Atomic Force Microscopy: Exploring Nanostructures - M2

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The study of magnetic domains in data carriers was conducted, leading to a deeper understanding of Atomic Force Microscopy (AFM) principles and greater familiarity with the Magnetic Force Microscopy (MFM) method. The image analysis was successful, as high-resolution images were obtained for nearly all analyzed samples. However, the high-memory-capacity hard drives proved too demanding to measure precisely. Basic measurements were performed on these images to analyze the structure and characteristics of the magnetic domains. This study demonstrated the effectiveness of the MFM technique in visualizing and interpreting magnetic domain patterns across various data storage media.

1 Introduction

1.1 Atomic Force Microscopy

Atomic Force Microscopy (AFM) is a high-resolution type of Scanning Probe Microscopy (SPM) used to gather information about a sample. It was invented to overcome the limitations of Scanning Tunneling Microscopy (STM) faced, primarily the requirement for the sample to be conductive or have a conductive layer. AFM addressed this issue by implementing various methods that leverage atomic forces, mainly Pauli exclusion principle and van der Waals forces. These methods can be categorized into those that make direct contact with the sample, those that operate in a semicontact mode through intermittent contact and the ones that doesn't include any contact at all [1].

1.2 AFM System Principles

AFM systems vary depending on the technique used, but they share certain common components. Figure 1 presents a simplified schematic. The system always includes a scanner that either moves the detection system over the sample or moves the sample itself. When the detection system remains stationary, the scanner typically operates using piezoelectric materials, which change their length when an electric field is applied. This change in length is relatively small; therefore, piezoelectric components (such as the piezo actuator shown in Figure 1) are integrated into the system. By synchronized contraction and extension, the piezo actuator adjusts the sample plane angle to cover a greater relative distance in the XY coordinates. The inner part of this piezoelectric system controls the vertical movement (Z-axis) by raising or lowering the sample.

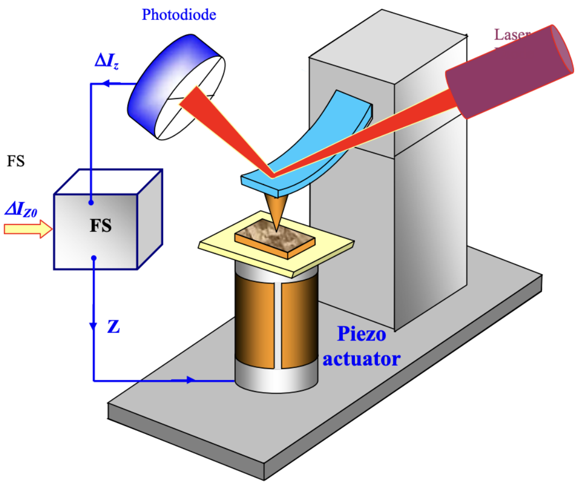

Figure 1: Simplified scheme of AFM feedback and detection system [2].

The detection system consists of a probe mounted on a cantilever. In contact mode, the probe is pressed directly into the sample, while in semi-contact or non-contact modes, the probe is oscillated by modulating the electric current applied to another piezoelectric system. The position of the cantilever is monitored by a laser beam reflected from its surface onto a photodiode.

The aforementioned piezo actuator and photodiode are connected to a feedback system that dynamically calculates the system's response to continuously changing conditions on the sample surface. Depending on the method, different parameters are modulated. Typically, one parameter is kept fixed while another (or others) is dynamically adjusted to produce an image. The method used in this study was the semicontact 2-pass MFM, the details of which will be presented in Section 1.3.

1.3 Semicontact 2-Pass MFM

Magnetic Force Microscopy (MFM) in 2-pass mode integrates semicontact mode and non-contact mode, as shown in Figure 2. During the first pass, the probe operates in semicontact mode, tracing the surface and providing information about its topography. It then increases its relative height and performs a second pass above the sample. This second trajectory follows the topography path, ensuring a constant height. During the second scan, all changes in the cantilever's deflection are caused by magnetic forces, thus providing an accurate mapping of magnetic domains [2].

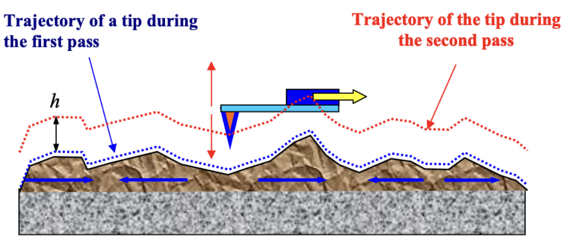

Figure 2: Two-pass technique of the MFM [2].

