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To cite this article: M R Koblischka et al 2007 J. Phys.: Conf. Ser. 61 119

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Abstract. To optimize the performance of the high-frequency magnetic force microscopy (HF-MFM) technique, we investigate the effect of varying the frequency of the amplitude modulation on the magnetic contrast achieved. As samples, we employ hard disk writer poles. We find that the optimum condition for the HF-MFM operation is the use of a modulation frequency being about half of the cantilever resonant frequency. Together with optimized cantilevers, a clear improvement of the magnetic imaging is obtained. Furthermore, we can deduce that the optimum parameters for imaging must be determined for each experimental system (hard disk writer pole and cantilever) individually.

1. Introduction
The high-frequency magnetic force microscopy (HF-MFM) technique is employed to visualize the high-frequency stray fields emanating of hard disk writer poles. HF-MFM is an extension of the standard MFM technique, using a commercial AFM system as a basis. In the literature, there were two basically different methods described: the amplitude-modulation technique [1] and the direct phase detection method [2]. In the amplitude-modulation technique, the piezoelectric element driving the cantilever is switched off, and the driving force stems solely from the high-frequency magnetic field. Some authors also employed the amplitude-modulation technique with operating piezoelectric element, but using only a small modulation frequency \( \omega_m \) [3,4]. The direct phase detection method requires that always two images (with HF-current and without) have to be recorded, which subsequently have to be subtracted from each other. Recently, a so-called dual-vibrational technique [5,6] was introduced, which combines features of both former techniques. The key to the dual-vibrational technique is that the cantilever is driven not only by the piezoelectric element, but additionally by the amplitude-modulated, high-frequency stray field of the hard disk writer pole. This double driving of the cantilever requires now several parameter adjustments. As a consequence, for optimum magnetic contrast in the HF-MFM images the modulation frequency employed should then be related to the oscillation frequency of the cantilever. Furthermore, the depth of the amplitude modulation (modulation voltage, \( U_m \)) also may influence the resulting magnetic contrast. Therefore, in order to optimize the achievable magnetic contrast we investigate in this contribution the effects of varying the modulation frequency \( \omega_m \) and voltage on the magnetic contrast achieved.

2. Experimental procedure
Figure 1 presents a schematic drawing of the HF-MFM setup, which 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 50 nm. The current to the writer pole is controlled by a current-measurement probe (Tektronix CT-6).

Figure 1. (a) Schematic drawing of the HF-MFM setup. (b) schematic of an amplitude-modulated wave with the two amplitudes, $a_c$ and $a_m$.

As cantilever, we employed micromachined Si tips (Nanoworld Services GmbH, 2-3 Nm$^{-1}$) with a resonant frequency $\omega_r/2\pi$ in the range between 65...80 kHz [7]. As magnetic coating, we use 30 nm thick CoCr coatings, but also ferrite coatings like (Ni,Zn)Fe$_2$O$_4$ and Ba$_3$Co$_2$Fe$_{24}$O$_{41}$ (BCFO), which are about 50 nm thick. The performance of the ferrite coatings was discussed in detail in Refs. [4,8,9]. Using CoCr-coated tips, we could reach carrier frequencies up to 1 GHz, and with the ferrite-coated tips, $\omega_c$ up to 2 GHz is possible. As samples, we employ hard disk writer poles from SEAGATE. Figure 1 (b) presents a schematic of the amplitude-modulated wave, illustrating the definition of the modulation depth. The modulation depth is measured in a percentage of the carrier wave amplitude $a_c$, that is, 100% modulation depth indicates that both amplitudes are equal in size.

3. Results and discussion

In the operation of the HF-MFM technique, a high-frequency current is fed into the hard disk writer pole, and is then there transferred into a high-frequency magnetic field. This implies that the HF field, $H_{gap}$, contains all the magnetic information of the writer pole via $H_{gap} = N I/[\ell_{gap} (\mu_0 / \mu)]$ [10]. Here, $\ell_{gap}$ denotes the gap length, and $\ell_c$ the core length. Therefore, the specific type of each hard disk head plays an important role in the HF-MFM imaging process.

Firstly, we will describe the HF-MFM measurement on a hard disk writer pole in the "standard" configuration. Figure 2 presents the HF-MFM image of the stray fields emanating from the writer pole at a carrier frequency, $\omega_c / 2\pi = 500$ MHz and a modulation frequency $\omega_m / 2\pi = 1$ kHz, i.e., $\omega_m \perp \omega_c$. The cantilever employed here is a CoCr-coated tip. The inset in the image gives a schematic arrangement of the hard disk head as comparison. The width of the writer pole is 300 nm. Additionally, the cross track and downtrack profiles are given. The downtrack profile exhibits two peaks which are of comparable height. The write gap is, however, located in the middle of the first peak, where also the cross track profile is taken. For a comparison of different hard disk writer poles, this configuration of the HF-MFM technique is clearly sufficient as the signals from the writer poles are strong enough. However, if a weak magnetic signal is to be investigated, it is important to optimize all parameters available to achieve a strong magnetic contrast. Figure 3 presents the effect of
changing the modulation depth. For this experiment we have again chosen a carrier frequency of \( \omega_c = 2\pi \times 500 \) MHz and \( \omega_m = 2\pi \times 1 \) kHz. The sample is a writer pole from the same batch as the one shown in Fig. 2; the cantilever employed here is a BCFO-coated tip. The distribution of the HF field is similar to that of Fig. 2. The modulation depth is varied between 10% and 100%. If a higher modulation depth is selected, the resulting HF-MFM signal gets stronger, but it is also clearly visible that the resolved details are getting blurred. The best configuration for the experimental situation here is the one presented in Fig. 3 (c), even though the effect is relatively small. If also the modulation frequency is increased further (see Fig. 4), higher modulation depths than 50% are not possible anymore for HF-MFM imaging.

