Measurement of in-plane magnetization by force microscopy

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(Received 31 May 1988; accepted for publication 1 August 1988)

We present data which show that the magnetic force microscope is capable of detecting the component of the magnetic field parallel to the surface of a sample under study. Images of bits in a Co-alloy thin-film disk and of laser-written bits in a TbFe film were taken with a magnetized tip tilted at 45° with respect to the surface normal. In both cases the asymmetric part of the image of a domain is interpreted in terms of gradients in the in-plane component of the magnetic field. The bits written in the Co-alloy disk were decorated with small magnetized particles, allowing identification of the domain boundaries and the asymmetric component of the force microscope image due to in-plane magnetization.

Many current schemes for information storage, including magnetic tape, floppy disk, and hard disk, read and write binary bits in the form of magnetic domains in which the direction of magnetization lies parallel to the sample surface. At present these bits can be imaged by a variety of high-resolution techniques, including Bitter decoration,[1] Lorentz microscopy,[2] and scanning electron microscopy with polarization analysis (SEMPA).[3,4] Each of these techniques has proven useful, but not without shortcomings. In the case of Bitter decoration, the information provided is limited to an outline of the domain boundary, and, following imaging, the sample surface is contaminated with a very fine magnetic dust. The Lorentz technique relies on thinning of the sample in order to allow transmission of the electron beam. SEMPA is a nondestructive technique which provides magnetization direction and magnitude, but which requires operation in vacuum, clean surfaces, and lengthy acquisition times.

In this letter, we present the first direct evidence that the in-plane component of the sample magnetization can be detected with the magnetic force microscopy (MFM).

The measurements were taken with a force microscope[5] using optical heterodyne detection of tip motion.[6] This version of the force microscope traces contours of constant force gradient, and for these magnetic studies used an etched music wire tip similar to those used previously to image magnetic heads and vertically recorded bits.[7,8]

For the work described here we used a music wire tip that was electrochemically etched in a solution of H_2SO_4:H_2O 1:1 by applying 7 VAC to the tip in a sequence of pulses of 10 ms duration. The tip was etched to a length of 350 μm with the diameter tapering from 3 μm to a final tip radius of approximately 200 nm. The final 80 μm length of the tip was bent at 45° with respect to the sample, instead of perpendicular as before.

The wire was initially magnetized prior to etch. We believe, based on considerations of minimum magnetic field energy, that the end of the sharpened tip consisted of a single magnetic domain with the direction lying parallel to the axis of the tip. This view is supported by the following experiments.

In the first experiment, we imaged a thin-film TbFe disk in which bits had been defined thermomagnetically. The net magnetization in this media is aligned normal to the sample surface, and a bit corresponds to a region in which the direction of magnetization is reversed with respect to that of the surrounding film. In force microscope experiments using a tip bent at 90° (i.e., normal to the surface), the image of a bit was rotationally symmetric about its center.[8] The images of three 1-μm-diam bits taken with the 45° bend tip are shown in Fig. 1, and appear skewed to the side, which is expected since the tilt of the final domain in the tip away from normal breaks the symmetry of the (relatively) circular bits. (The bits were purposely written with low bias magnetic field in this sample in order to produce incomplete reversal of magnetization.)

In a second experiment, the same 45° tip was used to image bits written in a Co-alloy thin-film disk. A track consisting of a series of 1's, that is, a sequence of domains of alternating magnetization, was written in the disk, with each bit 17 μm wide and 2 μm long. In order to locate the bit track for coarse positioning of the tip, a dilute solution of small (10 nm) iron oxide particles in alcohol was placed over the track, highlighting the domain boundaries. A SEM picture of a portion of the track is shown in Fig. 2, clearly outlining the written bits. The images which were obtained by MFM were taken in a region near the edge of the Bitter pattern, so that the density of particles was lower than shown in the SEM photo. A typical MFM result is shown in Fig. 3, showing a portion of the written track upon which is super-

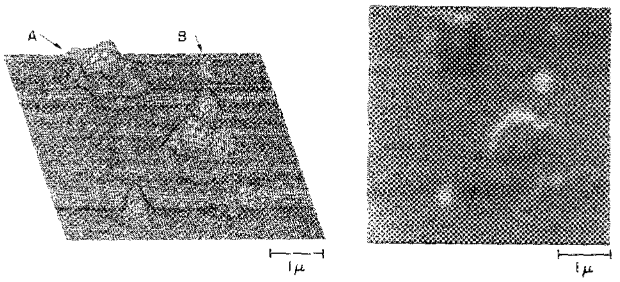

FIG. 1. Five micrometer square force images (presented as both line drawing and gray-scale image) of several 1 μm diameter, thermomagnetically written bits, one of which is labeled as A, in 500-Å-thick TbFe film. A magnetized steel tip oriented at 45° with respect to the sample was used, causing in-plane field to be detected as asymmetry in the image. The symmetric appearance of the nonmagnetic topographic features such as B emphasizes the magnetic origin of the asymmetry seen in the bits.

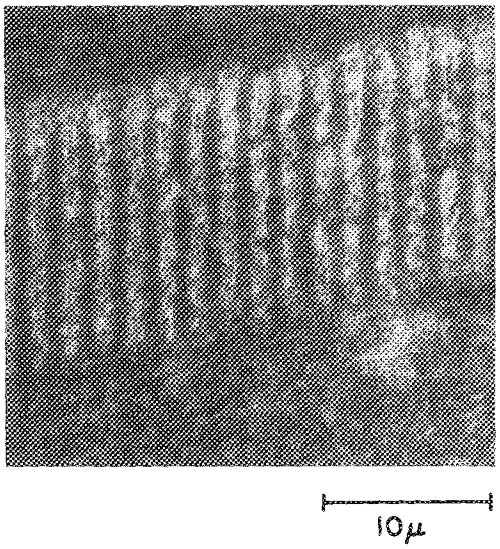

FIG. 2. Scanning electron micrograph of a single track of domains of alternating magnetization in Co-alloy sputtered thin-film disk. Contrast is achieved by decoration with 100 Å iron oxide particles, which highlight domain boundaries.

