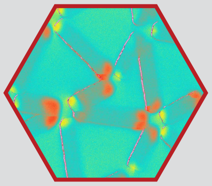
Magnetic Imaging with FusionScope®

Leverage FusionScope's high-vacuum environment and precision tip placement to perform complementary SEM, AFM, and MFM analysis of magnetic micro- and nanostructures.



The ability to visualize magnetic domains at the nanoscale is not only of paramount importance to understand the underlying physics of novel material systems, but is also critical for industrial applications, notably magnetic recording. Advances in hard disc drives (HDDs) continue to propel bit densities higher and higher. Additionally, magnetoresistive random access memory (MRAM) remains an attractive solution that has the potential to become a truly universal memory that combines non-volatility, high storage density, with speed and power efficiency. While still in its infancy, racetrack (also known as domain wall memory) functionalizes the motion of domain walls that move along tracks that can be arranged in a 3D array, thus dramatically increasing the storage density. An extension of racetrack memory uses topologically protected magnetic solitons, skyrmions, as the storage elements, which could also provide gains in storage density and energy efficiency. Looking even further in the future, reconfigurable magnonic crystals, and the closely related artificial spin ice arrays, can be leveraged for novel neuromorphic computing schemes. For all these topics Magnetic Force Microscopy (MFM) can play an important role, because it provides high-resolution imaging of magnetic domains and structures at the nanoscale.

This Application Note briefly introduces MFM. It then highlights the unique capabilities offered by FusionScope, including the ability to:

- Perform MFM with Scanning Electron Microscopy (SEM)
- Work in vacuum
- Work with sharp, high-aspect-ratio tips created with focused electron beam-induced deposition (FEBID).

Finally, a couple of example measurements, highlighting the unique capabilities of FusionScope, will be discussed.

Principle of MFM

A two-step process is utilized for MFM imaging. First, the topography of the sample is measured, often in amplitude modulation mode. In the second step, the same line is traced at a fixed distance above the surface – known as the lift height – and the phase shift and amplitude are recorded.

Owing to the increased distance from the surface during the second scanning step, the cantilever tip experiences no interaction with short-range van der Waals forces from the surface. Instead, it only interacts with long-range magnetic forces that remain detectable at this distance. If the cantilever is equipped with a permanent magnetic tip, these magnetic interactions can be mapped using this method (Figure 1). It is important to remember when it comes to interpreting MFM images that the forces are proportional to field gradients, so contrast (which is often most visible in the resulting cantilever phase) will be strongest in those regions.

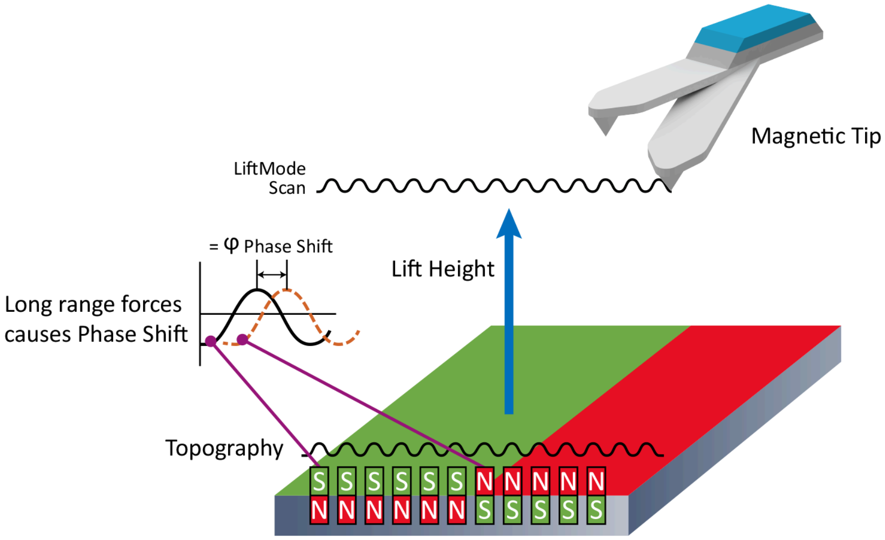


***Figure 1:** Schematic of magnetic force microscopy (MFM) using Lift Mode scan.*

MFM with FusionScope

Performing MFM with FusionScope utilizes two techniques that improve image quality (see Figure 2 and Figure 3). As a high-vacuum environment is strictly necessary for scanning electron microscopy (SEM), MFM must also be performed in vacuum when using the FusionScope. Furthermore, to maximize compactness and ease-of-use, FusionScope utilizes electrical readout via easy-to-use piezoresistive self-sensing cantilevers. The use of sharp, high-aspect-ratio FEBID tips also provides additional gains in image quality.

