Development of specific cantilevers for use with high-frequency MFM

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In order to improve the spatial resolution achieved by the magnetic force microscopy (MFM) technique and its derivatives, we employ here advanced MFM tips fabricated using focused ion beam milling. For high-frequency MFM (HF-MFM), the high frequency properties of the magnetic cantilever coating play an important role. Based on a theoretical analysis of the HF-MFM signals, we find that the frequency dependence of the initial susceptibility of the magnetic cantilever material is crucial for the performance of HF-MFM. Therefore, besides the commonly employed CoCr-coating, we use different types of ferrites in form of thin films as magnetic coating on cantilevers. Our experiments show that we can operate HF-MFM successfully at carrier frequencies up to 2 GHz using ferrite-coated cantilevers. For a high spatial resolution of the MFM, thinner magnetic coatings are required. The selected ferrites differ in the initial susceptibility and the high-frequency properties. The HF properties of thin films are considerably different as compared to the bulk properties.

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]. The "standard" MFM cantilever coatings consist mainly of CoCr [4]. 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. HF-MFM is a further development of the magnetic force microscopy (MFM) technique, enabling the measurement of (i) high-frequency currents via their magnetic stray field and (ii) the stray fields emanating from hard disk writer poles. To enable the measurement of the high-frequency magnetic fields, an amplitude-modulation technique is employed, and the cantilever is also driven by its piezo element, so a dual-vibrational technique results [5,6]. By means of HF-MFM, the emanating stray fields from hard disk writer poles were measured at carrier frequencies up to 2 GHz [7]; and HF currents within integrated circuits were measured up to 4.6 GHz [8]. In order to optimize the performance of the HF-MFM technique and to obtain a spatial resolution like in the conventional MFM technique, several parameters must be chosen carefully. An important parameter with a huge influence on the imaging capability of the HF-MFM technique is the choice of the modulation frequency, \( \omega_m \). In the current imaging experiments, \( \omega_m \) was chosen to be the resonance frequency of the cantilever employed. For the HF-MFM imaging of the stray fields of hard disk recording heads, often \( \omega_m \) is chosen to be much smaller than \( \omega_{res} \). In a recent paper [9], we investigated these parameters experimentally and obtained that the optimum \( \omega_m \) is about \( 1/2 \omega_{res} \); this cannot be understood using the simple descriptions in the literature [10]. The recent HF-MFM experiments [7,10-13] have clearly demonstrated that it is advantageous to employ ferrite thin films as magnetic coatings for the HF experiments in the GHz range. Therefore, the theoretical description should give detailed information about the ideal magnetic coating for the HF-MFM experiments. To achieve this goal, we have to separate to cases, (i) HF-MFM of high-frequency currents and (ii) HF-MFM of recording heads.

In all former experiments using the HF-MFM technique, cantilevers coated with layers of CoCr were employed like for conventional MFM [14-17]. As the essential reason for the signal detection in HF-MFM is the non-linearity of the magnetic material provided by the hysteresis [18], 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 \( \text{Ba}_2\text{Co}_{17}\text{Fe}_{22}\text{O}_{41} \) (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. Theoretical treatment

Figure 1 presents a schematic view of our HF-MFM setup. The optical sensor, the hase measurement, the lock-in amplifier and the piezoelement are from a commercial AFM/MFM setup; in our case a VEECO/DI Nanoscope model IV. Additionally, a HF generator coupled with an independent modulation source provides the amplitude-modulated HF-current for the HF-MFM experiments. The HF current to the writer pole is controlled by a current-measurement probe (Tektronix CT-6). In order to be able to measure high-frequency currents or high-frequency stray fields from hard disk writer poles with the HF-MFM technique, it is necessary to employ amplitude modulation. To apply a modulation scheme, a non-linear dependence between force and current is required; in the optimum case this dependence should be quadratic. A calculation of the forces acting on the cantilever in both cases (i) and (ii) was performed in Ref. [19]; for simplicity, we regard here only the main result obtained from the calculation of HF-MFM of high-frequency currents. The calculation is based on the point-dipole model for the cantilever [20].

\[
F_z = -\mu_0 |\mathbf{m}| \frac{\partial H_z}{\partial z} = -\mu_0 |\mathbf{m}| \frac{x \cdot z \cdot I}{\pi (x^2 + z^2)^2}.
\]

(1)

In order to simplify this equation, we take all parts depending on position but being independent of the current together as \(c_1(x,y,z)\) and \(c_2(x,y,z)\). With that, equation (1) can be rewritten as

\[
F_z = c_1 \cdot I + c_2 \cdot I^2
\]

(2)

with

\[
c_1 = -\mu_0 |\mathbf{m}| \frac{x \cdot z}{\pi (x^2 + z^2)^2}
\]

(3)

and

\[
c_2 = -\mu_0 \cdot \chi_m(\omega) \cdot \frac{x^2 \cdot z}{2\pi^2 (x^2 + z^2)^3}
\]

(4)

This quadratic dependence of the force acting on the cantilever on the flowing current enables the use of a modulation/mixing technique, so that also high-frequency currents can be measured. The ideal choice is the amplitude modulation technique, which is also applied in electrostatic force microscopy (EFM) [21].

