Magnetic force microscopy using electron-beam fabricated tips

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We used a new concept of tip preparation for magnetic force microscopy (MFM) proposed recently based on coating electron beam deposited carbon needles with appropriate magnetic thin film materials. In combining the advantages of electron beam fabricated needles with those of already widely used thin film tips, high resolution MFM tips can be prepared routinely and reproducibly on all type of cantilevers. Due to the fabrication procedure, which is described in detail, the effective magnetic tip volume is formed by a homogeneous, magnetically isolated, high aspect ratio thin film element favoring a single domain tip behavior. To reinforce the inherent shape anisotropy an additional uniaxial anisotropy is induced along the tip axis by applying an external field during the deposition of the ferromagnetic alloy. Because of the parallel side walls and the rounded tip end, most of the stray field will emanate from the apex region, resulting in a high field density and only little influence on the magnetization within the sample of interest. By using a material with high saturation magnetization, the thickness of the magnetic layer can be drastically reduced, leading to an increased resolution. To demonstrate the potential of the new concept various MFM observations on different types of materials for magnetic storage technology have been performed without changing the presented basic preparation parameters.

I. INTRODUCTION

Among the rapidly growing family of scanning probe microscopes (SPM) evolving out of the invention of the scanning tunneling microscopy (STM)¹ and the atomic force microscope (AFM),² magnetic force microscopy (MFM), first demonstrated by Martin *et al.*,³ was one of the first techniques used for the characterization of technologically relevant materials, e.g., magnetic recording media. The potential of MFM to investigate written bit patterns in a submicron scale has been demonstrated on a number of materials under ambient conditions and with minimal or no sample preparation (for recent reviews see Refs. 4–7). In magnetic force microscopy the probe is formed by a small ferromagnetic tip mounted on a cantilever. While scanning above the sample's surface the forces (or force gradients) acting on the tip due to the stray field emanating from the sample are detected. As the resulting map of the stray field distribution is only indirectly related to the magnetization within the sample, it is necessary to simulate the MFM response assuming reasonable micromagnetic models for the magnetization distributions within the sample. This is not straightforward, however, because other effects like surface topography, always visible in scanning force microscopy,⁴ the unknown magnetic state of the tip,⁸ and the influence of the magnetic tip on the magnetization within the sample⁹ may influence the observed picture in an unpredictable manner. In special cases, where the magnetization distribution of the sample can be described by simple models and the influence of surface topography can be neglected due to either very smooth surfaces or special topography subtraction techniques,¹⁰ reasonable agreement between calculated and measured MFM response signals has been achieved assuming magnetically "hard" samples, mostly true for written bit structures in thin film recording media.

II. EXPERIMENT

A. Magnetic force microscope

The principal setup of our MFM is described in detail elsewhere.¹¹ We are usually working in the "dynamic," i.e., constant force gradient mode, where the cantilever with the magnetic tip is oscillating in the z direction with a fixed amplitude of 25–30 nm on its resonance frequency while scanning in the x – y direction a certain distance over the sample. The position of the cantilever is detected by a Michelson type of interferometer. Due to the interactions of the magnetic tip with the stray fields of the sample the effective spring constant of the cantilever is changed leading to a shift in its resonance frequency.^{3,12} Using FM detection¹³ the shift is fed back to the z position of the sample to keep the interaction constant and recorded to form an image. The resulting images thus display a surface of constant force gradient above the sample.

B. Tip preparation

As in other scanning probe techniques, one of the most crucial parts in a magnetic force microscopy is the force sensor, i.e., the usually unknown magnetic behavior of the ferromagnetic tip. Whereas in the beginning for MFM mostly etched ferromagnetic³ or magnetically coated tungsten wires⁵ have been used, nowadays batch fabricated, micromachined cantilevers coated with magnetic thin films are commercially available.¹⁴ Recently, a combination between thin film and electron beam fabricated tips has been proposed to achieve very high resolution in MFM.¹⁵ Electron beam induced deposition (EBID) of carbonous or metallic materials out of a vapor of organic or metal–organic components in commercial scanning electron microscopes is well known in microelectronics.^{16–19} The advantages of high aspect ratio needles grown by EBID on top of STM²⁰ and AFM²¹ tips

have been demonstrated when imaging structured surfaces in order to minimize convolution effects between tip and sample.