Vacuum vs. Ambient Pressure: Improved Phase Contrast

Environmental conditions – for example, vacuum versus ambient pressure – can significantly impact the MFM signal quality. Figure 2 shows MFM scans of a [Co/Pt] multilayer test sample measured under vacuum (Figure 2a), and at ambient conditions (Figure 2). The perpendicular magnetic anisotropy of the [Co/Pt] multilayer sample results in *labyrinth* (also referred to as *fingerprint*) magnetic domains which predominantly point up or down relative to the film normal. This test sample therefore provides a useful metric for measuring lift phase resolution. The distributions of the measured phase under vacuum (Figure 2b) and at ambient pressure (Figure 2d) where the distance between the two peaks provides a measure of the phase contrast. Under ambient conditions, the observed phase shift contrast is 0.19°. However, under vacuum this increases to 0.28°, a nearly 50% increase.

This result confirms the present literature on the topic, which predicts that the phase shift is inversely proportional to the damping factor (also observable as an increase in Q-factor), being much smaller in vacuum than in ambient conditions.

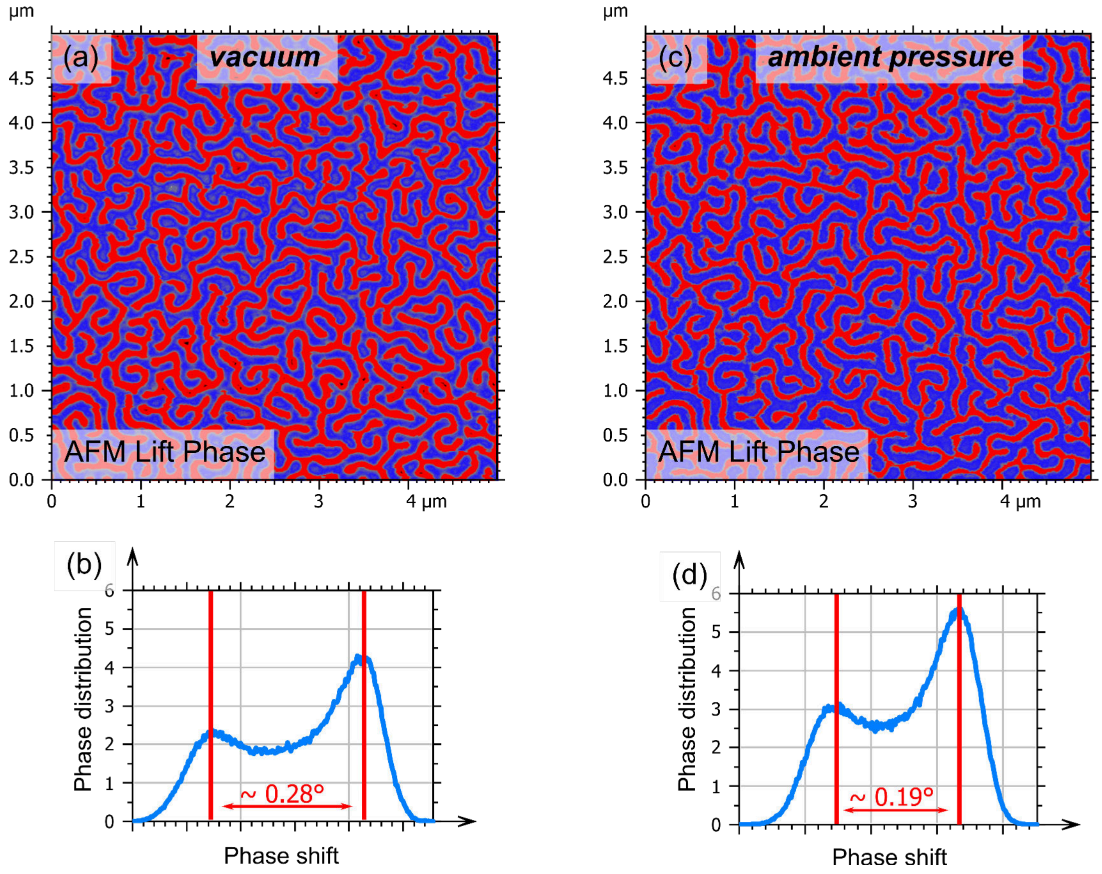


Figure 2: *The magnetic interaction between MFM tip and [CoPt] multilayer sample depending on the surrounding medium is shown. In* ***(a)****, the AFM lift phase (recorded in vacuum) is shown.* ***(b)*** *The corresponding phase distribution. The MFM data recorded under ambient pressure and the corresponding phase distribution are shown in* ***(c)*** *and* ***(d)****.*

Self-Sensing FEBID-Fabricated Magnetic Tips

