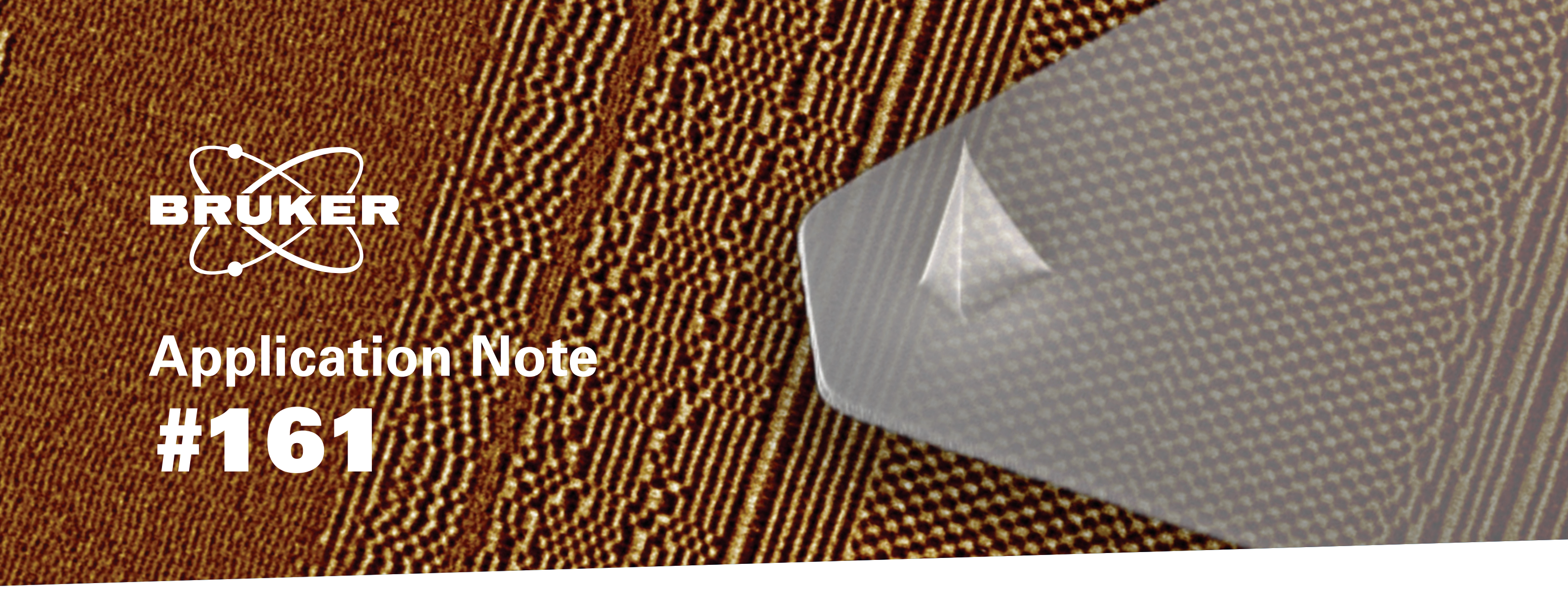

PeakForce Magnetic Force Microscopy

Magnetic force microscopy (MFM) is a high-sensitivity, high-spatial-resolution atomic force microscopy method for mapping magnetic field distribution on a surface. MFM has a wide range of applications in various fields, including materials science, magnetism, data storage, and even life science. This application note focuses on the benefits of replacing the initial TappingMode™ topographic scan in MFM with a PeakForce Tapping® scan.

MFM and PeakForce Tapping

In MFM, a magnetically coated atomic force microscope (AFM) probe tip interacts with the magnetic field gradients emanating from the sample, inducing a force on the tip that is detected by the probe's cantilever. To ensure that the measured force is primarily due to magnetic interactions, MFM is typically performed in a two-pass approach called LiftMode™, which was introduced by Bruker over 20 years ago.

A LiftMode process is shown schematically in Figure 1a. During the first pass, the AFM is traditionally operated in TappingMode to obtain a topographic image of the sample. In the second pass (lift scan), the tip is lifted to a constant height above the sample, and the magnetic force gradient is measured by observing the amplitude and phase of the cantilever, which is driven at or near one of its resonance frequencies. During this lift scan, van der Waals interactions are negligible and the probe experiences only long-range magnetic (and electrostatic) interactions, enabling the separation of topographic and magnetic contributions to the signal, as shown in Figure 1b and c.

