Theoretical and Experimental Study of Synthetic MFM Tips

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ABSTRACT

One of the extensively investigated issues for magnetic force microscopy is its low resolution as compared to other scanning probe techniques such as atomic force microscopy and scanning tunneling microscopy. This is mainly caused by the fact that the magnetically responsive coating covers the entire body of the tip as well as the relatively large sample-tip spacing. Recently, we have developed a new type of tip which effectively has a magnetic coating only at the tip apex and at the same time can be used at a smaller sample-tip distance due to its low moment. In this paper, the superior performance of the new tip is studied theoretically using an analytical model. The analytical results are supported by the experimental data.

Keywords: MFM, point-dipole, synthetic, high-resolution, analytical model

1 INTRODUCTION

Magnetic force microscopy (MFM) has been used extensively to study the magnetic properties of materials. The resolution of MFM is determined by many factors including the geometric shape of the tip, the materials and structures used to form the coating, the tip-sample distance, and in some cases the interaction between the tip and the sample. Generally speaking, a high-resolution MFM requires tips with small lateral dimensions and stable magnetic coatings with a highly localized stray field. The latter allows the scanning to be performed with a small tip-sample distance which gives a high resolution without disturbing the sample domain structures. Therefore, there are two approaches to improve the resolution of MFM. The first approach is to engineer the tip shape to achieve a smaller lateral dimension and the second to use different magnetic coating materials, such as superparamagnetic and antiferromagnetic materials to reduce the tip stray field. So far, many efforts had been made to improve the resolution of MFM through sharpening the tips using different approaches such as attaching carbon nanotubes to the original tips,[1,2] trimming the tips by focus ion beam (FIB),[3-6] electron beam lithography,[5,7,8] and ion beam etching,[9] selective deposition by self-field emission,[10] electron beam irradiation,[8,10,13,14] and focused electron beam decomposition and deposition.[16,17] Although all these techniques, to a certain extent, can improve the resolution, the primary drawback is that the tips must be processed one-by-one instead of using a batch process.

Based on this background, recently we have developed two different types of MFM tips.[18,19] In one of the designs, an exchange biased bilayer is used as the magnetic coating which significantly improves the stability of weak moment tips. In the second design, the stability is improved further using a ferromagnetic FM/Ru/FM trilayer. Furthermore, the tip functions effectively as a point-dipole due to the formation of a flux-closed structure at the tip apex when the two FM layers are coupled antiferromagnetically. In this paper, we analyze the tip using an analytical model and compare the results with experimental data.

2 THEORETICAL CONSIDERATION

Fig.1 shows the schematic of the synthetic MFM tip. The magnetic coating consists of two FM layers separated by a thin Ru layer. It is well known from exchange coupling studies that the FM layers can couple either ferromagnetically or anti-ferromagnetically, depending on the Ru thickness. The first antiferromagnetic coupling appears when the Ru layer is about 0.6-0.8 nm. In this case, as shown in Fig.1, an effective point-dipole will be formed at the tip apex due to the flux closure requirement. Intuitively, one can understand that the resolution of this kind of tip will be better than that of the single layer tip.

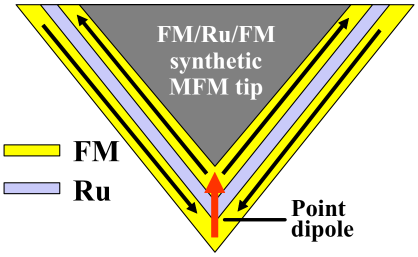


Fig.1. Schematic of the synthetic tip.

The MFM tip, as a magnetized body, when brought into the stray field of a sample, will have a magnetostatic potential energy E given by

$$E = -\mu_0 \int (\vec{M}_{tip} \cdot \vec{H}_{sample}) dV_{tip} \quad (1)$$

Then the force acting on the MFM tip is given by

$$\vec{F} = -\nabla E = -\mu_0 \iiint \nabla(\vec{M}_{tip} \cdot \vec{H}_{sample}) dV_{tip} \qquad (2)$$

Generally, we use the dynamic detecting mode, in which the signal detected is proportional to the force gradient in the linear range. For the tip with a uniform magnetization distribution in z direction, the force gradient in z direction is given by

$$F_z^{'} = -\mu_0 \iiint M_z(\vec{r}^{'}) \frac{\partial^2 H_{sample}}{\partial z^2} dV_{tip}(\vec{r}^{'} + \vec{r}) \qquad (3)$$