**Figure 2.** HF-MFM image of a SEAGATE hard disk writer pole at \( \omega_c = 2\pi \times 500 \) MHz. The inset gives the schematic arrangement of the writer pole. Downtrack and cross track profiles are given as well.

An improvement of the HF-MFM technique may be given by an optimum setting concerning the modulation frequency, \( \omega_m \). The signal mixing process to drive the cantilever implies that the resulting HF-MFM signal gets stronger if the modulation frequency corresponds to a fraction of the cantilever resonance frequency [5,6]. Therefore, we may expect to obtain a maximum HF-MFM signal at some modulation frequency which is a half or a third of the cantilever resonant frequency, \( \omega_r \). Figure 4 presents the effect of varying the modulation frequency itself, while keeping the modulation depth constant at 25%. The HF-MFM signal remains unchanged in the area between \( \omega_m = 2\pi \times 1 \) kHz up to \( 2\pi \times 20 \) kHz (Fig. 4 a), but then the signal starts to increase at 22 kHz, which corresponds to about 1/3 of the cantilever resonance frequency. The strongest signal is obtained at a modulation frequency of 30.4 kHz, which approximately corresponds to about 1/2 of the cantilever resonant frequency. If a different, smaller modulation depth is chosen, the effect of changing the modulation frequency is similar to the one shown in Fig. 4. If the modulation depth is higher than 50%, the increase of the modulation frequency leads to unwanted interference effects, which do not allow to perform HF-MFM imaging anymore. The present experiments clearly reveal that an optimum setting of the modulation frequency and modulation depth brings another improvement of the achievable HF-MFM signal. However, the present experiments also show that these two parameters have to be optimized individually for each experimental configuration, i.e., cantilever and hard disk writer pole.
Figure 3. Comparison of different modulation depths at constant carrier and modulation frequency. HF-MFM images (5 x 5 µm$^2$) obtained at $\omega_c = 2\pi \times 500$ MHz, $\omega_m = 2\pi \times 1$ kHz and the modulation depth varies from 10% (a), 25% (b), 50% (c) to 100% (d).

With these improvements of the HF-MFM technique, the use of optimized cantilever coatings and cantilever shapes may bring further advances to the HF-MFM technique. The HF-MFM images of Figs. 3 and 4 are recorded employing ferrite-coated cantilevers (BCFO), which exhibit much better high-frequency properties compared to the CoCr-coatings used in former experiments [1-3,5,6]. The HF-MFM signals are found to be about 10 times as large as compared to CoCr-coated tips at medium frequencies, and about a factor of 2-3 larger in the high-frequency range. HF-MFM images were successfully recorded using BCFO tips up to 2 GHz. The ferrite coatings were found not only to improve the HF-MFM signals in the high-frequency range, but also at low frequencies as discussed in Refs. [8,9]. The MFM tip senses the time-averaged effective force, which can be expressed as [5]:

$$F_{eff} = \mu_0 \left( \frac{d}{dz} <m_{tip}(t)H_{gap}(t)> \right)$$
$$= 2 \mu_0 (\mu - 1) V H_0 dH_0/dz <f_1(t)f_2(t)>,$$

where $\mu_0$ is the permeability of free space, $\mu$ is the permeability of the tip material at the corresponding frequency, $H_0$ is the amplitude of the high-frequency magnetic field of the write head, and $V$ is the volume of the interacting part of the magnetic tip with the write head field. The magnetic moment of the MFM tip is $m_{tip}(t) = \mu_0 (\mu - 1) H_0 V f_1(t).$ The magnetic field of the write head is $H_{gap}(t) = H_{og}(t).$ This implies that we may expect the best performance of the HF-MFM technique if we can guarantee that $f_1(t) = f_2(t)$ in a wide frequency range. Therefore, also the magnetic material on the MFM tip plays an important role for the optimization of the HF-MFM technique as discussed in Refs. [8,9]. The ferrite coatings evidently fulfill the aforementioned condition up to 2 GHz, which is close to the cut-off frequency of the BCFO material. The remaining problem is the thickness of the coating; the
current thickness of about 50 nm is too thick to obtain also an improvement of the spatial resolution as shown in Refs. [11,12] using advanced MFM cantilevers with a high aspect ratio. A reduction of the thickness of the magnetic coating on the cantilevers had proven to be unsuccessful for the HF-MFM experiments [13]. In this case, HF-MFM images were only possible up to 400 MHz.

Figure 4. HF-MFM images (5 × 5 µm²) obtained by varying the modulation frequency at constant carrier frequency of 2π × 500 MHz. (a) 1 kHz, (b) 30.4 kHz, which corresponds to about 1/2 of the cantilever resonance frequency, \( \omega_r \). The modulation depth is kept constant at 25%.

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 contrast 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, a thin ferrite coating on the cantilevers would be desirable.

Acknowledgements Hard disk writer poles were kindly provided by Alan B. Johnston (SEAGATE Technologies, U.K). This work is financially supported by the EU-project “ASPRINT” (contract no. NMP4-CT-2003-1601), which is gratefully acknowledged.

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