Magnetic Imaging in the Presence of an External Field: Erasure Process of Thin Film Recording Medium

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Abstract...The evolution of microscopic magnetic structures on a thin film recording medium has been imaged by applying a progressively increasing external magnetic field. Images from magnetic force microscopy with an in situ magnetic field revealed features attributable to probe-induced and sample-induced effects. The probe effects result in the preferential sensitivity of the MFM imaging to the component of the local sample field in the direction of the probe's magnetization. The reorientation of the probe's magnetization with respect to the sample plane direction causes the change in instrument response from detecting surface magnetic charges (magnetization divergence sensing) to detecting the surface magnetization distribution. Sample effects are more prominent at higher fields and the microscopic features of the recorded patterns follow a characteristic sequence as the unfavorably magnetized areas switch in the direction of the external field.

I. INTRODUCTION

The remnant magnetization structures resulting from successive stages of erasure have recently been studied in thin film recording medium[1]. In this work, we extend those investigations by studying the behavior of recorded patterns while experiencing a progressively increasing external magnetic field. Our goals are to clarify image formation in magnetic force microscopy, as well as, to understand the mechanism of magnetization reversal in thin-film recording medium.

The experimental set-up was designed to expose the sample and the probe to the same controlled external DC field. The coercivity of the CoCr-coated probe was much lower than that of the sample which facilitated the delineation between the field and sample effects. In the following sections, we first discuss the consequence of the reorientation of the probe's magnetization due to weak magnetic field biasing, and subsequently study the sample's micromagnetic reconfiguration in response to the applied field. We focus on a number of key points, namely, the expansion of the favorable domains at the expense of the others, the increase in transition edge ripples across the track, the "re-texturing" of the unfavorable areas, the coalescence of neighboring expanding domains causing percolation and leading to the eventual collapse of the isolated clusters at the highest fields.

II. EXPERIMENT

An electromagnet was incorporated in a commercial magnetic force microscope (Digital Instruments Nanoscope III), and designed to have a small air gap directly underneath the cantilever probe. The sample was placed inside the gap region and experienced an external magnetic field which was oriented primarily along the surface plane and in the direction of the recorded tracks. The average strength of the external field was calibrated against the input current by using a miniature Hall probe and achieved as high as 3000 Oe with tolerable Joule heating. Imaging drifts due to thermal effects were insignificant and fluctuations in the applied field were minimal. Space limitations of this paper preclude detailed discussion of the design which will be furnished elsewhere.

The sample was prepared from a conventional removable rigid disk whose characteristics have previously been studied [1]. Standard magnetization curves were measured using a vibrating sample magnetometer and the following macroscopic properties were obtained: \( H_C = 926 \) Oe, \( M_r = 5.0 \) memu/cm\(^2\), \( S = 0.81, S^* = 0.86 \), and the in-plane orientation ratio \( M_z(par)/M_z(per)\sim 1.5 \) and positive particle interaction. The data consists of more than 100 images taken in succession, each of which is associated with a fixed external field and taken in increments of about 10 Oe near the medium coercivity.

III. RESULTS AND DISCUSSION

Direct interpretation of image formation in MFM can be derived from Figs. 1 (A) and (B). For an arbitrarily magnetized probe, the contrast mechanism of magnetic force microscopy (neglecting probe-sample electrostatic forces) is given by [2]

\[
\Delta F = \sum m_i \frac{\partial^2 H_z}{\partial z^2},
\]

where \( \Delta F \) is the change in force gradient and \( m_i \), \( H_z \) are the Cartesian components of the probe magnetization and the surface field, respectively. Prior to acquiring image (A), the probe was exposed to a 3.5 kOe magnet which aligned its magnetization normal to the sample surface direction, \( z \). In the absence of an external field, Eq. (1) predicts preferential imaging of the \( z \)-component of the surface field. The resulting image, Fig. 1 (A), exhibits narrow strips of alternating bright and dark strips which correspond to the \( z \)-component of the local field and are strongly enhanced at the regions where the divergence of the surface magnetization was large, i.e., the transition regions. Thus, it can be regarded as the image of magnetic charges arising from the longitudinal magnetization pattern. By comparison, image (B) was taken with a slight external field and the image shows contrast features that were broadened and extended across the entire bit lengths. The field of 100 Oe was too low to have perturbed the medium, so the image transformation can be attributed with the probe's magnetization reorientation in response to the external field. The reorientation led to a non-zero \( m_z \) term in Eq. (1), resulting in an increased \( H_z \) contribution in (B). Furthermore,
Fig. 1. Microscopic pattern evolution during successive erasure stages. MFM images of a specific 65 x 65 μm² area on thin film recording medium with increasing external DC magnetic field. The branch of the M-H loop corresponds to the state of the dark contrast regions.

Since the horizontal component of the field usually mimics the distribution of magnetization[3,4] then the contrast mechanism in (B) can be thought of as being due to the distribution of the local surface magnetization. It is then clear that with external magnetic field biasing, the MFM can be used either as magnetic charge sensing or magnetization-sensing instrument.

It is worthwhile to point out that the application of a uniform field is not expected to introduce extraneous local effects in the images. Hence, with appropriate design of an electromagnetic element, one may be able to adapt the MFM to faithfully image the individual components of the local surface field[5] unencumbered by the external field. Similarly, by constraining the probe magnetization in a rigidly fixed orientation, one can avoid the complications of a changing probe magnetization in image interpretation. This approach is ideally suited in cases where the sample magnetization is orthogonal to the applied field and has a high anisotropy field, or when the coercivity of the sample along the applied field is much higher than that of the probe. The latter condition is true in our experiments and since the probe was saturated at low fields, additional probe-induced effects are expected to be minor at the higher fields.

