mA. \( \Delta \Phi \) decreases with increasing tip–current separation. Fitting the data in Fig. 3 by using (4), we obtained the ratio of the magnetic moment of the tip and the effective magnetic charge of the tip \( m_z/q \) to be 0.36 \( \mu \)m. To minimize errors, only the points with \( \Delta \Phi \) greater than 0.4° were used for the fitting.

\( f_0 \) and \( \Delta f_0 \) were obtained from the resonance curve in the cantilever tune of MFM and were 72.4 and 0.52 KHz, respectively. From (5), the quality factor \( Q = 139 \). Therefore, from (4) we estimated the magnetic moment of the tip to be about \( 1.7 \times 10^{-12} \) emu and the effective magnetic charge of the tip to be about \( 4.7 \times 10^{-6} \) emu/cm.

The estimated magnetic moment of the tip is one order larger than its nominal value \( 10^{-13} \) emu. The discrepancy could be caused by several sources: The assumption of a certain spring constant rather than measuring it directly, where in reality the spring constant in MESP tips varies from tip to tip; the monopole plus dipole model to describe the MFM tip, which is not accurate in reality; the poor quality control over the fabrication of the wires. In the calculation above, we assumed the shape of the wires to be ideally rectangular and (4) only included the dipole moment of the current wires. This is not true in practice. In fact, it was found that not only did the shape of the wires deviate from the rectangular shape, but also irregularity and asymmetry were found in the topography of the wires. In that case, magnetic multipole interactions will be significant sources of the tip–wires interaction and must be included in the calculation. We found that the predicted profile only agreed qualitatively with the experimental results. The topography of the wires reflects the limitations of the photolithography technology, especially the lift-off technology. It was found that in the fabrication process, ion-milling was a better choice than lift-off. With ion-milling, a well-defined shape of the wires can be obtained. Once ion-milling in stead of lift-off is used, better accuracy will be achieved in the calibration of the MFM tips.

8. Digital Instruments, Santa Barbara, CA.