Specialized probes with nanowhisker structures for high resolution magnetic force microscopy

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Abstract. Creation and study of specialized nanowhisker probes with magnetic coating are performed for high-precision imaging of various objects by means of atomic force and magnetic force microscopy. Thin layers of Ni and Co are deposited on the surface of nanowhisker structures to perform visualization of magnetic fields on the sample surface, in particular, structure of pits on a hard disk drive (HDD). It is revealed that probes with nanowhisker structures covered with magnetic coating due to their high aspect ratio demonstrate a higher spatial resolution and contrast of magnetic fields visualization in comparison with standard magnetic probes.

1. Introduction

Scanning probe microscopy (SPM) is one of the main methods of high precision material investigation and modification with nanometer resolution. Advantages of SPM are ability to visualize geometric dimensions of surface features of various materials as well as to perform measurements of mechanical properties, the spatial distribution of adhesion forces, electric and magnetic fields on the surface of samples.

Magnetic force microscopy (MFM) should be also distinguish as one of promising technique in nanotechnology due to its ability to perform both highly accurate reading of magnetic fields distribution [1] and recording of magnetic information [2, 3]. The important role of nanoprobes for MFM resolution should be noted. Indeed, geometric parameters and the type of probe determine the sensitivity of this method, the resulting resolution and the contrast of obtained images.

The aim of this work is to create and study a new type of magnetic probes based on whisker structures, including the simulation of magnetic probes with different geometric shapes.

2. Experimental setup

Producing of nanowhisker structures on the summits of probes and control of their parameters were performed by means of scanning electron microscope CrossBeam Neon 40 (Carl Zeiss, Germany) [4, 5]. Study of nanowhisker probes possibilities were carried out on SPM complex Ntegra Aura (NT-MDT, Russia).

Deposition of magnetic materials (Ni, Co) on the top of probe pyramid surface was produced by electron sputtering with Auto 500 Edwards (BOC Edw., England).
3. Results and Discussions
Investigation of the probe with nanowhiskers (NW) in the air was carried out in tapping mode, increasing the stability of NW probes and reducing damaging effects of the probe to the sample. Study of micro- and nanostructures of test lattice TGQ01 with calibrated geometric parameters demonstrated a two-fold decreasing of broadening on vertical steps projection of the surface using NW probes in comparison with standard probes. Furthermore, imaging of nanoscale channels in electron resist PMMA on Si substrate revealed improvement of penetration ability using NW probes. The phenomenon of lateral resolution and penetration ability improvement in case of NW probes can be explained by the high aspect ratio of nanowhisker structures (length to diameter ratio) [6].

Distribution of magnetic fields on test specimens in the form of segments of a magnetic hard disk (HDD) was investigated with standard and specialized NW probes whose surfaces were coated with thin layers of magnetic material (Ni, Co). Magnetic fields study was performed with two-pass method. On the first pass information about topological features was obtained, while the second pass at a fixed height (10 nm) from the sample surface gave information about magnetic fields according to probe oscillation phase shift. The magnetic probe oscillated at the resonant frequency \( f_0 \approx 133 \) kHz during the distribution of magnetic fields measurement. The presence of magnetic field provided additional damping effect influenced on a phase shift between the driving force and the vibrations of probe. Our investigation showed that a NW probe with Ni or Co magnetic coatings gives opportunities to obtain better contrast of MFM phase in comparison with a standard probe (see Fig. 1, 2). In case of Co coating MFM images were more contrast. The thickness of magnetic coating was 50 nm. Increasing of magnetic thickness led to a deterioration of image quality due to reduction of probe sharpness, while decreasing resulted in a lack of sensitivity to magnetic fields.

