

Magnetic Force Microscopy Under Applied Perpendicular Fields with Asylum Research AFMs

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Abstract

Understanding and engineering magnetic properties at the nanoscale is one of the key challenges in developing next-generation data storage and logic elements. The Variable Field Module (VFM3) accessory for Asylum Research MFP-3D AFMs allows us to directly observe magnetic configurations at the nanoscale using magnetic force microscopy (MFM) while the sample is under either in-plane or out-of-plane applied magnetic fields.

Data storage and logic computing are ultimately based on the interplay between electrical and magnetic properties. Direct high-resolution observation of the magnetic state of thin films or patterned nano-elements and their behavior while under applied magnetic fields helps develop the deep understanding required to engineer these properties. For this task, magnetic force microscopy is the tool of choice.

Practically, a silicon tip covered by a magnetic film is used in tapping mode. After the topography of each line is measured, the same line is scanned again while lifting the tip by a constant offset (typically tens of nm) above the measured topography to measure long-range forces acting on the tip. Because the distance to the surface is constant, only electrostatic and magnetic forces will vary across the surface and will affect the oscillation of the cantilever.

By ensuring that the sample is well grounded, electrostatic effects can be excluded, leaving only magnetic forces. This magnetic force originates from the interaction of the magnetic moment of the tip and the stray magnetic field originating from the sample (Figure 1). Depending on the orientation of the fields, the force can be either attractive or repulsive. The force is probed through the shift of the phase of the cantilever oscillation, where the sign indicates whether the force is net repulsive or attractive and the magnitude measures the strength. More quantitatively, this force is expressed by $\vec{F} = \mu_0 \vec{\nabla} (\vec{m} \cdot \vec{H})$, where \vec{m} is the tip magnetic moment and \vec{H} is the stray magnetic field.¹

In this application note we present two examples that demonstrate how MFM using the Asylum Research MFP-3D Infinity AFM with the VFM3 module is helping us develop next generation materials.

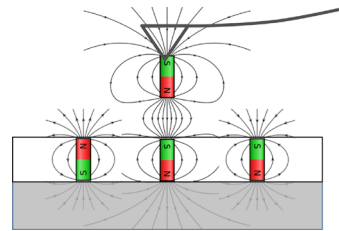


Figure 1. Schematic of the magnetic interactions between the magnetic AFM tip and a sample with magnetic domains.

Example 1

Systematic study of films exhibiting perpendicular magnetic anisotropy

The sputtered Co/Ni thin film described here exhibits perpendicular magnetic anisotropy (PMA), which means simply that its magnetic domains are aligned perpendicular to the plane of the film. This is a technologically useful property as it allows, for instance, the reduction of bit size in hard drives² and a reduction in power consumption for next generation STT-RAM.³ MFM can be used to study the evolution of magnetic domain structure in thin films exhibiting PMA as a function of applied field. However, until now, the ability to apply perpendicular fields to samples during MFM was only available to researchers who custom-built this instrumentation. Now, using the VFM3 module on the MFP-3D Infinity AFM, we are able to easily make these measurements while applying out-of-plane fields up to $\sim \pm 1500$ Gauss. An example is shown in Figure 2, which shows a Co/Ni thin film sample imaged using MFM under an applied perpendicular magnetic field (~ 210 G). The color represents the MFM phase data, revealing the magnetic texture of the sample, while the 3D surface shows the very smooth topography of the film. Here, the observed contrast is due to the presence of magnetic domain walls separating ferromagnetic domains.

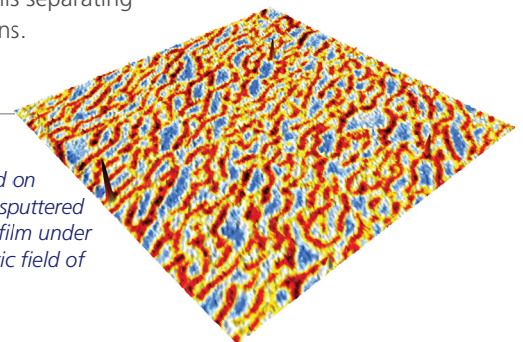


Figure 2.

MFM phase data painted on the 3D topography of a sputtered cobalt/nickel multilayer film under a perpendicular magnetic field of ~ 210 G, $10 \mu\text{m}$ scan.

Up to now, these experiments were a long and laborious task. The field had to be manually adjusted after each series of images. Complicating matters, the custom-built magnet systems capable of applying out-of-plane fields during MFM were based on electromagnets. These generated significant heat during operation and therefore high drift in the AFM measurements, which required constant intervention to compensate. The VFM3 offers two significant benefits that make these measurements much simpler and faster. First, the VFM3 uses permanent magnets to apply the field to the AFM sample.⁴ This eliminates the Joule heating inevitable with electromagnets and makes the instrument far more stable. Second, the VFM3 field strength can be directly controlled by the Asylum Research MacroBuilder software. This simple graphical-based tool allows the creation of macros that automate repetitive AFM measurements.