An amplitude-modulated current is sent through the sample. This current is characterized by its carrier frequency, \(\omega_c\). The modulation current has a low-frequency, \(\omega_m\). The relation of both currents is called the modulation depth, \(m = \omega_m / \omega_c\). The amplitude-modulated current is now written as follows:

\[
I = I_0 \cdot [1 + m \cdot \cos(\omega_m t + \phi_m)] \cdot \cos(\omega_c t + \phi_c)
\]

(5)
Inserting this current into Eq. (2), we obtain for the force on the cantilever an expression having in total 13 components:

\[
F_x = \frac{1}{2} c_2 \cdot m^2 \cdot I_0^2 \left[ \frac{1}{2} c_1 \cdot I_0 \cdot \cos(\omega t + \phi) + \frac{1}{2} c_1 \cdot m \cdot I_0 \cdot \cos(\omega t + \phi) - \omega m t + \phi_m \right] + \frac{1}{2} c_2 \cdot I_0 \cdot \cos(2\omega t + 2\phi_m) + \frac{1}{2} c_2 \cdot m \cdot I_0 \cdot \cos(2\omega t + 2\phi_m - \omega m t - \phi_m) \]

The cantilever acts like a low-pass filter, so that all components comprising a high-frequency part (i.e., such components with frequencies much higher than the resonance frequency of the cantilever) can be disregarded. For the highest possible sensitivity (i.e., the maximum force) of the high-frequency technique, the resonance frequency of the cantilever employed is chosen as the modulation frequency. In these conditions, we obtain for the force on the cantilever

\[
F_{\text{res},x} = c_2 \cdot I_0^2 \cdot m \cdot \cos(\omega_m t + \phi_m). \tag{6}
\]

Equation (7) allows us to draw some important conclusions concerning the operation of HF-MFM. As \(c_2\) is much smaller than \(c_1\), therefore the corresponding force is much smaller than the force which could be measured from a current with the resonance frequency of the cantilever. Furthermore, \(c_2\) also depends on the frequency itself, as it contains the magnetic properties of the magnetic cantilever coating. \(c_2\) includes further the susceptibility of the cantilever material as a function of the frequency. This implies that the ideal HF-MFM cantilever material should have a large \(\chi(\omega)\), respective \(\mu(\omega)\), which should also be reasonably high in the high-frequency range. This condition could e.g., be fulfilled by the head material itself. However, to avoid skin effects which could disturb the cantilever oscillation, an ideal candidate for such a material are non-conducting ferrites, which can be prepared in form of thin films onto the cantilevers. Figure 2 illustrates possible behaviours of \(\mu'(\omega)\) in the high-frequency regime.

\[
F_{\text{res},x} = c_2 \cdot I_0^2 \cdot m \cdot \cos(\omega_m t + \phi_m). \tag{7}
\]

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**Fig. 2** Schematical drawing of possible high-frequency behaviour \([\mu'(\omega)]\). (a) illustrates the behaviour corresponding to the observations of Fig. 4 (thickness dependence), and (b) shows possible \(\mu'(\omega)\) behaviour for ferrite films, where the \(\mu'(\omega)\) dependence can be influenced by chemical doping.

The behaviour shown in Fig. 2 (a) illustrates the observations of Fig. 4, where different thicknesses of the same material (here: CoCr) lead to the observed situation. Figure 2 (b) presents \(\mu'(\omega)\) for ferrite films where by means of chemical doping the high-frequency behaviour can dramatically be varied; see, e.g. the measurements of Ref. [22]. These basic conclusions also hold for the case of the measurements of stray fields emanating from recording writer poles; the more complicated situation caused by the magnetic properties of the core material are responsible for a reduction of the optimum frequency, which is now slightly larger than \(\frac{1}{2}\) of \(\omega_{\text{res}}[23]\).
3. Experimental results

3.1 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) [11]. 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 [24]. 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. [25-27]; the materials employed are NiZnFe\(_2\)O\(_4\) spinel ferrite and Co\(_2\)Z-type hexaferrite (Ba\(_3\)Co\(_2\)Fe\(_{24}\)O\(_{41}\), BCFO). 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.

3.2 Results

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.

Fig. 3 SEM and TEM views of the “supersharp” SSS tips. (a) and (b) show the tips without a magnetic coating. The scale bar is 100 nm long. Here, the extremely small apex radius of 10 nm is clearly visible, and also the much stronger shank of the tip providing an improved stability. Image (c) presents an SEM image of the SSS tip with a 10 nm thick CoCr coating, and (d) is a TEM image of the tip apex with the magnetic coating, showing the small tip radius achieved here after the magnetic coating.
Fig. 4 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 [14-17]. 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.

Fig. 5 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.
Fig. 6 HF-MFM images of a longitudinal 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 $4 \times 4 \mu m^2$.

Figures 6 and 7 present HF-MFM images of longitudinal recording heads stemming from SEAGATE, obtained using cantilevers with ferrite coatings. The cantilevers employed here are of the pointprobe-type [24]. 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.

Fig. 7 HF-MFM images of longitudinal 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 longitudinal writer head structure.
3.3 Discussion

The fabrication process of the ferrite-coated cantilevers is described in Refs. [25-27]. 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 [28], 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. Recent work focuses, therefore, on the preparation of thin ferrite coatings directly on Si [29].

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. [30], 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. This implies that for low frequencies, such types of cantilever coatings can be applied. However, for HF-MFM in the high-frequency range above 500 MHz, 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.

Figure 8 presents finally a high-resolution HF-MFM measurement on a perpendicular recording writer pole (SEAGATE type VENUS) employing an advanced cantilever (Nanoworld Services, SSS type) with ferrite coating (30 nm thickness). The HF-MFM conditions for this image are as follows: carrier frequency 1 GHz, modulation frequency 1 kHz, modulation depth 50%. A ferrite-coated SSS-tip is employed for imaging. The HF current is 30 mA. The insets show 3D- and 2D-plots of the emanating stray field from the writer pole.

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 as magnetically active material 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 which will be the future direction of development.
improve also the achievable spatial resolution of the HF-MFM technique, an improved preparation technology for very thin ferrite coatings (approx. 10 nm thickness) on the cantilevers of the SSS-type would be desirable for future experiments.

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References