![Fig. 1. MFM images of HDD magnetic field obtained by standard probe (a) and NW probe (b) with magnetic 50 nm Ni coating.](image)

![Fig. 2. MFM images of HDD magnetic field obtained by standard probe (a) and NW probe (b) with magnetic 50 nm Co coating.](image)
Fig. 3 and 4 shows MFM images of individual pits obtained with standard and whisker magnetic probes covered with thin layer of Co. One can see that whisker probe is characterized with improvement of sensitivity, phase contrast and spatial resolution of MFM image.

Fig. 3. MFM image of individual pits (a) and cross-section (b) obtained with standard probe.

Fig. 4. MFM image of individual pits (a) and cross-section (b) obtained with NW probe.

It should be also noticed that so-called "cross effect" linked with the influence of magnetic probe on sample magnetic field distribution was observed (Fig. 5). The phenomenon of "cross effect" is more significant in the case of NW probes compared to standard probes.

Fig. 5. Observation of the "cross effect" with standard probe (a) and NW probe (b).
Numerical simulation of magnetic probes with geometry of standard probe and NW probe was carried out. Simulation was performed by means of COMSOL Multiphysics software based on finite element method for solving physics-based problems. A distribution of magnetic field was calculated by Maxwell’s equations. Magnetized ferromagnetic layer of probes and HDD’s bits were used as sources of magnetic field.

Field induced in a paramagnetic material of the probe, unmagnetized ferromagnetic material of HDD’s surface and environment was calculated as:

$$ B = \mu_0 \mu_r H $$

where $B$ is the magnetic flux density (T), $H$ is the magnetic field intensity (A/m), $\mu_0$ is the permeability of vacuum ($4\pi \cdot 10^{-7}$ H/m), $\mu_r$ is the relative permeability.

Resulting field in the bits and the magnetic part of the probe was performed with the following expression:

$$ B = \mu_0 (H + M) $$

where $M$ is the magnetization vector (A/m).

Calculation of forces acting on the probe was obtained by integration of Maxwell stress tensor over the boundary of the probe. Maxwell stress tensor for only magnetic field can be written as:

$$ \sigma_{ij} = \frac{1}{\mu_0} B_i B_j - \frac{1}{2\mu_0} B^2 \delta_{ij} $$

where $B_i$, $B_j$ are the components of magnetic field, $\delta_{ij}$ is the Kronecker's delta.

During simulation magnetizations of ferromagnetic layer of the probe and HDD’s bits were set as $-300$ emu/cm$^3$ and $\pm 600$ emu/cm$^3$, respectively, where minus indicated the direction of the magnetization vector against the z-axis. The distribution of magnetization for standard probe and NW probe is shown in Fig. 6.

![Fig. 6. The distribution of magnetization z component for Standard probe (a) and NW probe (b)](image)

The relative permeability of paramagnetic material of the probe, unmagnetized ferromagnetic material of HDD’s surface and the environment were set as 12, 4000 and 1, respectively. The thickness of magnetic layer of probes and HDD was set as 50 nm and 30 nm respectively. Width of bits was set as 120 nm. Calculation of forces acting on the probe was carried out at a distance of 8 and 12 nm from the HDD’s surface. Force gradient was calculated at a distance of 10 nm from the HDD’s surface by division of difference of force at 8 and 12 nm by 4 nm.

The simulation confirmed that NW magnetic probes are more sensitive in comparison with standard probe for individual bits and provides better MFM resolution (Fig. 7).
Fig. 7. Force gradients for standard and NW probes: (a) near the beginning of bits (thick line); (b) for individual bits. Zero level indicates gradient above unmagnetized ferromagnetic material of HDD

4. Conclusions
Magnetic probes based on whisker structures were created and studied. The approbation of these probes was carried out on test samples with calibrated geometric parameters and magnetic disks. The simulation of MFM images was performed for magnetic probes with different geometry. A comparison of the results obtained by standard magnetic probes and specialized magnetic NW probes was carried out. Both theoretically and experimentally data showed that magnetic NW probes significantly improves the sensitivity, contrast and spatial resolution of magnetic force microscopy.

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