Contrast simulation in the phase shift dynamic magnetic force microscopy depending on the MFM probe geometry and materials

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Abstract. The gradient of the magnetic force caused by the interaction of various shapes magnetic nanoprobes with magnetic materials has been simulated. Because the force gradient is proportional to the phase shift in probe oscillations the data obtained allow us to compare the contrast of dynamic magnetic force microscopy images for probes with various shapes. A comparison of standard pyramidal probes and probes with cylinder-shaped nanowiskers with different aspect ratios has been carried out. The probes with optimal parameters such as the shape, the thickness and type of the magnetic coating giving the maximum phase shift and as a result giving the best quality visualization of magnetic fields on the sample surface in the phase shift mode have been selected.

1. Introduction
In magnetic force microscopy (MFM) when studying complex nanoscale structures the problem of detecting of small areas of magnetization is exist. It is well known that the spatial resolution and sensitivity of the MFM are determined by the shape and material of the probes used [1]. Increasing the sensitivity and resolution of the MFM technique is necessary, first of all, for high-precision magnetic mapping and diagnostics of nanoelectronic elements, in particular, reading and writing magnetic information on magnetic media with an accuracy of single domains.

A lot of methods allow forming a magnetic probe from different materials of almost any shapes [2-5]. Therefore, the selection of the optimal shape and magnetic material of the probe before carrying out experimental research is a necessary step to improve the quality of MFM measurements.

Thus, the main purpose of this work was to identify the optimal parameters of high-aspect magnetic probes for magnetic force microscopy by simulating their geometry, magnetic material and coating thickness of the magnetic layer.

2. Simulations for various MFM probes
The simulations for standard Si cantilevers and high-aspect probes coated with a thin layer of magnetic material were performed. The geometry of the high-aspect probes corresponded to the geometry of the nanowhisker (NW), which is grown on the top of the silicon pyramid of a standard
cantilever by the method of a focused electron beam in the presence of precursor gases in a scanning electron microscope (figure 1 a) with subsequent deposition of a thin layer of magnetic materials [3]. The MFM probe model is shown in the figure 1 b, c.

The Gauss law was used to determine the distribution of the magnetic field:
\[ \mathbf{V} \cdot \mathbf{B} = 0, \]
where \( \mathbf{B} \) is the magnetic induction vector, [T].

Equation (1) was solved by the finite element method in the COMSOL Multiphysics software package.

The following relationship was satisfied for the magnetized areas of the magnetic deposition of the probe and the magnetic domain:
\[ \mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}), \]
where \( \mu_0 = 4\pi \cdot 10^7 \) is the magnetic constant, [N/m]; \( \mathbf{H} \) - vector of the magnetic field strength, [A/m]; \( \mathbf{M} \) is the material magnetization vector, [A/m].

For magnetization vector in the magnetic domain the value of \( |\mathbf{M}| = 6 \cdot 10^5 \) A/m was chosen. The change in the geometrical dimensions of the NW and the thickness of the deposition was calculated at the fixed value \( |\mathbf{M}| = 3 \cdot 10^5 \) A/m (for Co coating). Separately, the effect of a change in the magnetization modulus was studied with \( |\mathbf{M}| = 2,8 \cdot 10^4 \) A/m (for Ni coating) and \( |\mathbf{M}| = 1,9 \cdot 10^6 \) A/m (for CoFe coating).

![Figure 1. SEM image of NW probe (a) and NW high-aspect MFM probe model in the COMSOL Multiphysics (b): 1 - the top of the standard probe, 2 - the magnetic coating material, 3 - NW, 4 - magnetic domain. The extended area of the probe and the domain is shown on the right (c).](image)

The size of the magnetic domain was chosen as 30 nm, the thickness of the ferromagnetic coating of the probe was varied from 20 to 50 nm, the width of the NW was varied from 25 to 75 nm and the height was varied from 250 to 750 nm.

3. Results and Discussions

It was found that the NW probe has twice larger gradient values compared with the standard probe with the same deposition thicknesses of magnetic material (figure 2 a). Gradient increase was revealed with a gradual rising of the deposition thickness up to 50 nm (to \( \sim 15 \) \( \mu \)N/m for standard probe and to \( \sim 30 \) \( \mu \)N/m for NW probe).

NW thickness increase from 25 nm to 50 nm (the magnetic material has a constant thickness of 50 nm) leads to gradient decrease from \( \sim 35 \) \( \mu \)N/m to \( \sim 30 \) \( \mu \)N/m, after which the gradient change almost not occurs. Thickness change of the NW while maintaining the overall diameter of the whisker reveals the same gradient decrease, but with smaller absolute values by \( \sim 8\% \).
Figure 2. The force gradient for probes interacting with a single 30 nm domain (half of the cross section relative to the center is shown) with varying thickness of the magnetic coating (a) and probe coating material (b). NW length is 500 nm, NW diameter is 50 nm without coating, the total diameter is 150 nm. Coating thickness is 50 nm (b).

A gradual gradient increase was observed by increase of NW length (figure 3 b) from 250 nm (~25 μN/m) to 750 nm (~40 μN/m). A gradual gradient increase also was observed by increasing angle of inclination of the NW relative to the normal of the surface (figure 3 a). This can be explained by the large overlap of the magnetic fields of the sample and the probe during interaction at increasing angle.

The lowest gradient values were obtained using Ni coating, the maximum value of which was 5.8 μN/m for the NW probe and 4.3 μN/m for the standard probe. Co coating has large values of 31.4 μN/m for the NW probe and 17.2 μN/m for the standard probe, which gives a twofold change in the force gradient. The best material turned out to be CoFe, which gave values of 239 μN/m for the NW probe and 97.5 μN/m for the standard probe (~ 2.5 times change), which makes it most demanded in MFM measurements (figure 2 b).

Figure 3. The field gradient of NW with a Co coating interacting with a single 30 nm domain when changing the angle «α» of the NW- probe tilt (a) and NW length «L» (b).
4. Conclusions
The influence of probe geometry, the thickness of the coating of the magnetic layer, the angle of probe inclination and the type of magnetic material on the MFM data were studied. Force gradient increase was found increasing the thickness of the magnetic coating, lowering the thickness and increasing the length of the NW, which should lead to an improvement in the contrast of the MFM image in phase contrast mode. The CoFe turned out to be the optimal coating material, which gives the highest values of the force gradient.

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