MFM in 2-pass mode provides images of both height and phase. In this study, the first pass will be neglected, as the objective is to investigate the magnetic domains of various samples. Therefore, using the non-contact mode during the second pass, the phase profile is processed into an image.

2 Experiment

2.1 Experimental Setup

The experimental setup is schematically shown in Figure 3. It includes a Magnetic Force Microscope connected to the SPM controller, which analyzes the signal and processes it into an image that is then displayed on a portable computer (PC). An external camera is also attached to the PC, which is used to confirm the probe's position above the sample before calibration. The microscope, along with the sample inside, is described in detail in Sections 1.2 and 1.3.

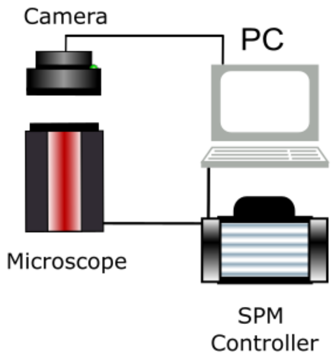

Figure 3: Schematic view of the experimental system.

2.2 Samples and Probes

During the study, the following samples were analyzed using MFM 2-Pass method:

1. VHS Sample,
2. 250 GB Hard Drive sample,
3. 1 GB Hard Drive sample,
4. 4.3 GB Hard Drive sample,
5. 60 GB GB Hard Drive sample.

The probe that was used in this study is shown in Figure 4.

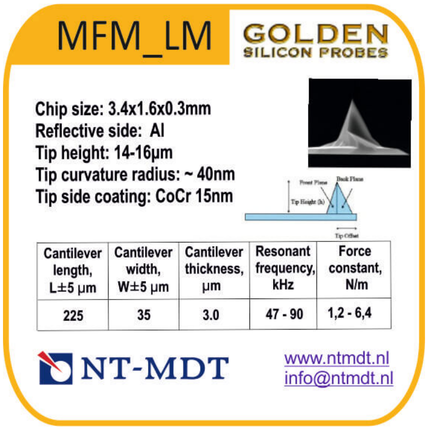

Figure 4: The probe used in MFM [3].

2.3 Calibration Process

The calibration process was the same for each sample. After properly placing a probe and sample inside the microscope, it was necessary to ensure that the sample was positioned directly below the probe and to check for any external contaminants that could obstruct the clarity of the measurement. This verification was performed using the external camera, as shown in the schematic view in Figure 3.

The microscope includes a built-in laser (Section 1.2) that needed to be aimed at the center of the sample. This alignment was performed using the mechanical adjustment wheel and a flat screwdriver for calibration in the XY plane. The next step involved determining the cantilever's resonance frequency using a built-in function of the microscope's dedicated software (Nova Px 3.4.0 rev. 16107).

Once these steps were completed, the probe was lowered closer to the sample. After selecting the semi-contact 2-pass MFM mode, the vertical scanning direction (necessary for 2-pass mode), the scanned area, and the resolution, the scanning process could begin. During the first pass, both height and phase were measured, while in the second pass, only the phase was recorded.

The scanning process was adjusted by modulating the scan rate, gain, and height (elevation increase between passes) to achieve the highest possible resolution. These parameters were selected arbitrarily through methodical trial and error to optimize image quality.

3 Results

3.1 VHS

The first analyzed sample was a piece of a VHS magnetic tape. The imaging difficulty for this sample was expected to be low, as it was served as an introductory exercise. As anticipated, the obtained image was of very high resolution, as presented in Figure 5.

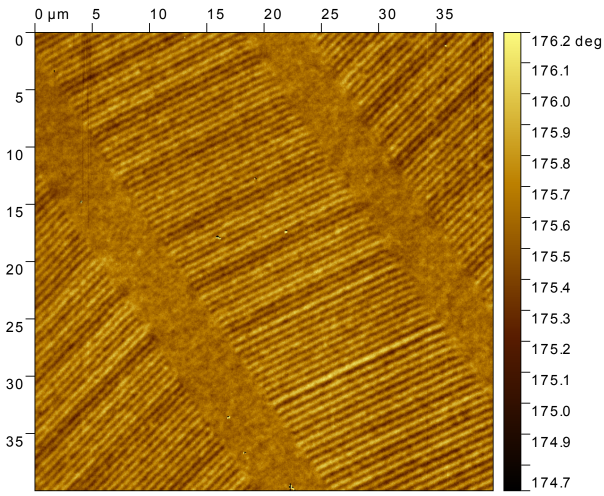

Figure 5: High-resolution image of the VHS sample obtained using the MFM 2-pass method. The analyzed region measures 40 × 40 microns.