Here, $\vec{r}$ is the position vector of the tip apex and $\vec{r}^{'}$ is the position vector of a point inside the tip with respect to the tip apex. The above equation implies that the MFM response is given by a three dimensional convolution between the magnetization distribution on the entire tip body and the fringe field from the samples. Although the integration in real space can generate the MFM signal at each point, it is more instructive to deal with this kind of the problem in the spatial frequency domain in which the tip magnetization and sample fringe field will be decoupled in the linear-response regime. The latter is generally referred to as frequency response analysis of MFM.[20] In order to simplify the problem and at the same time to have a clear physics picture, S. Porthun *et al.*[21] has developed a one-dimensional model for MFM imaging of a periodical magnetization pattern given by

$$M_z(k,x) = M_s \cos(kx), \qquad (4)$$

For a bar-shaped tip with a uniform magnetization $\boldsymbol{M_t}$, depth D in y-direction, height H in z-direction and width t in x-direction (Fig.2), the frequency spectrum of the force gradient is given by

$$F_z^{'}(k,d) = -\mu_0 \frac{M_s M_t}{2}(D \cdot kt) e^{-kd} (1-e^{-k\delta})(1-e^{-kH}) \frac{\sin(kt/2)}{kt/2} \qquad (5)$$

Here, μ_0 is the permeability of vacuum, M_s is the sample saturation magnetization and M_t is the tip magnetization, d is the tip-sample distance, δ is the thickness of the media, and k is the spatial frequency. In the above equation, the last term sets a cut-off frequency beyond which the MFM tip cannot produce truthful information of the sample fringe field. The term $\boldsymbol{e^{-kd}}$, originating from the tip-sample distance, simply reduces the high-frequency components against the low-frequency ones. It is interesting to note that the media thickness and tip height actually enhance the high-frequency response, particularly when they are comparable with the feature sizes of the magnetic patterns on the sample. The latter can be satisfied easily for the sample thickness, but it is not true for the tip height because it is normally in the micrometer range for commercial tips. However, if one has two identical tips with their magnetization being oriented in opposite directions and their physical position being shifted against each other by a small distance Δd in the z direction, the net frequency response will be given by

$$F_z^{'}(k,d) = -\mu_0 \frac{M_s M_t}{2}(D \cdot kt) e^{-kd} (1-e^{-k\delta})(1-e^{-kH})(1-e^{-k\Delta d}) \frac{\sin(kt/2)}{kt/2} \qquad (6)$$

The multiplication factor $\boldsymbol{(1-e^{-k\Delta d})}$ will boost the high-frequency components because $\boldsymbol{(1-e^{-k\Delta d}) \approx k\Delta d}$ for small Δd. When H >> Δd, the tip function effectively as a point-dipole tip.

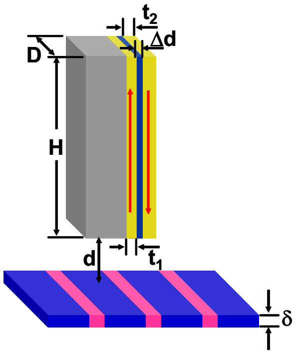


Fig.2. Schematic of simplified MFM tip.

The synthetic tip which we have reported in our earlier work consists of two ferromagnetic layers antiferromagnetically coupled via a thin non-magnetic layer. Although the inner and outer layers have a slightly different shape, they are more or less equivalent to the two identical tips that we have just discussed above. This explains why the synthetic tip has a higher resolution than the conventional single layer tip. Of course, it should be noted that the absolute value of the MFM signal from the synthetic tip weakens due to the partial cancellation of the signal from the two layers with opposite magnetization directions. It is also obvious that the multiplication factor $\boldsymbol{(1-e^{-k\Delta d})}$ will become $\boldsymbol{(1+e^{-k\Delta d})}$ when the two magnetic layers are coupled in parallel. This will result in the degradation of resolution, though the absolute strength of the signal will be enhanced.

