Search for the optimally suited cantilever type for high-frequency MFM

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Abstract. To optimize the performance of the high-frequency MFM (HF-MFM) technique [1-4], we performed a search for the best suited cantilever type and magnetic material coating. Using a HF-MFM setup with hard disk writer poles as test samples, we carried out HF-MFM imaging at frequencies up to 2 GHz. For HF-MFM, it is an essential ingredient that the tip material can follow the fast switching of the high-frequency fields. In this contribution, we investigated 6 different types of cantilevers, (i) the "standard" MFM tip (Nanoworld Pointprobe) with 30 nm CoCr coating, (ii) a "SSS" (Nanoworld SuperSharpSilicon™) cantilever with a 10 nm CoCr coating, (iii) a (Ni,Zn)-ferrite coated pointprobe tip, (iv) a Ba₃Co₂Fe₂3O₄₁ (BCFO) coated pointprobe tip, (v) a low-coercivity NiCo alloy coated tip, and (vi) a permalloy-coated tip.

1. Introduction

Magnetic force microscopy (MFM) is a method enabling a high spatial resolution even in ambient conditions. Using low-moment magnetic tips, a resolution down to the 20 nm regime in ambient conditions could be reached [1-3]. However, the high frequency (microwave) response of magnetic materials and fast time-domain phenomena are fundamental properties that are also closely related to applications such as magnetic data storage. Therefore, the ability to evaluate in practice the high-frequency performance of magnetic recording heads is crucial to magnetic disc drive designs for high data-rate application. To achieve this goal, the MFM technique was further developed into the high-frequency MFM (HF-MFM) technique enabling the characterization of the harddisk writer pole field at high frequencies. The "standard" MFM cantilever coatings consist mainly of CoCr [4]. In all former experiments using the HF-MFM technique, cantilevers coated with layers of CoCr were employed like for conventional MFM [5-10]. As the essential reason for the signal detection in HF-MFM is the non-linearity of the magnetic material provided by the hysteresis [11], it is important to employ a magnetic coating which still exhibits sufficient hysteresis and permeability even at high frequencies. Therefore, in order to find an optimally suited magnetic cantilever coating for the HF-MFM experiments, we investigated 6 different types of cantilevers, (i) the "standard" MFM tip (Nanoworld Pointprobe) with 30 nm CoCr-coating, (ii) a "SSS" (Nanoworld SuperSharpSilicon™) cantilever with a 10 nm CoCr coating, (iii) a (Ni,Zn)-ferrite-coated pointprobe tip, (iv) a Ba₃Co₂Fe₂3O₄₁ (BCFO)-coated pointprobe tip, (v) a low-coercivity NiCo alloy coated tip, and (vi) a permalloy-coated tip. The performance of all these types of cantilevers is discussed in detail.
2. Experimental procedure

The HF-MFM setup is built up on the basis of a commercial AFM system (Veeco/DI Nanoscope model IV). For the dual-vibrational technique, the cantilever is oscillated by both the high-frequency field from the writer pole and by the piezoelectric element. The phase shift of the cantilever was measured as it was scanned over the recording head at the air-bearing surface. The tip-to-sample distance was typically around 50 nm. The current to the writer pole is controlled by a current-measurement probe (Tektronix CT-6) [12]. As samples, we employ hard disk writer poles stemming from SEAGATE. As base for the advanced cantilevers, we employed micromachined Si tips of the pointprobe-type (Nanoworld Services GmbH, 2-3 Nm$^{-1}$) with a resonance frequency $\omega_r$ in the range between $2\pi \times 65...80$ kHz [13]. The "standard" coating for MFM cantilevers is a 30 nm thick film of CoCr. The preparation of the ferrite coatings was discussed in detail in Refs. [11,14,15]. The ferrite coatings are about 50 nm thick. Using CoCr coated tips, we could reach carrier frequencies up to 1 GHz, and with the ferrite coated tips, carrier frequencies $\omega_c$ up to 2 GHz are possible.

![Figure 1](image)

**Figure 1.** SEM (a,b,c) and TEM (d) images of a SSS-type cantilever. Images (c,d) present the cantilever with a magnetic coating of 10 nm CoCr.