In Figure 5, three distinctive paths of magnetic domains are visible, separated by empty regions. Within each path, clearly visible magnetic stripes store information. Notably, during the measurement, the imaging quality improved spontaneously, suggesting a change in the probe's condition - either due to the addition or removal of contamination at the probe's tip. Regardless of the cause, this improvement resulted in high-resolution imaging, allowing for a more detailed investigation of smaller regions. The middle path was selected for further analysis, with the results presented in Figure 6.

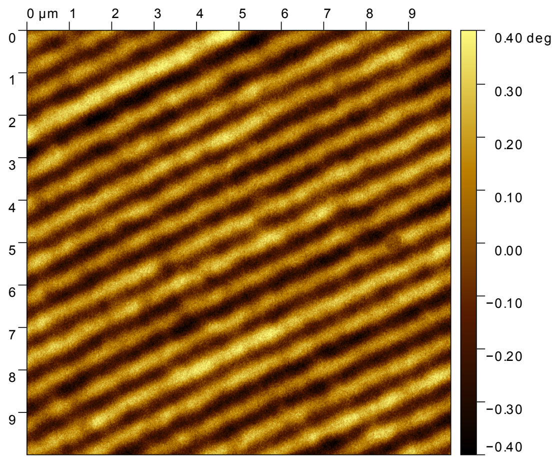

Figure 6: High-resolution image of the VHS sample obtained using the MFM 2-pass method. The analyzed region measures 10 × 10 microns.

The smaller region of 10 × 10 microns shown in Figure 6 maintains high resolution, making the gaps between individual magnetic stripes clear and well-defined. This improved resolution enabled further investigation of an even smaller region, as presented in Figure 7.

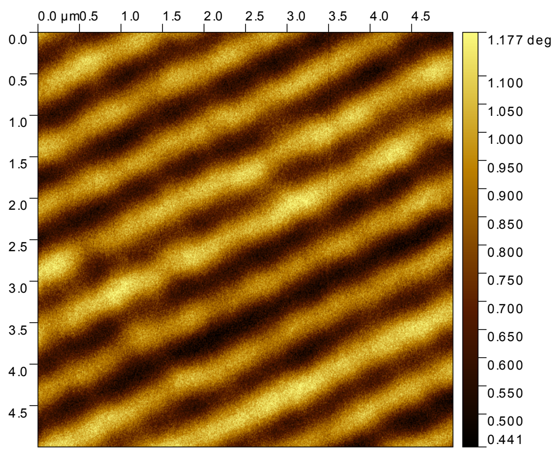

Figure 7: High-resolution image of the VHS sample obtained using the MFM 2-pass method. The analyzed region measures 5 x 5 microns.

The 5 × 5 microns region can be challenging to image for an inexperienced researcher. At this scale, the quality of the probe and its wear become critical factors in maintaining image sharpness and resolution. Despite these challenges, the obtained image is of relatively high resolution, providing insight into the relationship between the magnetic stripes. It is worth noting that the spacing and brightness of both the dark and bright stripes are inconsistent. This variability is an expected outcome, as these inconsistencies reflect the encoded data stored on the magnetic tape, which can be interpreted by a decoder.

Having imaged the same region at three different resolutions, the image from Figure 5 was used to perform measurements, as presented in Figure 8.

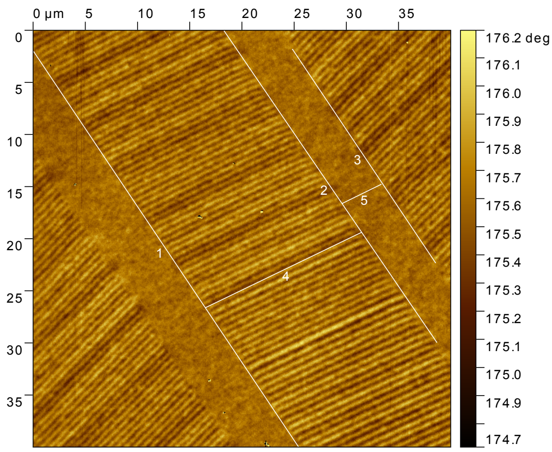

Figure 8: High-resolution image of the VHS sample obtained using the MFM 2-pass method with drawn markers.