The MFM image quality (that is, phase contrast and lateral resolution) depends most strongly on the quality of the tip. FusionScope utilizes advanced 3D nanoprinting techniques, specifically FEBID, to fabricate sharp, high-aspect-ratio magnetic tips. These tips, with a radius of approximately 10 nm, are printed on standard silicon or tipless cantilevers, allowing for high-resolution MFM imaging (Figure 3). The magnetic material used for these tips includes Fe- and Co_3Fe-based materials.

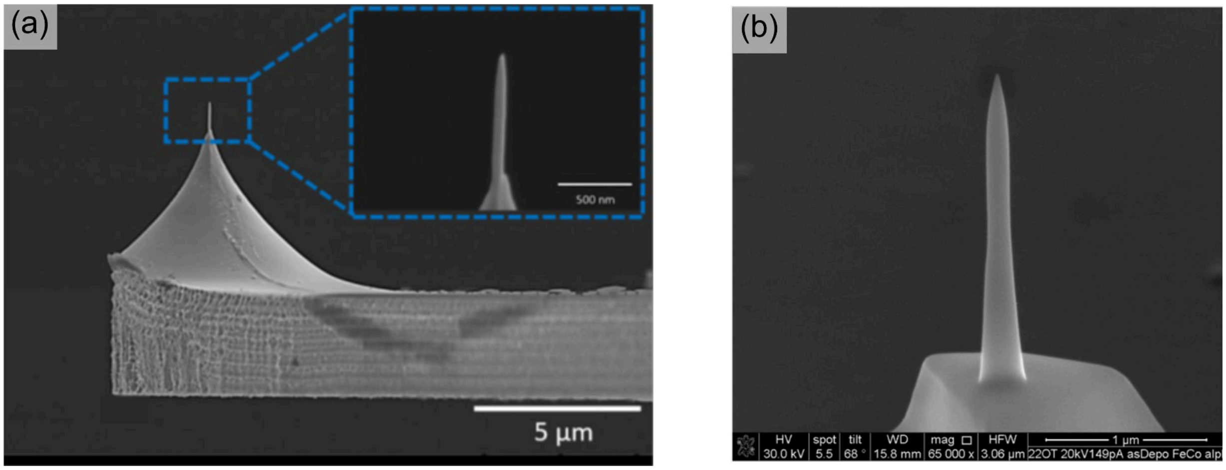


Figure 3: ***(a)*** *Magnetic Fe-based tip fabricated via 3D nanoprinting using FEBID for high resolution MFM imaging.* ***(b)*** *Zoom-in of Co_3Fe-based magnetic tip fabricated via FEBID.*

For comparative studies highlighting the benefits of such FEBID-printed tips compared to more conventional coated tips see **[1]** and **[2]**.

Correlative MFM with FusionScope

The ability to use SEM imaging in conjunction with an up to 80-degree tilt angle of the joined sample platform and MFM scan head assembly, what we refer to as Profile View, allows the experimenter to precisely position the MFM tip at the region of interest. This is particularly useful for lithographically defined samples where the lateral extent of a given feature may be below the resolution limits of a conventional optical microscope.

$Ni_{81}Fe_{19}$ Nanorods

Arrays of permalloy ($Ni_{81}Fe_{19}$) nanorods, fabricated by standard electron beam lithography and liftoff techniques **[3]**, provide a convenient playground to study magnetic interactions and frustration at the nanoscale. Three distinct nanorod arrays with varying degrees of interconnectivity were examined. These different structures were readily identified using a combined coordinate system alongside SEM imaging. The first row of Figure 4 illustrates the correlation between SEM and AFM topography, while the use of Profile View, displayed in the second row of Figure 4, allows for the precise selection of individual nanorods.

