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# Simulation of high-resolution MFM tips for high-density magnetic recording media with low bit aspect ratio

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**Abstract**

To design the high-resolution magnetic force microscopy (MFM) tips suitable for high-density magnetic recording media with low bit aspect ratio (BAR), the transfer functions of tips with various sharpened tip-ends were calculated for a checkered perpendicular magnetization pattern and the resolution of these tips was estimated by considering the resolution limit due to thermal noise at room temperature. The cylindrical tip with a spheroidal tip-end having a large ellipticity is found to be a suitable candidate for high-resolution MFM imaging of magnetic recording media with low BAR. For the tips with ellipticities larger than $\tan 45^\circ$, there are no zero-signal frequencies. The sensitivity shows a maximum around an ellipticity of $\tan 70^\circ$. The spheroidal tip shows a much smaller tip thickness dependence compared to the bar shape tip with a flat tip-end or an ellipsoidal tip-end, because only the tip-end mainly contributes to signals in case of the spheroidal tip.


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## 1. Introduction

With the recent development of high-density perpendicular magnetic recording media and nanoscale magnetism for magnetic thin film, nanometer spatial resolution is strongly required for Magnetic Force Microscopy (MFM). In order to realize nanometer resolution with MFM, it is important to develop sensitive MFM tips with small effective tip volume. There are many studies about high-resolution MFM tips, such as perforated tips [1], tips using electron beam-induced deposited carbon needles [2], focused ion beam modified tips [3] and elongated magnetic bar tips using silicon micromachining techniques which are named CantiClever tips [4]. On the other hand, with the current trend of decreasing bit aspect ratio (BAR) in high-density magnetic recording

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media, such as patterned media, MFM tips suitable for media with low BAR will be also needed.

To design high-resolution MFM tips and discuss the resolution of fabricated MFM tips, simulation is useful. The authors previously approximated the MFM signals of CantiClever tips for one-dimensional media, which correspond to media with infinite BAR. The sharpened bar tips having two ellipsoidal flat planes at the tip-end were found to have high-resolution in the range of high ellipticity. On increasing the ellipticity of ellipsoidal tip-end planes, zero signal spatial frequencies disappear in the range of ellipticity larger than $\tan 45^\circ$ and the sensitivity of tips has a maximum around $\tan 80^\circ$ [5]. However, with decreasing BAR of media, the resolution of ellipsoidal tips is predicted to decrease due to the occurrence of zero signal frequencies in the cross track direction. Therefore, it is important to design high-resolution tips suitable for the media with low BAR.

In this study, we approximate MFM signals of various shaped tips and evaluate the resolution of the tips for the media with low BAR and discuss the suitable design of MFM tips.

## 2. Methods

Fig. 1 shows the calculation model of MFM signals for a checkered perpendicular magnetization pattern. A cylindrical tip with spheroidal tip-end (spheroidal tip) and a bar shape tip having two ellipsoidal flat planes at the tip-end (ellipsoidal tip) are used. Here $d$ is the diameter of the spheroidal tip or the side length of the ellipsoidal tip. $\Delta l$ is the length of the tip. The $z$ direction is perpendicular to the sample surface. The magnetization of the tips is perpendicular to the surface ($M_z = M_t$), which means there is no fluctuation of magnetization direction during the observation. The MFM signal is expressed by the following equation [5–7]:

$$F'_z = -\frac{\partial^2}{\partial z^2} U = -\frac{\partial^2}{\partial z^2} \mu_0 \int_{\text{tip}} M_{\text{tip}}\, H_{\text{sample}}\, \mathrm{d}V_{\text{tip}}. \tag{1}$$

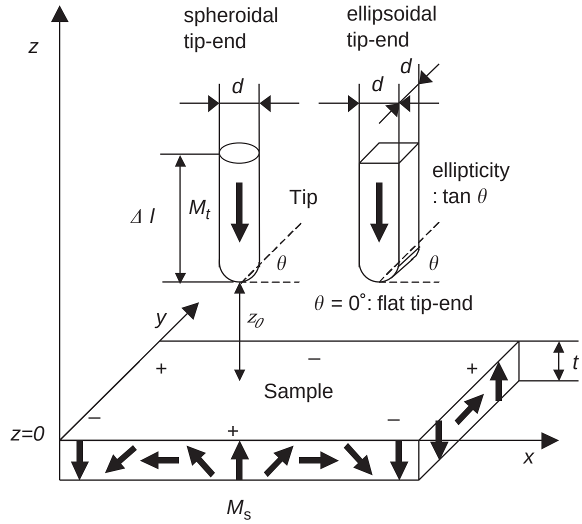


Fig. 1. Calculation model of MFM signals.

Here a sample with checkered perpendicular magnetization pattern ($M_z = M_s \cos(k_x x)\cos(k_y y)$) and thickness $t$ is used. The perpendicular media with sharp transition are obtained by the superposition of sinusoidal perpendicular magnetizations with different spatial frequencies. After the superposition, the in-plane magnetization of a sample vanishes. Therefore, the authors neglect the in-plane component of magnetization. However, the model is enough to estimate the MFM resolution, because the first harmonic component of spatial variation of perpendicular magnetization is dominant near the resolution limit. At high spatial frequency region, perpendicular media with sharp transition are observed like sinusoidal perpendicular media by MFM. From this point of view, it should be noted that MFM observations do not represent a real distribution of magnetization in perpendicular media transitions at high recording density. The amplitude of $F'_z$ for this system was calculated by substituting the following equations in Eq. (1):

$$M_{\text{tip}} = M_t, \tag{2}$$

$$H_{\text{sample}} = \frac{M_s}{2} \cos(k_x x)\, \cos(k_y y) \times \left(1 - \mathrm{e}^{-\sqrt{kx^2 + ky^2}\, t}\right) \mathrm{e}^{-\sqrt{kx^2 + ky^2}\, z}. \tag{3}$$