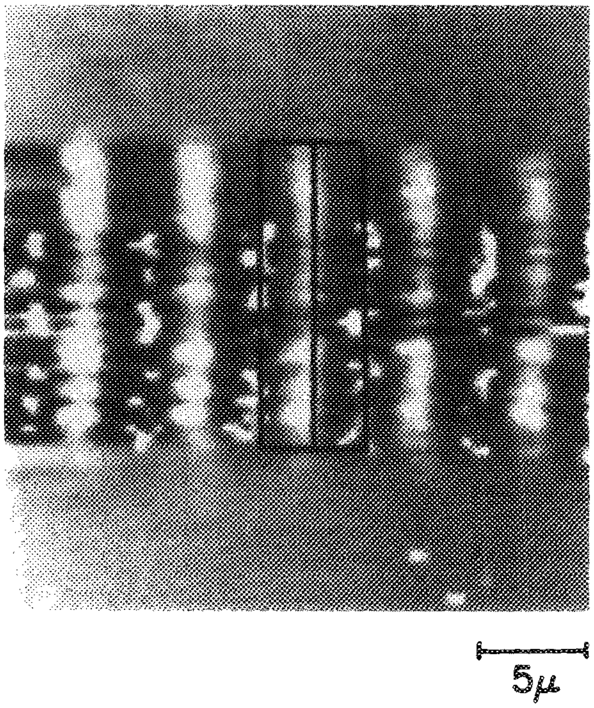

FIG. 3. Magnetic force microscope image of bit track in Co-alloy thin-film disk. Data were taken with tip tilted 45° with respect to sample. Half of the iron oxide particles are visible as compared to scanning electron micrograph in Fig. 2.

imposed the small white dots identifying the location of the iron oxide particles. Very similar images of thin-film bits without Bitter decoration have been obtained, indicating that the perturbation of the sample due to the presence of magnetic particles is negligible. The magnetic particles are seen more clearly on the domain boundaries where the tip-sample gap is smallest (darker in the image shown in Fig. 3). This is reasonable since the perturbation due to the magnetic particles drops off as the tip-to-sample increases.

Changing the orientation of the final magnetic domain in the tip from perpendicular to tilted can in general be expected to provide information about the in-plane magnetic field. The consequences of such a measurement are straightforward if the magnetic portion of the interaction of tip and sample is modeled as that of two ferromagnets. The interaction energy can then be written as $-\mu\mathbf{B}$, where μ is the tip magnetization and $\mathbf{B}$ is the field from the sample. If the tip is tilted away from normal then the energy contains a term proportional to the component of magnetic field from the sample which is parallel to the sample surface. In our microscope the tip traces contours of constant total force gradient, the magnetic part of which is given by

$$-\mu_z \frac{\partial^2 B_z}{\partial z^2} - \mu_x \frac{\partial^2 B_x}{\partial z^2},$$

where x and z refer to in-plane and normal, respectively.

The image of the vertical domain in TbFe clearly exhibits an asymmetry, reflecting the component of fringe field above sample which is parallel to the sample surface. The written domains in the Co-alloy disk also exhibit an asymmetry, which can be seen as a slight skew of the maxima in the MFM image in Fig. 3 with respect to the domain wall, determined by the position of the Bitter solution. The portion of the image due to the in-plane component of magnetic field, B_x, should be asymmetric about a domain wall, while the normal component of field is expected to give rise to an image symmetric about the domain wall. We can state with certainty that the in-plane component of magnetization has contributed to the images of Co-alloy thin-film disk, since the location of the domain walls is established by the presence of the Bitter decoration. In Fig. 4 we show the averaged cross section through several bits. The slight shift of the peak away from the domain boundary is due to the asymmetric portion of the image arising from the in-plane magnetization. Detailed understanding of the resultant profile is made difficult by the role that the van der Waals force plays in half of the bits, where the repulsive magnetic force must be balanced by an attractive surface potential. Experiments presently in progress are aimed at understanding the contrast mechanism in the MFM.

In summary, we have presented the first firm evidence

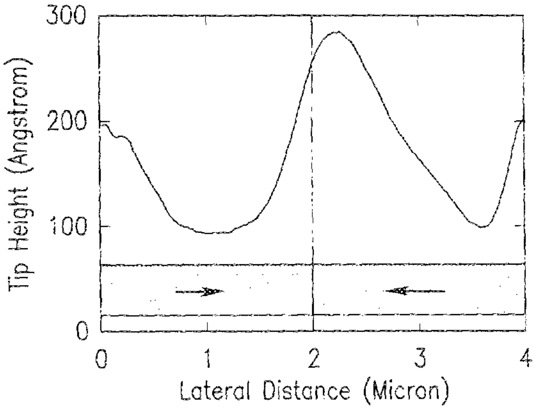

FIG. 4. Averaged cross section through bits shown in Fig. 3. Slight asymmetry in image with respect to domain wall (sketched below data) is due to in-plane magnetization.

that the magnetic force microscope is capable of detecting in-plane components of the sample magnetization. By using the Bitter technique to mark domain boundaries in the case of the Co-alloy disk sample, we have verified that both the in-plane and perpendicular components contribute to the MFM image.

We thank Martin O'Boyle for assistance with the optical measurement system, and Dan Rugar and Ken Johnson for supplying the TbFe- and Co-based samples, respectively.

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