Used together, we were able to automatically record hundreds of MFM images while varying the applied magnetic field. The MacroBuilder script is composed of one simple loop in which the magnetic field is first incremented while the tip is not in contact with the surface (Figure 3). Then the tip is engaged and the MFM Amplitude and Phase images are recorded. For this study, 190 images were acquired in 5 hours with the field strength being incremented by 5 G between each image. A subset of these are shown in Figure 4, which provide direct information about the magnetic domain evolution when the applied field is swept from negative magnetic saturation to positive magnetic saturation.

Analysis of this huge number of images also presents a challenge. Fortunately, MacroBuilder can also automate offline analysis functions. Here, an automatic post processing script calculated the 2D Fourier transform of each image (Figure 4). These clearly show the appearance of a structured domain pattern that appears before zeroing the magnetic field. The Fourier transform images also provide details about the development of a periodic and anisotropic domain structure as well as its period evolution. Moreover, the images were also automatically binarized using thresholding and masking to allow analysis of the evolution of both the area and the perimeter of the magnetic domains versus magnetic field. The area and the perimeter of the magnetic domains are plotted in Figure 5 for each of the 190 different magnetic field strengths. We see a clear difference in the evolution of these parameters.

This new tool from Asylum Research will enable more systematic studies of the evolution of magnetic domains in thin films under applied fields. The significant ease of use and productivity improvements that it delivers will allow us to spend less time taking data and devote more time to uncovering and understanding the fascinating physics at play in these magnetic materials.

Figure 3. MacroBuilder scripts are simply created using drag-and-drop modules. Here, a single loop was set to repeat 190 times, collecting MFM images after incrementing the field strength by 5 G at each step.

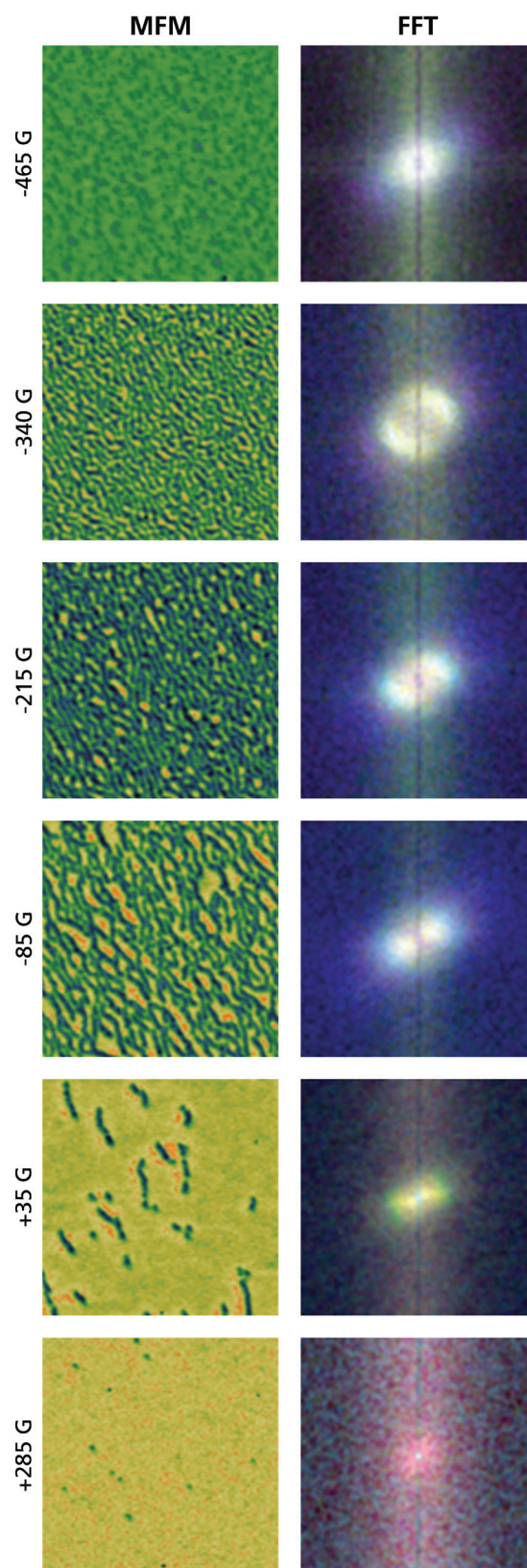


Figure 4. Representative MFM images and corresponding two-dimensional FFTs of the Co/Ni film at different perpendicular field strengths.