Our FM-detection scheme is optimized within a frequency range of 4–5 kHz using etched tungsten wire cantilevers. The wire has a thickness of 10 μm and a length of about 1 mm. The end is bent and etched with a solution of KOH to form a sharp tip. The etching process is the most critical part of the preparation and a lot of work has been done in the past to make well defined MFM tips in a reproducible way.²² In this paper a variation of the method proposed in Ref. 15 is used for tip preparation by growing well defined sharp needles with the EBID technique on top of the end of the etched tungsten wires. By covering one side wall of the needles with a magnetic layer, an effective magnetic shape can be achieved which offers many advantages compared to tips used so far. It has been confirmed experimentally than the deposition is possible on all types of cantilevers (see also Refs. 20 and 23) without changing the basic features presented here, although only MFM measurements obtained with needles deposited on etched tungsten wires will be presented in the following due to the mentioned experimental restrictions.

An ISI M7 scanning electron microscope (SEM) was used in spot mode to grow carbon “contamination” needles on top of the etched tungsten tips. In most cases the background pressure of organic components in the microscope vacuum chamber was sufficient to achieve adequate growing rates. For higher deposition rates additional material was supplied by a droplet of oil close to the sample. Usually the smallest spot size, 15 kV acceleration voltage, and a magnification of 40 000 $\times$ was chosen during growing. Figure 1(a) shows a series of needles deposited on a tungsten wire with a beam emission current of 110 μA at different dwelling times for the electron beam. After a nucleation period the growing is observed to be first linear and ends up into saturation for longer needles [Fig. 1(b)]. This is similar to observations reported in Refs. 18 and 20. Decreasing the emission current leads to a decrease in growing rate. The average shaft diameter of the needles was about 150 nm and the length was up to 1.5–2 μm , leading to aspect ratios of 10–13. High resolution images of the tip end show typical apex radii of about 30 nm (Fig. 2).

By using a special cantilever support it was possible to choose the growth orientation of the needle in the SEM to be exactly parallel to the z axis when transferred to the magnetic force microscope (Fig. 3). In this way uncertainties in the tip orientation usually hardly to overcome in bent wire cantilevers can be excluded *in situ*. The whole cantilever is covered afterwards from one side with a $\text{Co}_{80}\text{Ni}_{20}$ thin film in a standard evaporation apparatus. The nominal layer thickness is chosen to be 20 nm on a thickness monitor close to the sample. If the needle is grown slightly off center with respect to the tungsten tip, the latter can be used within a self-aligning process in order to form an isolated magnetic layer on the needle due to the shadowing effect (Fig. 3). An external field H_{ext} of about 0.4 T was applied along the tip axis during the evaporation of the ferromagnetic alloy to induce an additional anisotropy within the thin film element,

FIG. 1. Series of needles grown at 15 kV acceleration voltage, 110 μA beam emission current with different dwelling times [(a), bar length: 500 nm]. The growth seems to be linear at the beginning, reaching a saturation for longer exposure times (b). Decreasing the beam current leads to a decrease in the growing rate.

reinforcing the inherent shape anisotropy of the elongated, high aspect ratio needle.

III. RESULTS

With the now routinely prepared electron beam fabricated tips, MFM measurements were performed on a number of different materials used in magneto-optic and magnetic recording technology.

A. Multilayer for magneto-optic recording

Domain observations on written bit structures in magneto-optical (MO) recording media were one of the first applications of MFM.²⁴ Figure 4 shows an example of a single bit written in a $(\text{Co/Pt})_n$ multilayer MO disk ($d_{\text{Co}}=0.3$ nm, $d_{\text{Pt}}=1.0$ nm, $n=18$). Remarkably small details within the domain boundary and very sharp transitions are observed. Individual linescans reveal details smaller than 20 nm. The double contrast at the domain boundaries correlates with theoretical predictions assuming a single pole magnetic tip magnetized perpendicular to the sample.²⁵

FIG. 2. High resolution image of the end of a carbon needle grown by electron beam induced deposition (EBID) technique (bar length: 200 nm). The estimated apex radius is about 30 nm.

B. Perpendicular recording media

Another example are domains in media for perpendicular recording. In Fig. 5(a) the edge of a written bit track in a CoCrTa disk with perpendicular anisotropy is shown. After pre-erasing, several tracks are written with different densities using an experimental single pole head. Tracks with 300 kfi (kilo flux reveals per inch), corresponding to a width of individual bits of about 80 nm, are visible in MFM. The pic-

FIG. 3. Preparation of EBID needles for magnetic force microscopy on a bent tungsten wire cantilever. If the carbon needle is grown slightly off center with respect to the tungsten tip, the shadowing effect of the tungsten tip during the sidelong evaporation can be used to form a magnetically isolated thin film element on the needle (bar length: 500 nm).