The primary points of interest were the length of individual magnetic stripes (4), the width of a single path, and the distance between adjacent paths (5). Interestingly, the length of one stripe and the width of the path appeared to be visually coherent in the middle path. In contrast to the other paths, the magnetic stripes in the middle region appeared to be perfectly perpendicular to their length. This occurrence was entirely coincidental and should not be considered a general characteristic of VHS samples. It reflects the particular structure of the spontaneously selected region of the sample.

The results of the measurement from Figure 8 are presented in Table 1.

Table 1: Results of the measurement conducted on the image obtained using the MFM 2-Pass method on the VHS tape sample (Figure 8). Numbers 4 and 5 correspond to the respective markers. R represents the length of the marker, and Δz denotes the change in elevation.

4 - R [μm]	4 - Δz [nm]	5 - R [μm]	5 - Δz [nm]
16.59	-0.12	4.13	0.02

The analysis of the VHS sample was successful, resulting in three high-resolution images of different areas. Measurements conducted on one of these images produced reliable and sufficient results. This exercise familiarized the researcher with AFM operation and provided a deeper understanding of the 2-pass MFM method.

3.2 250 GB Hard Drive

Due to the very high resolution obtained during VHS imaging, caused by spontaneous probe behavior, the first analyzed hard drive had a memory capacity of 250 GB. However, the high domain density of this sample proved to be too challenging for an inexperienced operator. The obtained image contained only noise, suggesting that the sample might be defective or that the measurement conditions were too demanding.

3.3 4.3 GB Hard Drive

After the unsuccessful attempt to analyze the high-capacity hard drive, the focus shifted to the smaller drive with a memory capacity of 4.3 GB. To take advantage of the relatively new and well-performing probe, the larger of the two smallest drives was chosen. The resulting image is shown in Figure 9. Although the obtained image has relatively low resolution, it is still possible to distinguish the paths, magnetic domains, and even the spacing between the paths, though the latter appears somewhat blurry. Motivated to improve the imaging of magnetic domains, further imaging under a smaller field was conducted, with the results displayed in Figure 10.

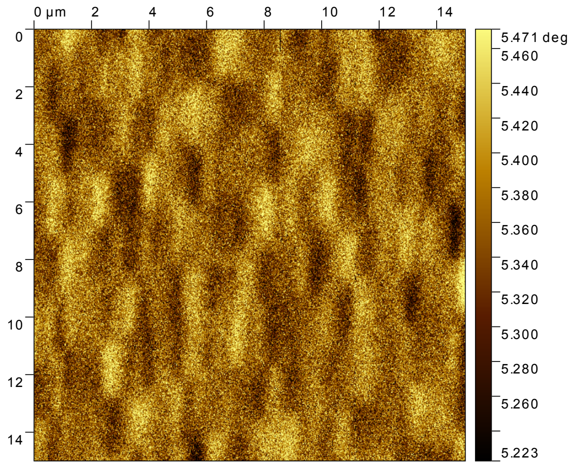

Figure 9: High-resolution image of the 4.3 GB HD sample obtained using the MFM 2-pass method. The analyzed region measures 15 × 15 microns.

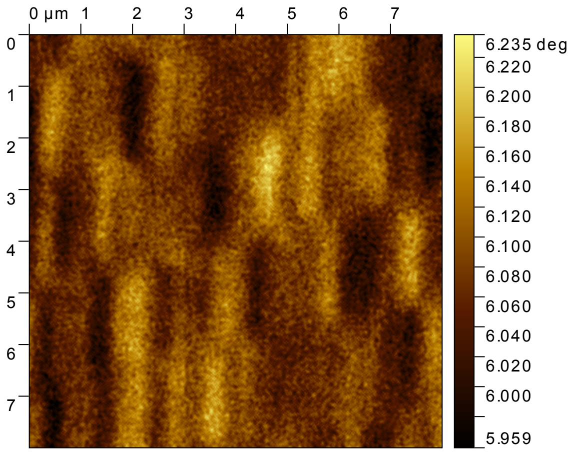

Figure 10: High-resolution image of the 4.3 GB HD sample obtained using the MFM 2-pass method. The analyzed region measures 8 x 8 microns.