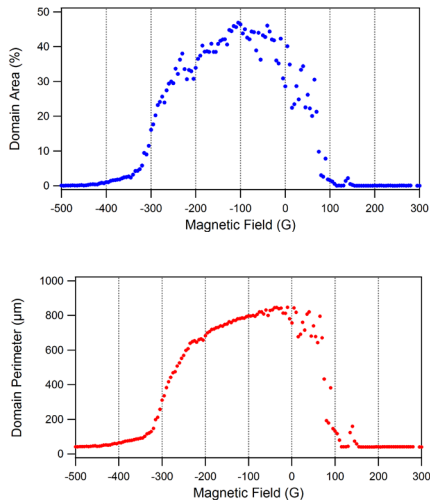


Figure 5. Built-in masking functions were used to automatically binarize each of the 190 MFM images and then calculate the corresponding area fraction occupied by the domains and their total domain perimeter. The graphs clearly show that the domain area (top) peaks near -100 G, while the perimeter length (bottom) reaches its maximum near 0 G. This information can be used to better quantify the shape evolution of the domains.

Example 2

Direct observation of magnetic skyrmions with AFM

Addressing the ever-growing demand for data storage will most probably require a new technical paradigm. Nanoscale magnetic skyrmions are one widely anticipated solution to this issue. They are arguably the smallest spin textures in magnetic thin films to appear in nature.⁵ They can be localized within a diameter of a few nanometers and can move like quasi-particles.⁶ These magnetic solitons, remarkably robust against perturbation due to the topology of their magnetic texture,⁷ are promising candidates to be the ultimate magnetic bits to carry and store information.⁶ We designed cobalt-based asymmetric multilayered thin films where the cobalt layer is sandwiched between two heavy metals, providing the additive chiral interfacial interaction necessary to induce these peculiar magnetic domains. This interaction, named Dzyaloshinskii-Moriya interaction, tends to tilt neighboring spins in a given direction and gives rise to the stabilization of the chiral circular domains that are nanoscale magnetic skyrmions (Figure 6). Skyrmions are different in nature from magnetic bubbles, which are stabilized by dipolar interactions and typically exist with diameters in the range of a few hundred of nanometers, and thus can be easily imaged by magnetic optical techniques (Kerr microscopy). Instead, skyrmions requires higher resolution nanoscale imaging tools.

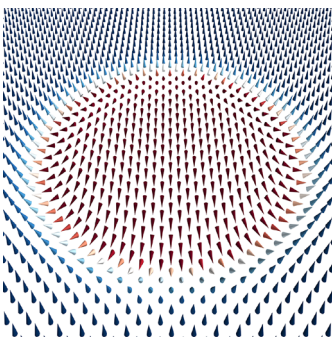


Figure 6. Schematic drawing of a skyrmion in a 2D ferromagnet with uniaxial magnetic anisotropy along the vertical axis. The magnetization is pointing up along the edges and pointing down in the center.

One such imaging tool is magnetization-sensitive scanning x-ray transmission microscopy (STXM), which offers resolution of about 30 nm and with which we first imaged magnetic domains in these multilayers. The study of their behavior in perpendicular magnetic applied fields allowed us to demonstrate that the nanoscale circular domains are actually magnetic skyrmions stabilized by a large Dzyaloshinskii-Moriya interaction.⁸ This discovery of stable sub-100 nm individual skyrmions at room temperature in a technologically relevant material opens the way for device applications in the near future.⁶ Nevertheless, STXM requires a synchrotron facility, which inherently limits the available time for these studies.

The recently developed VFM3 module from Asylum Research offers a promising alternative to these STXM experiments. Nowadays, thanks to the sensitivity of MFM measurements on the MFP-3D Infinity AFM, the ability to apply adjustable out-of-plane magnetic fields with the VFM3, and the automation capability of this system, we can now routinely and rapidly reproduce most of these STXM observations in our own lab on different multilayer systems (Figure 7) while circumventing the restricted beam time available at synchrotron facilities.

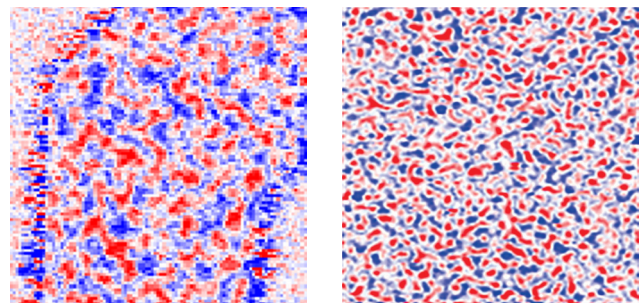


Figure 7. Comparison of STXM (left) and MFM (right) images of out-of-plane magnetization in a Ir/Co/Pt multilayer film under an applied perpendicular field of 80 G. Scan size 5 μm. MFM images easily reproduce the same qualitative domain structure at higher resolution.