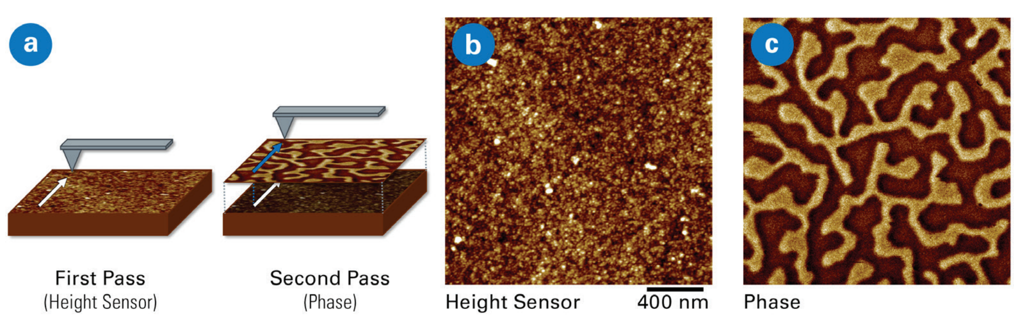

FIGURE 1.

(a) Schematic of LiftMode, showing first pass for height and second pass at lift height for magnetic data. (b) Height and (c) phase channels using PeakForce MFM on a perpendicular magnetization multilayer [Pt/Co/Pt]x25. Topography acquired during main scan and phase of the oscillating cantilever (representing magnetic domains) acquired during lift scan. Scan size 2x2 µm. Sample courtesy K. Bouzehouane, Université Paris-Saclay, Thales.

Bruker's PeakForce Tapping mode has replaced TappingMode in many topographic applications due to its direct force control and its capacity to operate at lower forces. These advantages result in a higher spatial resolution, the ability to image fragile samples, and extremely long tip lifetime/repeatability. In addition, PeakForce Tapping enables the simultaneous acquisition of quantitative mechanical property data for adhesion, modulus, deformation, and dissipation.

Another benefit of PeakForce Tapping is the availability of Bruker's ScanAsyst® routines, which automatically optimize critical feedback parameters, such as feedback gain and force setpoint, providing maximum ease of use and the same high performance independent of AFM operator experience level.[1] ScanAsyst was used for all images presented in this application note.

Combining PeakForce Tapping with MFM also allows for the correlation of magnetic and mechanical property measurements, as shown in Figure 2 on a 20 TB hard disk drive (HDD). Some ferrofluid drops were added onto the disk, resulting in a strong difference in adhesion and magnetic field. The 1x1 µm images shown illustrate high spatial resolution, resolving domains <30 nm.

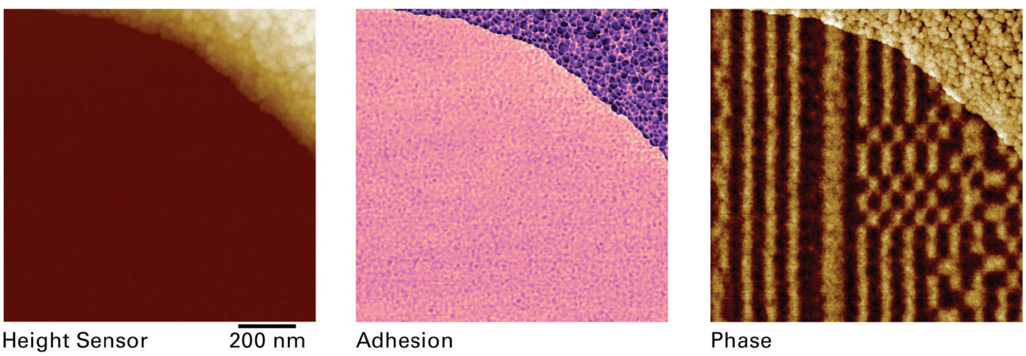

FIGURE 2.

20 TB HDD intentionally covered with some ferrofluidic drops in the top right corner. Topography and adhesion acquired during the main scan, and phase of the oscillating cantilever (representing the magnetic domains) acquired during the LiftMode scan. Scan size: 1x1 µm, lift height: 8 nm, oscillation amplitude: 10 nm. Sample courtesy S. Montoya, University of California San Diego.

Similar benefits to those above are conveyed when combining PeakForce Tapping with Kelvin probe force microscopy (KPFM) and electric field microscopy (EFM), as well. Bruker's suite of PeakForce KPFM™ modes in particular is well-established and has been used routinely for several years.[2]

Probe Optimization for PeakForce MFM

A broad range of cantilevers are compatible with PeakForce Tapping mode, since its operation does not depend on resonance behavior of the cantilever. Probes play an essential role in shaping the quality of MFM measurements, making the probe flexibility provided by PeakForce Tapping a critical advantage for MFM.