The cantilever development is twofold; one direction concerns the magnetic material itself, and the other one uses the advanced cantilevers as for conventional MFM. In the latter direction, there is the fabrication of the so-called SuperSharpSilicon™ (SSS) tips, which received a magnetic coating of 10 nm CoCr. This configuration ensures a low magnetic moment of the tip, and the advances in conventional MFM are clearly evident. Figure 1 presents electron microscopy images (SEM and TEM) of these tips. Note the extremely small diameter of the tip, which is also left intact after the coating with a layer of 10 nm CoCr. The performance of these tips was found to be excellent for
conventional MFM. Figure 2 presents a series of HF-MFM images obtained at different carrier frequencies ranging between 100 MHz and 1000 MHz.

![HF-MFM images](image)

**Figure 2.** Frequency dependence of the HF-MFM signal obtained using the supersharp (SSS) MFM-tip. The carrier frequency is varied from 100 MHz to 1000 MHz; the modulation frequency is kept constant at 1 kHz.

The modulation frequency is set at $\omega_m/2\pi = 1$ kHz. At frequencies below 500 MHz, the SSS tip delivers a very detailed view of the emanating stray field as compared to earlier HF-MFM experiments [5-7]. The MFM signal decays at frequencies above 500 MHz, even though several details can still be resolved at 1000 MHz. Above 1000 MHz, the HF-MFM signal vanishes completely, which is not observed using the standard cantilever. This implies that such a SSS-tip with a thin CoCr-coating is the best choice for HF-MFM measurements up to 500 MHz.

![SEM-images](image)

**Figure 3.** SEM-images of ferrite-coated tips of HF-MFM cantilevers. (a) shows a 50 nm-thick (Ni,Zn) ferrite-coated tip, and (b) a 50 nm thick BCFO coating.
Figures 3 and 4 present HF-MFM images using cantilevers with ferrite coatings. The cantilevers employed here are of the pointprobe-type [13]. The MFM signals recorded using these cantilevers are considerably larger as for the CoCr-coated tips, which is clear indication that the high-frequency properties of the ferrites are better suited for the HF-MFM imaging.

Figure 4. HF-MFM images of a write head at a carrier frequency of 1 GHz. Left and right images are produced by (Ni,Zn) ferrite- and CoCr-coated MFM tips, respectively. The corresponding downtrack profiles of stray fields are presented below the images. The size of the images is 4 × 4 µm².

Figures 4. HF-MFM images of writer poles using ferrite-coated cantilevers. Images (a,b) show images obtained using a cantilever with a (Ni,Zn)-ferrite coating, while images (c,d) use BCFO coatings. The modulation frequency is for all images 1 kHz. The inset in (b) presents a schematic of the head structure.
The fabrication process of the ferrite-coated cantilevers is described in [14]. About 40 cantilevers of each ferrite type were produced by RF sputtering, which all give similar imaging properties.

However, the remaining problem for the ferrite-coated cantilevers is the large thickness of the current coatings. A possible improvement may be provided by the use of buffer layers between the Si and the ferrite [16], so that finally a SSS-type cantilever could be coated with a ~20 nm-thick ferrite film. This should be the ideal configuration for the HF-MFM imaging.

Additionally, we have tested permalloy-coated tips and tips with very small coercivity (soft magnetic NiCo coating) for the HF-MFM imaging. The coercivity of the latter ones was measured to be around 1 Oe. As suggested in Ref. [17], even super-paramagnetic tips should perform well for the imaging of head structures. With these cantilevers of the pointprobe-type, we could successfully image the fields emanating from the writer poles. The resulting MFM signal is quite weak, but can still be detected. Especially the NiCo-coated tips show good switching properties at frequencies up to 500 MHz. However, for HF-MFM the conductivity of the cantilever plays also an important role, as in the high-frequency experiment eddy currents will be introduced. The advantage of the ferrite coatings, which are non-conducting, becomes clearly evident at carrier frequencies above 500 MHz.

Conclusions
Using for HF-MFM imaging the dual-vibrational technique with an optimized setting for the modulation frequency and modulation depth as well as advanced MFM cantilevers with ferrite coatings provides the best achievable magnetic contrasts in HF-MFM measurements. This is especially important for the measurement of high-frequency properties of soft magnetic materials. In order to improve also the achievable spatial resolution of the HF-MFM technique, a thin ferrite-coating on the cantilevers would be desirable.

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