Magnetic force microscopy with batch-fabricated force sensors

P. Grütter, D. Rugar, H. J. Mamin, G. Castillo, C.-J. Lin, I. R. McFadyen, and R. M. Valletta
IBM Research Division, Almaden Research Center, 650 Harry Road, San Jose, California 95120-6099

O. Wolter, T. Bayer, and J. Greschner
IBM Deutschland GmbH, GMTC, 7032 Sindelfingen, Federal Republic of Germany

In this paper the properties of force sensors suitable for magnetic force microscopy (MFM) made by coating silicon microcantilevers with various thin magnetic films are analyzed. These MFM force sensors are batch fabricated and their magnetic properties controlled by choosing appropriate coatings. Theoretical calculations show that thin-film MFM tips have a significantly reduced stray field, a good signal-to-noise ratio, and yield improved resolution when compared to etched wire tips. The sample perturbation due to the tip stray field is small, allowing the imaging of low-coercivity samples such as Permalloy.

I. INTRODUCTION

The crucial component of every magnetic force microscope (MFM)[1,2] is the force sensor (a sharp magnetic tip on a soft cantilever). In a previous publication,[3] we have shown that it is possible to batch fabricate force sensors suitable for MFM by coating microfabricated silicon cantilevers with a thin ferromagnetic film. In this paper we want to discuss in more detail the magnetic properties of thin-film force sensors[3–6] and present some imaging applications. Details concerning the instrument and its operation modes can be found in Ref. 3.

The microcantilevers used in this study have integrated sharp, high-aspect-ratio silicon tips suitable for general purpose force microscopy.[7] Figure 1(a) shows the geometry of these force sensors. The cantilevers are typically 500 μm long, 12 μm wide, and 5–7 μm thick. The integrated conical tips are about 10 μm long, have a tip radius of 5–50 nm, and a typical cone angle of 10° or less. This small cone angle is desirable for MFM tips due to the long-ranged nature of the magnetic interaction.

Three types of coatings were evaluated: evaporated Co, sputter-deposited $Co_{71}Pt_{12}Cr_{17}$, and sputter-deposited $Ni_{80}Fe_{20}$ (Permalloy). These films have magnetization values M_s of 1422, 450, and 835 emu/cm^3 and coercivities H_c of 190, 550, and 2 Oe, respectively. These properties were measured on flat silicon samples. The influence of the sharp tip geometry on magnetic properties is not clear; higher values of coercivity are expected. All films were nominally 15 nm thick.

In a previous paper[3] we showed that we could select the sample stray field component $\partial^2 H_i/\partial z^2$ ($i = x$, y, or z) to be measured in the MFM experiment by magnetizing the two high-coercivity thin-film tips in a suitably oriented external magnetic field of about 10 kG. This procedure also significantly enhanced the magnetic signal obtained with the high-coercivity thin-film tips. From an analysis of the symmetry of transitions on a longitudinal magnetic recording test sample we concluded that the magnetization direction of these tips is parallel to the direction of the externally applied field.[3]

In Fig. 1(b) we show a Lorentz microscopy image obtained in the differential phase contrast (DPC)[8] mode of a CoPtCr thin-film tip after a 10-kG magnetic field was applied along the tip axis. DPC micrographs allow the determination of the direction and the magnitude of the induction integrated along the electron trajectory at each point of the scanned image of the tip stray field. The pattern observed in Fig. 1(b) is expected for a tip homogeneously magnetized along its axis. The DPC image of this tip is thus consistent with the magnetic tip structure as inferred from the symmetry analysis of written transitions.[3] In contrast to the results obtained with magnetically hard CoPtCr-coated tips, no stray field was detected by DPC imaging of magnetized thin-film NiFe tips. This is expected for magnetically soft coatings.

II. TIP FIELD CALCULATION

An advantage of these thin-film-coated MFM tips is the smaller tip stray field compared to a ferromagnetic wire tip. The reduction in stray field is important when imaging soft magnetic materials, where a large tip stray field can induce domain-wall motion in the sample.[9,10]

We have calculated the tip stray field and its second derivative for a bulk and a thin-film tip using the following equation, valid outside the tip:

$$\mathbf{H}(\mathbf{r}) = \int_{\text{tip volume}} \frac{3\hat{n}[\hat{n}\cdot\mathbf{M}(\mathbf{r}')] - \mathbf{M}(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3}\, dV',$$

where $\mathbf{r}$ is the observer point outside of the tip, $\mathbf{M}(\mathbf{r}')$ is the magnetization of the tip, and $\hat{n} = (\mathbf{r}-\mathbf{r}')/|\mathbf{r}-\mathbf{r}'|$. We numerically evaluated this equation for a 10-μm-long conical CoPtCr bulk tip with a 5° half-angle and a conical shell with a film thickness of 15 nm (measured along the direction of the tip axis).