The results, however, were not satisfactory. The image resolution remained low, and the gaps between the paths did not become more distinctive. While the contrast between the magnetic domains appeared to increase slightly, it was still insufficient for detailed analysis. After comparing the images of both larger and smaller fields, the larger field was chosen for further measurements as it provided more extractable information. After applying further filters and other methods of increasing the image quality, the markers were drawn and the measurement was taken, the image is shown in Figure 11.

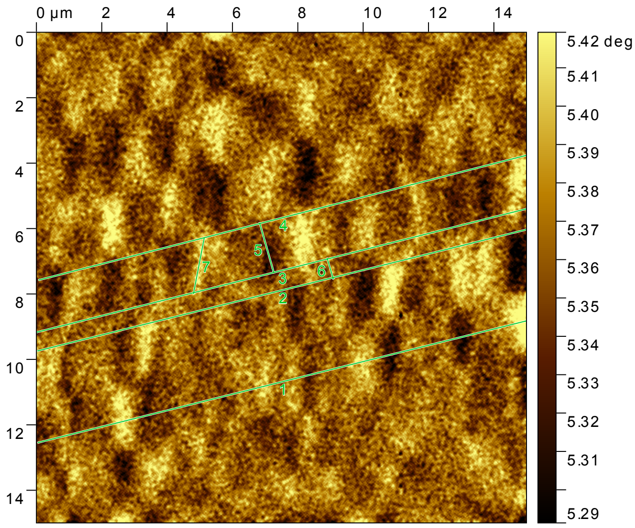

Figure 11: Image of the 4.3 GB HD sample obtained using the MFM 2-pass method with drawn markers.

The results of the measurements from Figure 11 are presented in Table 2. The first marker (1) represents the magnetic profile of a single path. The result of this analysis is shown in Figure 12.

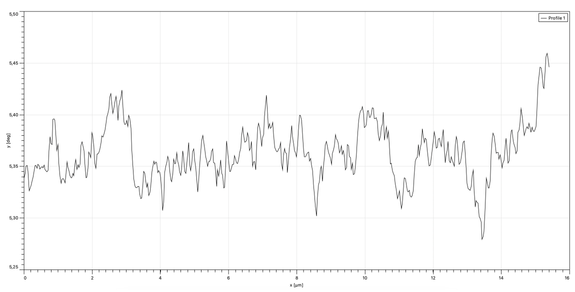

Figure 12: Magnetic profile of a single path from the 4.3 GB HD sample image obtained using the MFM 2-pass method. The profile corresponds to the first marker from Figure 11.

The profile shown in Figure 12 is highly noisy due to the low image resolution and the relatively large measurement range. As a result, the primary information that can be extracted from this profile is the position of the magnetic domains.

Table 2: Results of the measurement conducted on the image obtained using the MFM 2-Pass method on the 4.3 GB HD sample (Figure 11). Numbers 5, 6 and 7 correspond to the respective markers. R represents the length of the marker.

5 - R [μm]	6 - R [μm]	7 - R [μm]
1.58	0.64	1.73

Lengths 5, 6, and 7 from Table 2 correspond to the width of the path, the length of the gap between paths, and the length of the magnetic domains, respectively. The measurements align with the observed image, suggesting that the analysis was conducted successfully. While the 250 GB hard drive proved too challenging, the 4.3 GB sample was within the researcher's skill range and the capabilities of the experimental setup. This analysis enhanced the researcher's intuition and skills in calibrating the measurement parameters required for AFM imaging of hard drives.

3.4 1 GB Hard Drive

The analysis of the 1 GB hard drive, the smallest among the hard drive samples, was expected to be the easiest and to yield the best results. The lower capacity ensures the lowest domain density, making imaging conditions more straightforward. Analyzing this sample was intended to further enhance the understanding of working with an HD sample type, which could prove beneficial for more demanding measurements later. The resulting image is shown in Figure 13. The obtained image was of very high resolution. Even on a relatively large scale of 15 x 15 microns, the domains are clearly visible. There are many paths, and there is a clear distinction between them. After obtaining the high-resolution image, another measurement was conducted in a smaller field of 8 x 8 microns, the result of which is presented in Figure 14.