MFM measurements rely on detecting the phase or frequency shifts of an oscillating cantilever while scanning the sample surface at a fixed tip-sample (lift) height. Resulting sensitivity to phase or frequency variations scales directly with the cantilever's quality factor and detection frequency, and inversely with the spring constant.[3] It follows that lowering the cantilever's spring constant and/or increasing its quality factor and resonance frequency are key to enhancing measurement sensitivity.

The design strategy of our novel PeakForce MFM probes (shown in Figure 3) was to focus on reducing spring constant, promoting their use at generally low force regimes in PeakForce Tapping mode. To achieve this low spring constant, the cantilever thickness and width were reduced, and a paddle shape was adopted to support conventional laser spot sizes. Implementing these size and shape changes led to improvements in MFM sensitivity—a three-fold increase in phase sensitivity and a twelve-fold increase in frequency sensitivity. This increased sensitivity allows operation at lower oscillation amplitudes and smaller lift heights, leading to higher spatial resolution and higher throughput.

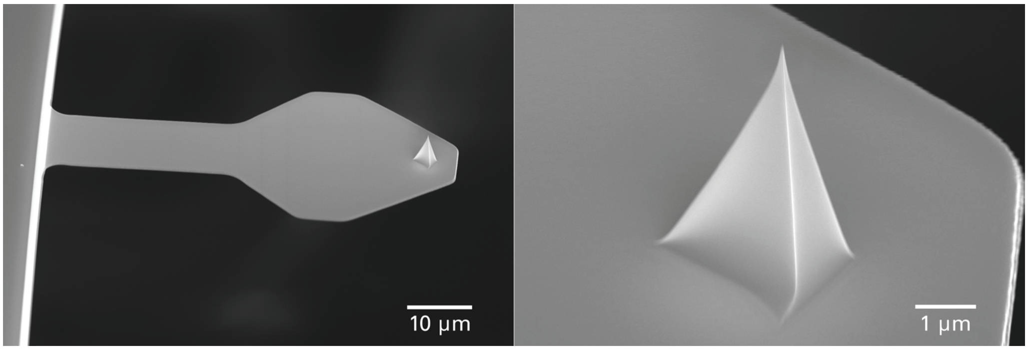

FIGURE 3.

PFMFM-LM probe with nominal spring constant of 0.4 N/m, and resonance frequency of 130 kHz. Cantilever has a length of 60 µm and has a paddle-shaped profile.

Increases in sensitivity from probe geometry changes also enabled the use of a thinner magnetic coating with a lower moment (coercivity <400 Oe and moment 0.3x10-13 emu). In general, lower-moment coatings result in lower signals, thus requiring higher sensitivity to maintain acceptable signal-to-noise ratios. Thinner coatings lead to higher spatial resolution and less tip-induced magnetization changes. A new, optimized process was also used to minimize stress-induced cantilever bending from the low-moment magnetic coating.

Figure 4 illustrates the obtained sensitivity and spatial resolution on Pt/Co/Pt multilayer samples. Comparisons to MFM imaging using conventional probes at equivalent settings (e.g., MESP-LM-V2) confirmed the superior performance of the PeakForce MFM mode and probes.

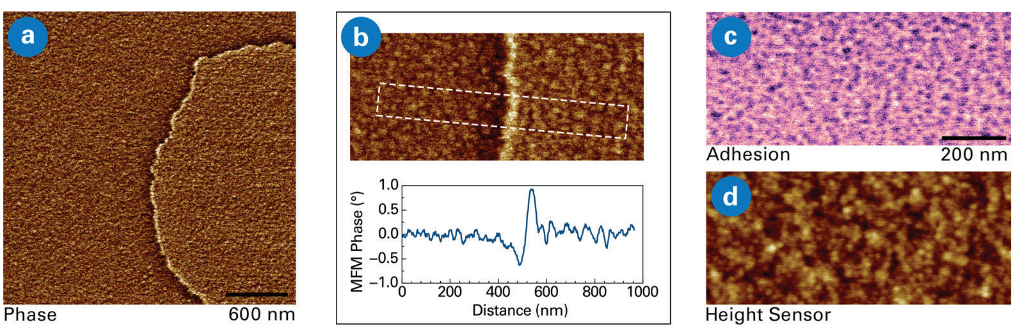

FIGURE 4.