Figure 2 shows the result of this calculation at a small tip-sample separation of 25 nm (typical of high-resolution imaging) and at the typical MFM operation distance of 100 nm. In Figs. 2(a) and 2(c) we present plots of the magnitude of the tip stray field. The thin-film tip gives a peak stray field of only 3 Oe with a FWHM of 450 nm at a distance of 100 nm. This is to be compared to the corresponding results for a solid conical wire of identical material and geometry: 68 Oe and 2200 nm FWHM. The tip stray field from a coated thin-film tip is much smaller and

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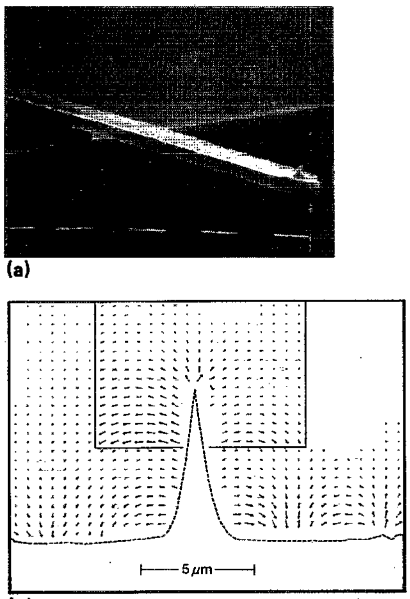

FIG. 1. (a) Scanning electron microscopy image of microfabricated Si force sensor with integrated tip. (b) DPC Lorentz map of the tip stray field. Arrows denote direction and magnitude of the integrated tip stray field induction. The arrows within the box surrounding the tip are magnified four times to enhance details.

more localized than that of the corresponding wire tip. This is a consequence of the reduced volume of magnetic material in the tip.

Imaging sensitivity (i.e., force gradient) is proportional to the second derivative of the tip stray field, which is presented in Figs. 2(b) and 2(d). The force derivative calculations indicate that the reduction in imaging sensitivity for thin-film tips due to the reduction in magnetic volume is not severe (6×10^{10} Oe/cm^2 compared to

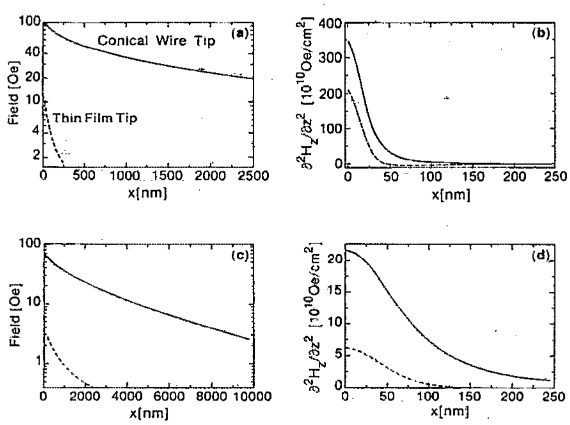

FIG. 2. Comparison of the stray field and sensitivity of bulk and thin-film tips. Calculations are for a 10-μm-long conical CoPtCr tip with a half-cone angle of 5° and a conical shell with a thickness of 15 nm (measured in the direction of the tip axis). The ordinate x is the lateral distance from the cone axis. Dashed line: 15-nm thin-film tip; solid line: bulk tip. (a) Stray field at 25 nm; (b) second derivative of tip stray field at 25 nm; (c) stray field at 100 nm; and (d) second derivative of tip stray field at 100 nm.

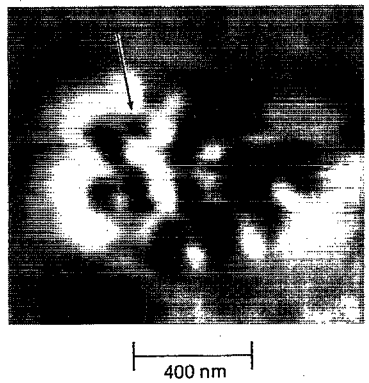

FIG. 3. Collapsed domains observed in thermomagnetically written mark on TbCoFe with a small applied field opposite to the writing direction. The mark diameter is approximately 800 nm; the arrow points to a magnetic structure smaller than 50 nm in diameter.

21×10^{10} Oe/cm^2 at 100 nm). Furthermore, this calculation indicates that a slightly better lateral resolution is to be expected for thin-film tips (FWHM of 50 nm compared to 70 nm at 100 nm distance).

We previously demonstrated the advantage of reduced stray field from thin-film tips by imaging a 30-nm thin patterned NiFe sample.[3] No tip-induced domain-wall motion was observed, in contrast to images taken previously with a bulk iron wire tip.[10]

III. IMAGING WITH CoPtCr THIN-FILM TIPS

With tips coated with CoPtCr thin films we can routinely achieve a 50-nm resolution. This is demonstrated in the following image of collapsed domains written magneto-optically in a 80-nm-thick TbCoFe alloy at low-bias fields (Fig. 3). From previous experiments this sample is expected to have magnetic structures very small in size.[11] MFM with thin-film tips can image marks smaller than 50 nm in diameter on this sample (Fig. 3). Similar structures have been observed by Lorentz microscopy[11] and MFM with bulk wire tips.[12]

A further example of high-resolution imaging can be found in Ref. 13. Details of transitions spaced as close as 160 nm on an experimental ultrahigh-density (1 Gbit/in.^{2}) magnetic recording sample were imaged with a thin-film CoPtCr force sensor.