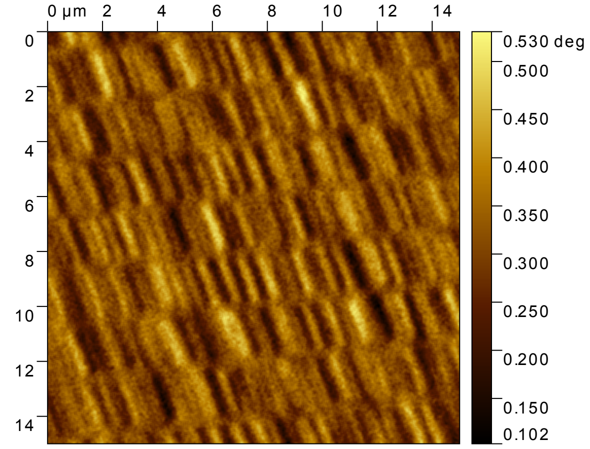

Figure 13: High-resolution image of the 1 GB HD sample obtained using the MFM 2-pass method. The analyzed region measures 15 × 15 microns.

In Figure 14, one can observe an improvement in the visibility of magnetic domains. The distinction between layers has become much clearer, particularly in terms of their beginnings and ends. Additionally, it is clearly visible how the dark and bright regions alternate within a single path to encode data.

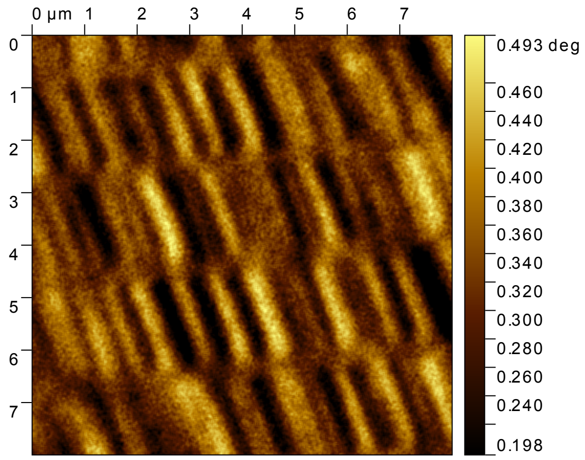

Figure 14: High-resolution image of the 1 GB HD sample obtained using the MFM 2-pass method. The analyzed region measures 8 x 8 microns.

Having obtained a high-resolution image, the measurement was conducted on a smaller field, as shown in Figure 14. The markers are displayed in Figure 15, and the obtained parameters are summarized in Table 3.

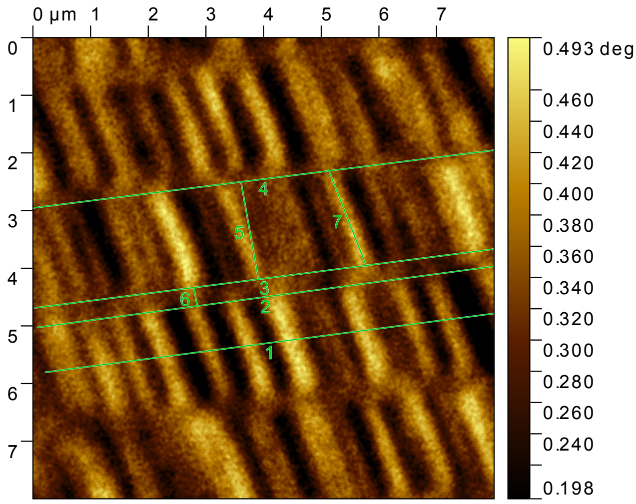

Figure 15: Image of the 1 GB HD sample obtained using the MFM 2-pass method with drawn markers.

The first marker (1) represents the magnetic profile of a single path. The result of this analysis is shown in Figure 16.

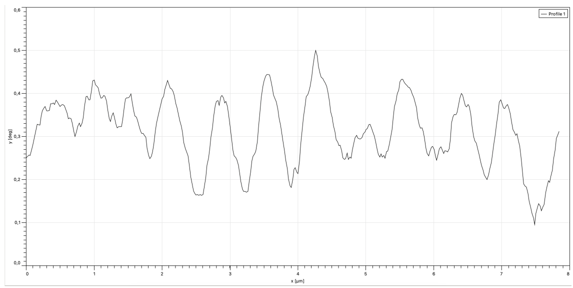

Figure 16: Magnetic profile of a single path from the 1 GB HD sample image obtained using the MFM 2-pass method. The profile corresponds to the first marker from Figure 15.