The above discussion suggests that it is important to control the Ru thickness precisely so as to obtain a higher resolution in the synthetic tip. The resolution enhancement of synthetic tip has been demonstrated in our previous work. In this paper, we report a systematic study of the effect of the Ru thickness on the performance of the FM/Ru/FM synthetic tips. Fig.3 shows typical calculated frequency response of both a single-layer tip and synthetic tips with different interlayer spacing. Other parameters used for the simulation are shown in the figure. As compared to the single-layer tip, the synthetic tips have a suppressed response at low frequency, which contributes to the improvement of resolution, though the cutoff frequency is still the same. In practice, the synthetic tip is expected to have a much better performance when the FM layers are very thin because it is thermally more stable than the single-layer tip.

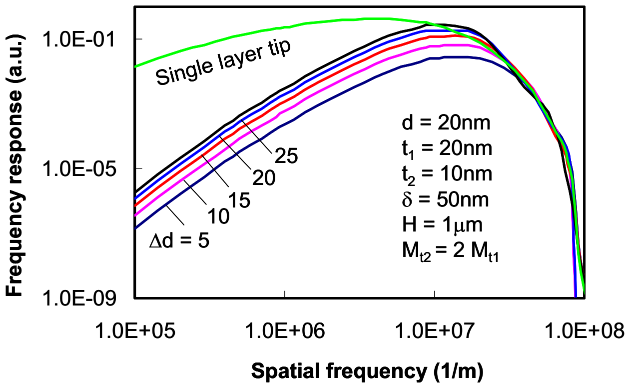
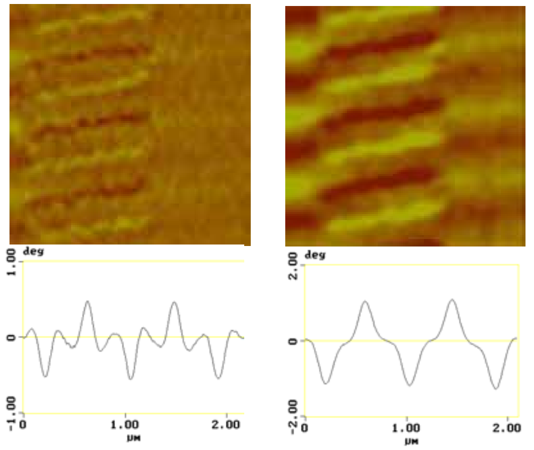


Fig.3. Calculated frequency response of single layer and synthetic tips.

3 RESULTS AND DISCUSSION

A series of MFM tips with the structure Cr(3 nm)/CoCrPt (20 nm)/Ru /CoCrPt (20 nm)/Cr(3 nm) (CCP is Co74Cr13Pt13) were fabricated by sputtering the multiple layers on the bare FMR tips from Nanosensor. The bottom Cr layer was used as a seed and adhesion layer. The sputtering conditions were optimized in our work on spin-valves. All the tips were designed to have the same layer configurations except that the nominal thickness of the Ru layer is varied from 0.2 nm to 1.2 nm with a step of 0.2 nm, and at 1.6 nm, 2.4 nm, and 3.2 nm, respectively. The nominal values were obtained from the growth rate on flat substrates; the actual thickness on the tips may differ from the nominal values due to the topographical effect near the tip apex. Nevertheless, the comparison among different tips is still valid and meaningful because care has been taken to make sure that all other parameters are the same and the only changing parameter is the thickness of the Ru layer. All the MFM imaging experiments were performed at room temperature in air using a commercial scanning probe microscopy (Digital Instrument Dimension 3100), operated at the tapping/lift mode with a lift-height of 30 nm. As it is expected, the fabricated synthetic tip shows oscillator behavior with respect to the Ru layer thickness. Detailed comparison of the performance of tips with different Ru thicknesses will be discussed elsewhere. Here we only focus on those with a nominal thickness of 0.6-0.8 nm which leads to an anti-parallel coupling between the two FM layers.

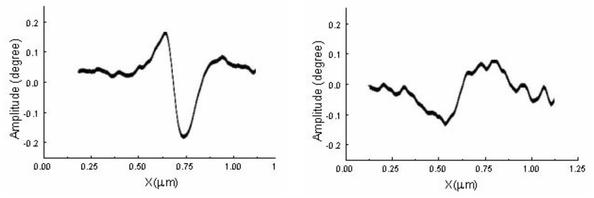
The MFM images obtained from a synthetic tip and a conventional MESP tip are shown in Figs. 4(a) and 4(b), respectively, together with the averaged down track profile. The full width at half maximum of the transition decreases from 130 nm for the MESP tip to 110 nm for the synthetic tip for the specific patterns which we have measured. It is obvious that not only the zigzag transition but also the structure of the grains can be seen clearly in the images obtained from the synthetic tip. The superior performance of the synthetic tip compared to the conventional tip is attributed to the stable magnetic configuration and the concentration of magnetic charges at the tip apex to form the point dipole. The latter makes the effective volume of the tip much smaller than that of the conventional tip. The point-dipole response can be seen from the overshot in the down track profile of the synthetic tip, but not in that of the conventional tip.