As an example of an application of coated tips, we have studied the effect of changing the write current of a magnetic recording head. Changes in the current affect the writing field emanating from the head and thus the magnetic structure written on a longitudinal recording media. Tracks 8 μm wide were dc magnetized before transitions spaced 5 μm apart were written at various write currents. In Fig. 4(a), written with a small current, only bit cells oriented parallel to the dc-magnetized state are saturated (marked with a star). Because of the well-aligned magnetization the MFM image of this region thus does not show a lot of structure. In contrast, the small writing field from the head is not large enough to write saturated bit cells oriented antiparallel to the dc-magnetized direction. Considerable structure can be observed in these bit cells by MFM, attributed to the partially demagnetized media state. Figure 4(b) shows results for writing at optimal write currents. We observe clear transitions, giving good

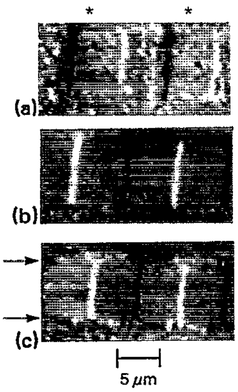

FIG. 4. MFM image obtained with an axially magnetized CoPtCr tip. The transitions are spaced 5 μm apart and were written on a dc-erased track on a longitudinal recording disk at different head writing currents. Stars and arrows are referred to in the text. (a) Low write current, (b) optimum write current, and (c) high write current.

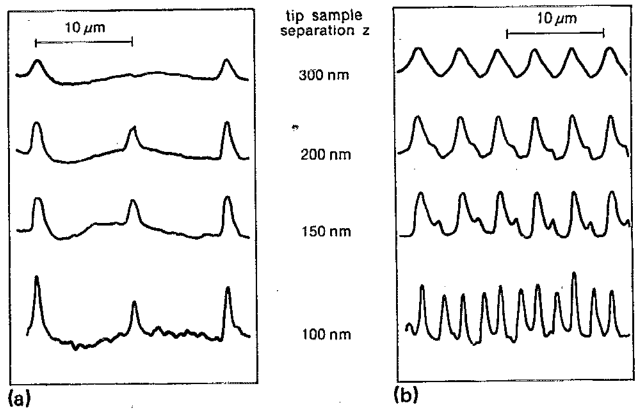

FIG. 5. MFM response obtained with a NiFe thin-film tip at different tip-sample distances. (a) and (b) show averaged scanlines of tracks with transitions spaced 10 and 2 μm apart, respectively, as a function of tip-sample distance. Note that the transitions spaced 10 μm apart always give rise to an attractive interaction, in contrast to the higher-frequency transitions spaced by 2 μm.

bit definition and square, saturated bit cells. At write currents higher than normal [Fig. 4(c)], a clear bit definition is also observed. Additionally, however, significant curvature of the transitions is observed at the edge of the track (marked by arrows). Similar effects have previously been observed by Lorentz microscopy.[14]

IV. IMAGING WITH PERMALLOY TIPS

Thin-film NiFe (Permalloy) tips are magnetically soft.[3] It was found that a strong enough sample stray field orients the effective tip magnetic moment, thus leading to attractive interaction only. In Figs. 5(a) and 5(b) we present averaged line scans of tracks with 10- and 2-μm transitions, respectively, as a function of tip-sample distance. Every other transition becomes very weak when the tip-sample distance exceeds a rather sharp threshold. The threshold distance is transition-frequency dependent. It is smaller for transitions written at a high spatial frequency. This explains why every second higher-frequency transition in Fig. 5(b) is very weak. For distances larger than this threshold repulsive interaction is observable: The sample stray field is not strong enough anymore to orient the effective tip magnetic moment.

This behavior can qualitatively be understood as a consequence of the transition stray field distance dependence, which is a function of transition frequency (Wallace spacing loss).[15] In order for the overall magnetic interaction to be attractive, the sample stray field has to be larger than the effective coercivity of the tip. From the experimental data in Figs. 5(a) and 5(b) and a calculation of the stray field distance dependence we estimate an effective coercivity of about 40 Oe and an effective tip length of about 500 nm for the NiFe thin-film tips.

V. SUMMARY AND CONCLUSIONS

In summary, we have demonstrated that tips coated with thin magnetic films have a significantly reduced perturbation effect on soft magnetic samples (compared to bulk wire tips) due to their reduced magnetic volume. This will allow the routine imaging by MFM of magnetically soft samples such as Permalloy or garnets with coercivities as small as 1 Oe. From an analysis of measurements performed on a magnetic recording test sample as a function of distance and transition frequency we determined an effective coercivity of 40 Oe and an effective tip length of 500 nm for thin-film NiFe force sensors. The possibility to batch fabricate and control the magnetic properties of force sensors will make MFM a more practical and easier to use technique with a larger scope of applications.

ACKNOWLEDGMENTS

The authors thank T. R. Albrecht, P. Wimmer, and P. Güthner for assistance in the design and construction of the instrument, S. E. Lambert for the longitudinal recording test sample, and I. A. Beardsley for helpful discussions.

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