The remaining images depict the erasure process, together with a branch of the M-H loop corresponding to the magnetization state of the dark-contrast regions. Since only the average gap field could be measured with the Hall probe, a separate determination of the local field at the scan location was done by assigning the coercive field to the image with roughly 50% switching of the reversed magnetized areas. The rest of the images were then identified relative to this and their positions were labeled on this loop. The bright areas in image (B) correspond to the magnetization oriented in the direction of the applied field. The overall high frequency background noise has not been suppressed in order to provide a qualitative sense on instrumental limits. Note that the "texture" of the bright
and dark areas in (B) are very similar to each other, indicating that the surface magnetization was equally saturated in one direction as it was in the other. The transition regions between opposite magnetized regions were straight with the exception of slight spatial variations averaging about 0.5 μm across the track. These edge ripples arose from the combined effects of background noise as well as the intrinsic zigzag and localized vortex formations at the transition regions that tend to minimize the magnetostatic energy [5]. This configuration was quite stable and no discernible sample effects have been observed until roughly 200 Oe below the coercivity.

According to the data, the process can be divided into three distinct stages, namely (i) the onset of erasure, which occurred at field slightly below the medium coercivity [(C)-(D)]; (ii) the mid-stage, as the coercivity was traversed [(E)-(F)]; and (iii) the final stage [(G)-(H)] for fields higher than the coercivity. The onset stage was characterized by a subtle expansion of the bright areas and the distinctive roughening of the transition region. The increase in transition edge irregularity suggests that the leading edges of the favorably magnetized ripples have extended into areas previously magnetized in the opposite direction. Direct comparison of the bit lengths in images (B) and (D) confirms that transition roughening intensified and that the bright regions have extended by an average of about 1 μm into the dark regions. In addition, the interiors of the dark areas have significantly coarsened at 865 Oe, in contrast with the relatively unchanged interiors of the bright areas. This suggests that the magnetization reduction at the unfavorable areas were accomplished by means of the local reorientation of magnetic moments, not only in the transition areas but over their entire regions. This is in qualitative agreement with the results of micromagnetic simulations at various states along the hysteresis loop [7] and where the observed roughening may be attributable to the formation of a large number of vortex structures. Within instrumental limits, the local redistribution did not appear completely random which would have produced non-correlated patches on the surface. Instead, there was a tendency to form triangular microstructures in the interior regions that extended up to the transition regions. Similarly, note that the onset of erasure is accompanied by the switching of moments at the track edges in the direction of the field. This can be perceived as the slight widening (between the images (B) and (D)) of the regions which separated the tracks, implying the relative ease by which the cross track magnetization components were reoriented by an average angle of 90° [5,8]. The overall result was an apparent shortening of the track width.

As the field approached coercivity, the primary mechanism of magnetization reversal at mid-stage appeared to be the initial coalescence of growing edge ripples followed by their expansion along the track direction and subsequent widening across the track. Image (D) shows areas where adjacent domains have broken-through or “percolated” through the entire length of the unfavorable domains. (Arrows indicate some examples.) At those areas, large neighboring transition edge ripples have coalesced and initiated the breakup of the unfavorably magnetized bits [7,9]. The number of these percolated areas increased with larger fields, as readily seen at 926 Oe. The unfavorably magnetized areas lost their continuity across the track and were subdivided by portions that realigned with the external field. An interesting feature of these patterns was the appearance of horizontal streaks in some areas formed by percolation. This suggests some correlation of magnetization switching along the direction of the track which most probably resulted from the positive inter-particle interaction of the medium. As the field was raised further, the streaks widened across the track as is readily apparent at 977 Oe. Thus, in contrast with the onset of erasure, magnetization reversal at this mid-stage process did not occur as the continued displacement of the entire transition boundaries along the track direction. Instead, reversal occurred by percolation and the subsequent cross track expansion. This new channel for reversing magnetic moments was presumably more energetically favorable than the displacement of the transition boundary.

The final stages of erasure are shown in Figs.1 (G)-(H). By 1027 Oe, with the exception of isolated remnants of unswitched clusters, most parts have been reoriented in the direction of the field. These pinned areas required fields significantly higher than coercivity to completely switch and the terminal distribution of the remaining clusters appeared to be non-correlated with their previous patterns. Their random distribution probably reflects the local fluctuations in the magnetic properties of the medium and corresponds to the residual tail of the ensemble's switching distribution.

CONCLUSIONS

The capability to produce magnetic force microscopy images in the presence of an external magnetic field has been realized and applied to study magnetization reversal of thin film media. Characteristic image alterations introduced by probe effects were observed at very low fields and were explained on the basis of the probe's magnetization reorientation. The intermediate steps leading to full medium saturation were determined by following the evolution of the patterns starting from the initial displacement of the transition boundary and terminating with the switching of isolated clusters. These observations help elucidate the nature of magnetization reversal in granular systems. Clearly, our qualitative results may be further refined by analyzing the "roughening" behavior. In the future, it may be possible to determine parameters such as the effective size of a switching unit and relate them with the noise and performance characteristics of the recording medium.