Perpendicular magnetization multilayer [Pt/Co/Pt]x5 domain walls. (a) MFM phase image (scan size 3x3 µm) and (b) phase data across the interface shows high sensitivity and spatial resolution. (c) Adhesion image co-localized with phase and (d) height images showcases the powerful capability of PeakForce MFM to additionally analyze mechanical properties. Sample courtesy K. Bouzehouane, Université Paris-Saclay, Thales.

MFM Combined with Torsional Resonance

In conventional MFM and PeakForce MFM, the cantilever is oscillated vertically. This oscillation can be replaced by an (essentially) horizontal one, creating a torsional mode[4] called TR-MFM. In TR-MFM, the tip selectively detects the field that has a force gradient parallel to the tip. These in-plane force gradient components can be measured with the same resolution and signal-to-noise ratio as flexural modes at the same location. Studies evaluating the use of TR-MFM for imaging magnetic structures have shown its ability to obtain magnetic contrast free from topographic influence and a 15% lateral resolution improvement over standard MFM, an improvement that is directly related to the extremely small tip-sample separation.

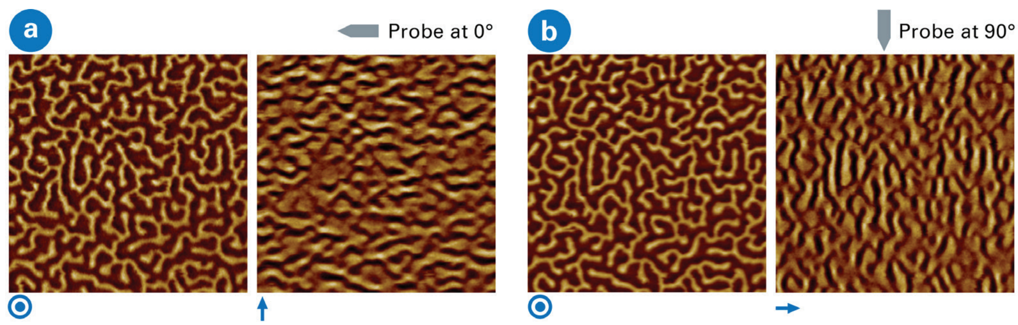

FIGURE 5.

PeakForce MFM with vertical (left in image pairs) and lateral (right in image pairs) magnetic domain imaging. A torsional resonance was applied during the lift scan to acquire the lateral field images. In (a), the probe was oriented at 0°. Upon rotating the sample 90°, the vertical field remains the same, but the lateral field rotates. Tip oscillation direction is indicated beneath each image. Scan size 3.8x3.8 µm. Sample: perpendicular magnetization multilayer [Pt/Co/Pt]x25, courtesy K. Bouzehouane, Université Paris-Saclay, Thales.

Obtaining both components of the force gradient provides a new dimension of information, leading to a better understanding of the force and its gradient source. Figure 5 shows an example where both the vertical and lateral magnetic fields are measured in PeakForce MFM (same samples as Figure 1). The lateral magnetic field images at 0° and 90°, obtained through torsional resonance measurements, show a directional influence that is not present in the vertical magnetic field. This approach provides insight into the magnetic field in all three dimensions.

PeakForce Tapping Enhances Magnetic Force Microscopy

The integration of PeakForce Tapping with MFM represents a significant advancement in the field of high-resolution magnetic imaging. By replacing the traditional TappingMode with PeakForce Tapping on the first pass, researchers can achieve superior spatial resolution, enhanced sensitivity, and the ability to image delicate samples with greater precision. The novel PeakForce MFM probes (PFMFM-LM), designed with reduced spring constants and optimized magnetic coatings, further enhance measurement sensitivity and spatial resolution. Additionally, the combination of PeakForce Tapping MFM with torsional resonance techniques provides a comprehensive three-dimensional understanding of magnetic fields. These innovations collectively offer a powerful toolset for exploring magnetic properties at the nanoscale.

Authors

Peter De Wolf, Ph.D., Senior Director of Technology and Application Development, Bruker
(peter.dewolf@bruker.com)

Bede Pittenger, Ph.D., Senior Staff Applications Scientist, Bruker
(bede.pittenger@bruker.com)

Shuiqing Hu, Ph.D., Senior Staff System Design Engineer, Bruker
(shuiqing.hu@bruker.com)

Rakesh Poddar, Development Engineer, Bruker
(rakesh.poddar@bruker.com)

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Bruker Nano Surfaces and Metrology

Santa Barbara, CA • USA

Phone: 1.805.967.1400 / 800.873.9750
productinfo@bruker.com

www.bruker.com/PF-MFM