The profile shown in Figure 16 is noisy due to limitations in image resolution. However, the positions of the magnetic domains can still be reliably determined based on this profile.

Table 3: Results of the measurement conducted on the image obtained using the MFM 2-Pass method on the 1 GB HD sample (Figure 15). Numbers 5, 6 and 7 correspond to the respective markers. R represents the length of the marker.

5 - R [μm]	6 - R [μm]	7 - R [μm]
1.71	0.33	1.80

3.5 60 GB Hard Drive

The last analyzed sample was a 60 GB hard drive. This sample had a higher magnetic domain density, requiring greater familiarity with the 2-Pass MFM technique and the imaging of hard drives. The measurement was conducted, but despite numerous repetitive attempts, the image consistently defied expectations. After careful examination, it was determined that the distortion in the imaging was caused by artificial contamination on the surface of the hard drive sample. After changing the analyzed part of the sample, the first obtained image, covering a 30 x 30 micron region was obtained. It is shown in Figure 17.

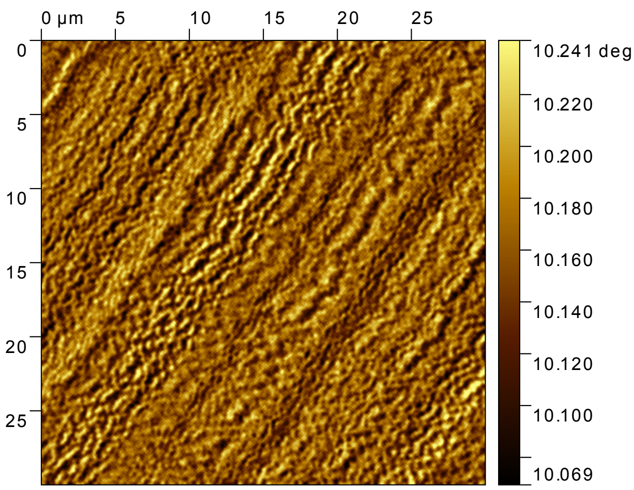

Figure 17: Image of the 60 GB HD sample obtained using the MFM 2-pass method. The analyzed region measures 30 × 30 microns.

It is unclear what exactly is being shown in Figure 17. While white and black stripes can be distinguished, it is not evident how they form paths. Additionally, no clear distinction between paths can be observed. There are also regions that are likely not used for coding data, such as the brown, valley-like path on the right side of the image. To better observe the magnetic domains, a further measurement was conducted, drastically reducing the analyzed field and focusing on the top-left corner. The result is presented in Figure 18. After shifting the focus to a smaller part of the

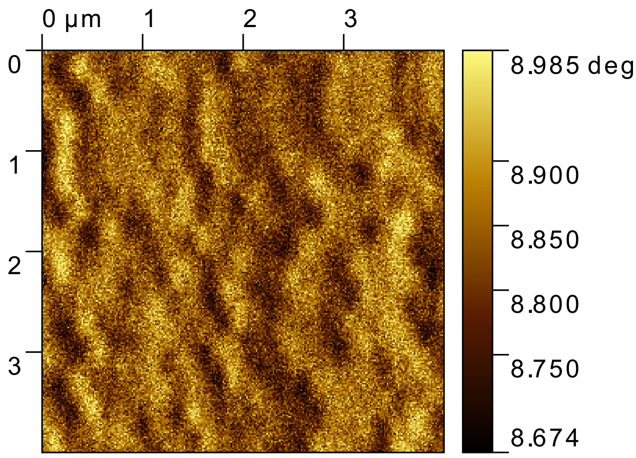

Figure 18: Image of the 60 GB HD sample obtained using the MFM 2-pass method. The analyzed region measures 4 x 4 microns.

image, the magnetic domains began to unravel. It became clear where the domains were located and how they could form a path; however, the spacing between the paths remained unclear. To uncover more information, another measurement was conducted using an even smaller region of just 2 x 2 microns in an attempt to observe the details of data encoding. The final image is presented in Figure 19.

