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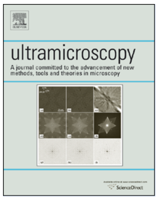

Effect of horizontal magnetization reversal of the tips on magnetic force microscopy images

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ABSTRACT

The effect of magnetization reversal of magnetic force microscope (MFM) tips based on low coercive thin-films on MFM images has been studied both experimentally and theoretically. By analyzing the MFM images obtained on structures with high magnetic stray fields we show that during the imaging process the magnetic state of the probe is modified anisotropically: the horizontal component of the magnetization follows the external field, whereas the vertical component of the magnetization stays almost constant. The observed complex magnetic behavior of the tip is explained theoretically based on the shape anisotropy of the tip. The obtained results are important for interpretation of MFM images of structures with high magnetic moment. Moreover, these results can be used for characterization of both laboratory-made and commercially available MFM tips.

1. Introduction

Magnetic force microscopy (MFM) has become in the last two decades a versatile tool for high resolution magnetic imaging [1–4]. MFM images with a resolution down to 30 nm are routinely obtained at ambient conditions with commercially available thin-film magnetic probing tips, whereas a resolution below 10 nm with advanced tips has been reported [5]. Phase- and amplitude-detecting techniques are mostly used in practice for MFM imaging because of their high sensitivity and stability [2–9]. These techniques make use of either the phase or amplitude of the oscillations of the MFM tip as a signal to characterize the magnetic field of the sample. Since these values also depend on the magnetic state of the tip, the simplest approach of MFM is to avoid any changes of the magnetic state of the tip during scanning by employing tips with magnetically hard coatings. However, even such coatings do not guarantee the stability of the magnetization of the tip, if samples with high fields are studied. In this case a reconstruction of the distribution of the magnetization inside the studied sample based on MFM images is not possible without knowledge of the magnetic properties of the tip [10]. It is extremely difficult to characterize independently the magnetic structure of the tip during the scanning process. Therefore, attempts to quantify the properties of the MFM tips are based on imaging a well defined current-carrying micro-source of the magnetic field (micro-rings or parallel micro-wires) [11–16] or standard samples with known magnetic structures such as pieces of a hard disk [7,16–21] and are widely used for characterization of the magnetic structure of MFM tips. Using this approach hysteresis loops of the active magnetic volume for different tips were obtained experimentally [12,14–16]. The material of the magnetic coating, its thickness, and the initial domain structure inside the tips are the most important parameters determining the magnetic properties of the tips during imaging [5,14,16,17,22,23].

Standard analysis of MFM images is based on the simplified model of the magnetically hard tip considered as an effective magnetic dipole. Our results presented in this paper show that in some cases the simple dipole model of the probe has to be significantly improved. By comparing the results of numerical calculations with MFM images obtained on a piece of a hard disk with a known magnetic structure we demonstrate that the two components of the magnetization of the tip have different magnetic behavior: the horizontal component of the magnetization follows the external field, whereas the vertical component of the magnetization stays almost constant. The obtained results explain

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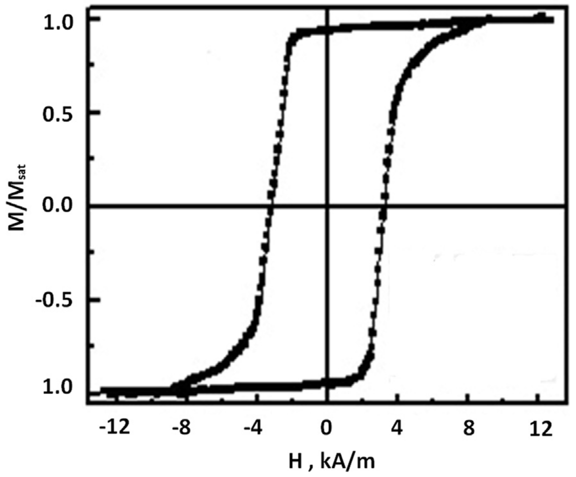

Fig. 1. Hysteresis loop of $Co_{90}Ni_{10}$ alloy recorded using the Magneto-Optical Kerr-Effect technique on the lever of magnetic probe.

several features of the MFM images, often observed with both laboratory-made and commercially available thin-film MFM tips with relatively low coercivity. Our results can therefore be useful for preliminary characterization of the prepared tips and proper interpretation of data obtained on samples with high magnetic stray field.

2. Materials and methods

The MFM measurements were carried out with SPM NTEGRA Aura (NT-MDT Co, Russia). Silicon cantilevers NSG11 (NT-MDT Co, Russia) with a conical tip covered by 50 nm thick $Co_{90}Ni_{10}$ film were used for imaging. The films were deposited using the RF-sputtering system Sputron-2 (Balzers) at Ar-plasma pressure 10^{-3} mbar and RF-power of 700 W, resulting in a deposition rate of 0.07 nm/s. The direction of deposition was parallel to the tip axis. Magneto-optic Kerr effect (MOKE) analysis of the magnetic properties of the CoNi film (see Fig. 1) on the lever has shown that the film is in-plane magnetized, having a coercivity of 4 kA/m. A samarium–cobalt magnet used for tip magnetization produces a magnetic field of 40 kA/m. A two-pass scanning technique was employed with a peak-to-peak amplitude of free cantilever vibrations of around 20 nm during the first pass and 10 nm during the second pass. The set-point amplitude during the first pass was 10 nm. The total tip-sample distance Δz during the second pass is equal to sum of the pre-set lift height and set-point amplitude of the first pass.