One step toward the manipulation of these skyrmions in an information device is to study their behavior in nanostructures. We have started this study on pads defined by e-beam lithography (diameters from 400 nm to 1 μm). Figure 8 shows the first results obtained on those structures. STXM images are shown for comparison with MFM images. It can be readily seen that the diameter of the pads radically changes the magnetic domain behavior under perpendicular magnetic fields, as anticipated by micro-magnetic simulations. The geometrical confinement combined with a perpendicular magnetic field allows us to stabilize single skyrmions in appropriate structures.

Our room temperature observation by MFM of individual sub-100 nm skyrmions in magnetic multilayers and patterned nano-structures represents an experimental advance that will be fundamental for the development of skyrmion-based devices for memory and/or logic applications.

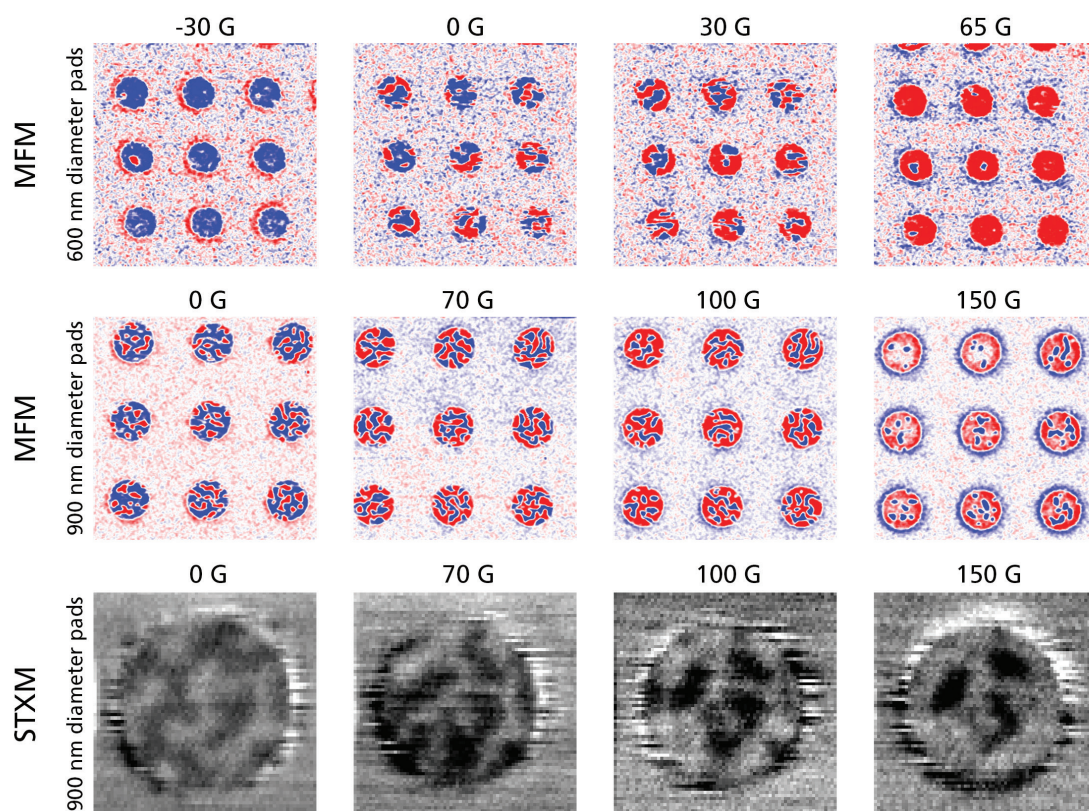


Figure 8. MFM imaging reveals domain behavior as a function of pad diameter and applied perpendicular magnetic field.

Each MFM image of nine pads (top and middle rows) was acquired in about 20 minutes each, compared to 60-90 minutes each for the STXM images at single pads, effectively increasing data throughput by 30-50X.

These examples perfectly illustrate how using MFM on the MFP-3D Infinity in combination with the VFM3 module readily enables nanoscale imaging of magnetic domains under applied magnetic fields and with a resolution otherwise only achievable in a synchrotron facility. Eliminating the time constraints imposed by working at a synchrotron should accelerate advances in this field. Additionally, the whole process from imaging to data processing can be fully automated to further increase productivity.

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