The results obtained were not easy to decipher, but someone experienced with hard drive imaging using MFM could likely identify the individual magnetic domains and the paths they form. It is also possible to estimate where the gaps between the paths might be, though it is clear that these features are distorted by low resolution and high noise. The image from Figure 19 was selected for conducting a measurement. In the Figure 20.

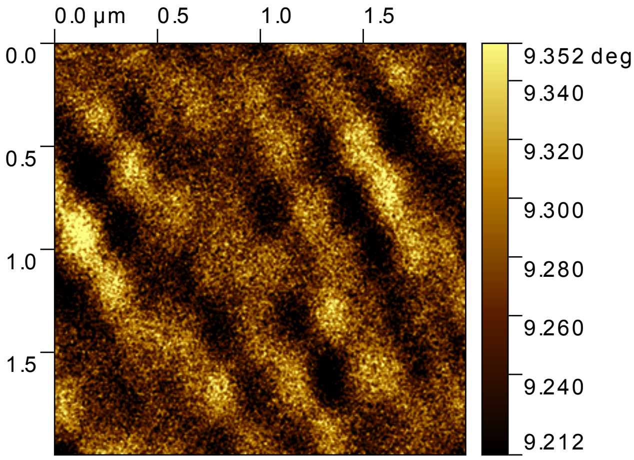

Figure 19: Image of the 60 GB HD sample obtained using the MFM 2-pass method. The analyzed region measures 2 x 2 microns.

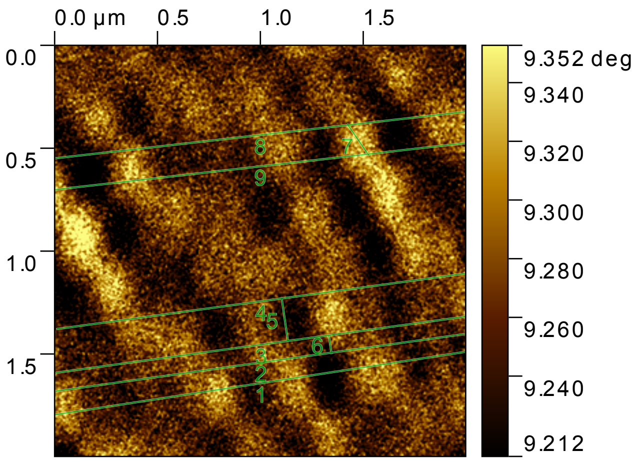

Figure 20: Image of the 60 GB HD sample obtained using the MFM 2-pass method with drawn markers.

The first marker (1) represents the magnetic profile of a single path. The result of this analysis is shown in Figure 21. The profile shown in Figure 21 is highly noisy due to the low image resolution. As a result, the primary information that can be extracted from this profile is the position of the magnetic domains. Markers 5, 6, and 7 were used to determine the width of the path, the distance between the paths, and the length of the domain, respectively. It is important to note that the drawn markers are estimates and provide only approximate values. The results are displayed in Table 4.

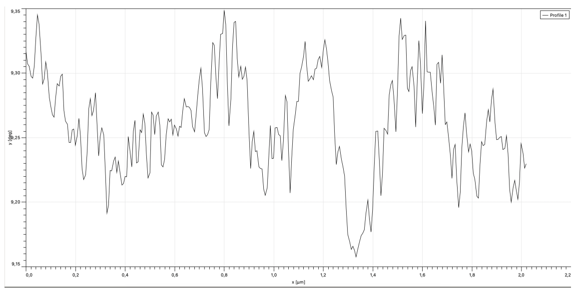

Figure 21: Magnetic profile of a single path from the 60 GB HD sample image obtained using the MFM 2-pass method. The profile corresponds to the first marker from Figure 15.

Table 4: Results of the measurement conducted on the image obtained using the MFM 2-Pass method on the 60 GB HD sample (Figure ??). Numbers 5, 6 and 7 correspond to the respective markers. R represents the length of the marker.

5 - R [μm]	6 - R [μm]	7 - R [μm]
0.21	0.088	0.18

The values obtained provide information about the scale of the analyzed objects. The analysis of the 60 GB hard drive was the most challenging measurement attempted in this study. Therefore, achieving satisfactory results that could lead to meaningful conclusions is a clear success and fulfills the objective of this study, which was to gain familiarity with AFM by analyzing analog and digital data containers using MFM methods. The researcher was able to grasp the experimental methodology and data analysis tools necessary to produce these results.

References

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