FIG. 4. Magneto-optically written bit structure in a Co/Pt multilayer disk. No splitting of the bit into a multidomain state is found and remarkably small details within the curved domain boundary are resolved (image size: $0.7 \times 0.7 \mu\text{m}$).

FIG. 5. The edge of a track written with 300 kfi in a CoCrTa disk for perpendicular recording [(a), image size: $1.6 \times 1.6 \mu\text{m}$]. An averaged scan along the track [lower half in (a)] clearly shows a sinusoidal variation (b).

FIG. 6. Tracks written with different densities in a commercial CoPt thin film disk (image size: $20 \times 20 \mu\text{m}$). For larger bit sizes no contribution of the in-plane components of the stray field is visible within the domains (note the strong influence of surface topography in this sample).

ture, however, reveals that the individual bits are already decayed in smaller structures which are comparable in size to the remnant domain structure visible outside of the track. As the MFM images reveal information on the stray field above the sample, it is possible to estimate roughly the signal accumulated in a recording head flying above the sample's surface by an averaged scan of the MFM data along the track. This is shown in Fig. 5(b), clearly demonstrating a pronounced sinusoidal variation.

C. Longitudinal recording media

Most of the work done with MFM up to now was concerned with the characterization of written bit patterns in longitudinal recording media.^{5,26,27} Here MFM proved to be able to give new insights in the magnetic behavior of the material in a submicron scale. The origin of noise in the reading process due to irregularities in the transition region between the bits, the overwriting behavior of the media, and errors due to positioning problems of the recording heads have been investigated so far. As an example, written tracks with different densities are imaged in a commercial CoPt thin film disk (Fig. 6). Two high density (25 kfp) tracks are shown separated by a lower density (5 kfp) pattern. For large bit sizes (e.g., low densities) only the stray field emanating at the transition regions between the individual bits is visible, whereas no contrast within the homogeneously magnetized areas is observed. This can be correlated to theoretical estimations⁵ assuming a single pole tip with the magnetization along the tip axis and the tip axis oriented perpendicular to the sample, thus probing only the z component of the stray field.

D. Soft magnetic materials

Like for other techniques used in imaging magnetic features, it was a challenge also for MFM to test the resolution limits on domain walls in soft magnetic materials^{9,14,28} as

FIG. 7. MFM observation of a transition (Bloch line) within a 180° wall in a Permalloy/Fe thin film (film thickness: 270 nm). The sign of the asymmetric contrast on both sides of the transition is reversed, shown by averaged scans [(1), (2)] across the two different wall segments. The origin of the structures pointing out of the transition region perpendicular to the wall are not yet understood (image size: $3.5 \times 3.5 \mu\text{m}$).

they are isolated micromagnetic structures with a nowadays well known internal magnetization configuration.^{29,30} Since it has been demonstrated experimentally⁹ and theoretically^{31,32} that walls in soft magnetic materials may be strongly affected by the MFM tip scanning above the sample, we found it worthwhile to characterize the influence of our magnetic tip on the structure to be observed. We used a Permalloy/iron multilayer sample where the typical basic domain wall and wall transition configurations are well known from magneto-optical Kerr effect observations.³³ All the domain boundaries typically observed by MFM in this material are found to reveal a slightly asymmetric double contrast. This is shown in Fig. 7 by two averaged scans [(1), (2)]

across two segments of a 180° wall on both sides of a transition (Bloch line) within the wall. Note that the transition is clearly visible due to a change in the main wall contrast, indicating both attractive (white) and repulsive (black) forces. Assuming an asymmetric Bloch wall,²⁹ the typical 180° wall configuration in this type of samples, the observed double contrast can be correlated with a single pole tip detecting mainly the Néel type character of the wall close to the surface.³² The distance of the two extremes in the measured profiles is determined to be about 300 nm. As this value is comparable to the surface wall width of an asymmetric Bloch wall in this material obtained by numerical simulations,³⁴ we conclude that the influence of our tip on the sample is very small or even negligible if we look at magnetically harder materials like recording media.

IV. DISCUSSION

With the electron beam fabricated magnetic thin film tips, MFM observations have been performed on various types of materials without changing the basic tip preparation parameters. During all the measurements we never found any partial switching of the magnetic state of the tip and all pictures fit very well with theoretical predictions assuming a single pole tip behavior. Both may be attributed to a single domain state of the effective magnetic volume predicted already in Ref. 15, but to check the validity of the concept, further detailed investigation of the magnetic structure of the tips, like the switching behavior in external fields, the internal domain structure, or the form of the fringing field at the tip apex region, are necessary.

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