(a) (b)

Fig.4. MFM images and averaged down-track profile of the magnetic response. (a) synthetic tip and (b) conventional tip.

The superior performance of the synthetic tip is also reflected in the imaging of Neel domain walls as shown in Fig.5. The cross-wall profile obtained from the synthetic tip is almost the same as the theoretical calculations.



(a) (b)

Fig.5. Cross-wall profile of Neel domain walls: (a) synthetic tip and (b) conventional tip.

The combination of the synthetic structure and point-dipole greatly reduces the spreading of the stray field of the tip. The anti-parallel coupling between the two FM layers also greatly reduces the interactions between the tip and the sample. This can be seen in the results shown in Fig.5 for imaging of cross tie 90^0 domain walls. This type of domain walls is very sensitive to external field and, therefore requires the use of a very low moment tip to image them. As it is shown in Fig.5, a very clear image of the cross tie 90^0 domain wall was obtained using a synthetic tip, but it could not be imaged using the conventional tip.

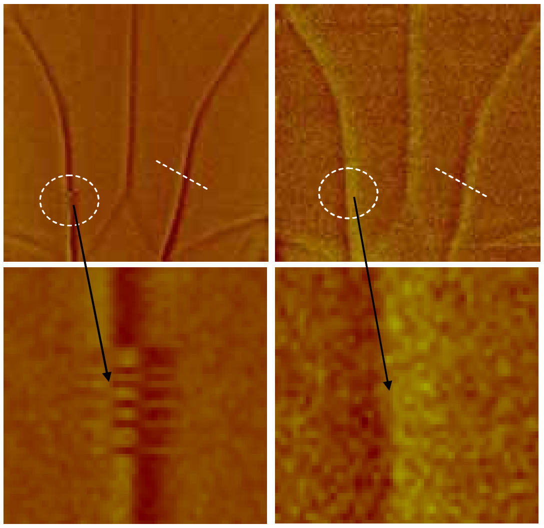

(a) (b)

Fig.5. MFM images of cross tie domain walls. (a) synthetic tip; (b) conventional tip.

The reduced tip-sample interaction can also be seen in the results shown in Fig.6 which are MFM images of a soft magnet nanostructure obtained at different lift heights. The influence of the tip-sample interaction in conventional tips can be seen from the movement of the boundary lines of the domain structures in different scans, which is not so obvious in images obtained from synthetic tips.

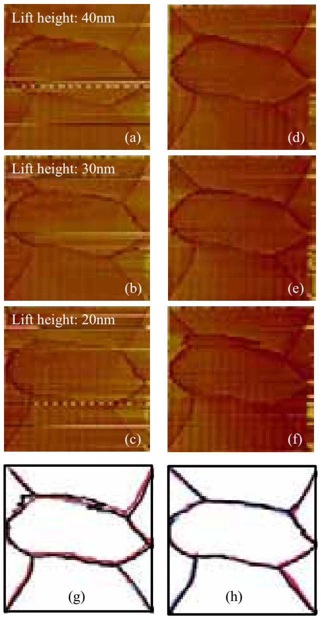


Fig.6. MFM images of a soft magnet. (a)-(c), conventional tip at a lift height of 40 nm, 30 nm and 20 nm, respectively; (d)-(f), synthetic tip at a lift height of 40 nm, 30 nm and 20 nm, respectively. (g) boundary lines of the domain walls for (a)-(c); (h) boundary lines of the domain walls for (d)-(f).

4 CONCLUSIONS

We have developed a novel type of MFM tips which does not only have a high resolution but also exhibits reduced sample-tip interactions. The superior performance of the synthetic tip has been studied both theoretically and verified experimentally. Further work is being done to improve the coating process so as to fabricate tips in a well-controlled fashion.

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