The magnetic properties of the probing tip were studied on a test sample, which was a piece of a hard disk with the in-plane magnetization (Fireball SE, 3.2 GB, Quantum, Singapore) having a maximum data density of 50 kfci. Details of the magnetic structure of such disks can be found elsewhere [2,3,7,16]. In the following discussion, the x-axis defines the direction along the track of the hard disk, and the z-axis is perpendicular to the sample surface as shown in Fig. 2. The phase-detecting MFM used in the present work is based on measurements of the phase shift of cantilever oscillations in the vicinity of the sample surface. With our setup, regions of the phase image with phase values below 90° correspond to attractive forces between the tip and the sample, while regions with phase values above 90° correspond to repulsive forces. In real measurements the phase of the freely oscillating cantilever may be slightly different than 90°. We assume that the tip axis coincides with the z-axis (i.e. oscillations of the cantilever are vertical).

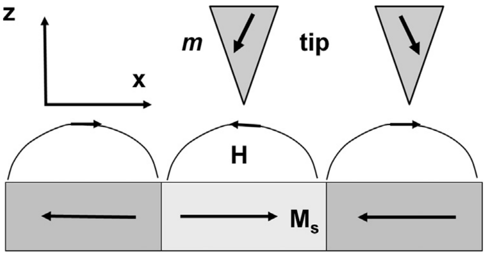

Fig. 2. Sketch of the stray fields of the sample and magnetization reversal of the probing tip magnetized under some angle with respect to the z axis.

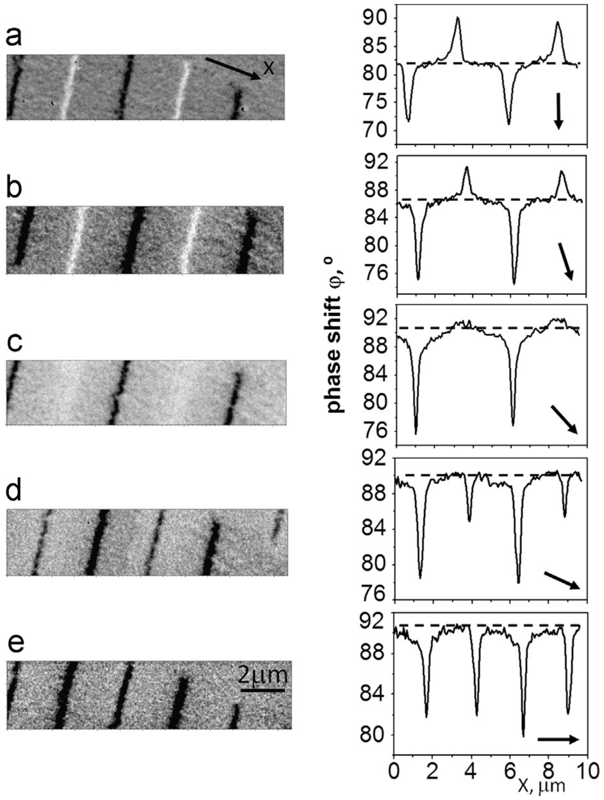

Fig. 3. Evolution of the MFM images recorded using tips pre-magnetized by an external field applied at different angles with respect to the tip axis as indicated by arrows: (a) 0°, (b) 20°, (c) 45°, (d) 70° and (e) 90°. Left panels: MFM images themselves. Right panels: corresponding average cross-sections taken along track. The dashed lines indicate the level of a zero force gradient ($\Delta\varphi = 0°$), $\Delta z = 20$ nm.

3. Results and discussion

The magnetic tip was initially magnetized by the external magnet along the z-axis and the results of phase shift measurements with such a tip are shown in Fig. 3(a). The cross-sections in Fig. 3 are average MFM profiles along the track direction (i.e. the x-axis) and the observed contrast in the phase-shift, $\Delta\varphi$ is related to changes in the second derivative of the sample field, which for a tip magnetized along z is

$$\Delta\varphi = -(Q/k)\mu_0 m_z \partial^2 H_z/\partial z^2 \quad (1)$$

where Q and k are the cantilever quality factor and the force constant, respectively, μ_0 is the magnetic constant and m is the tip magnetic moment [2,7,9]. The negative sign in (1) implies a phase change from 180° to 0° when the frequency crosses the resonance. The obtained MFM phase contrast then looks inverted in comparison to that of a real oscillator. Images similar to that shown in Fig. 3(a) can be found in a variety of papers related to characterization of both magnetic media and tip. Only bit transition regions