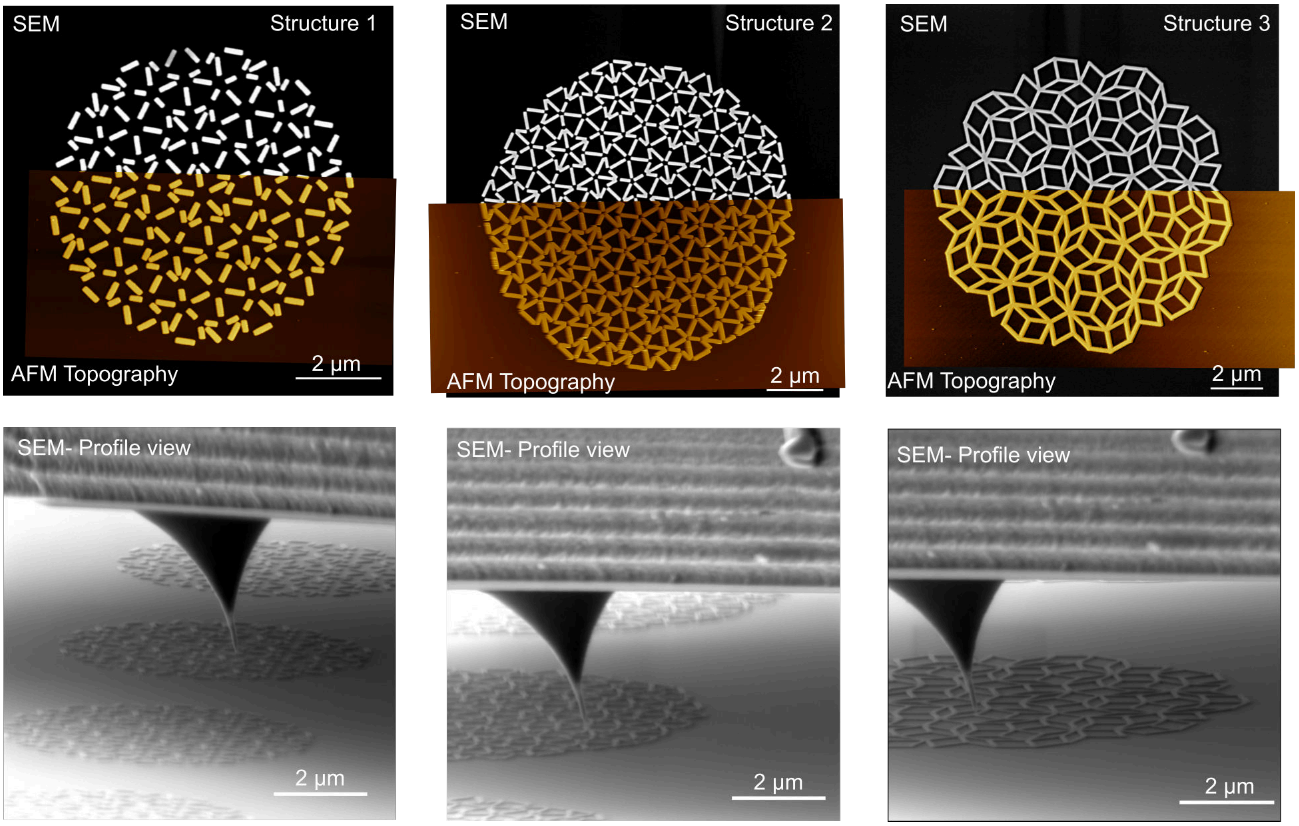


Figure 4: *Three different structures of $Ni_{81}Fe_{19}$ nanorods are shown:* ***Structure 1****: disconnected nanorods;* ***Structure 2****: almost interconnected nanorods;* ***Structure 3****: interconnected nanorods. In the first row the correlation between SEM and AFM topography of the three structures is displayed. In the lower row, the SEM Profile View of the FEBID tip engaged on the nanorod structures is shown.*

To investigate the magnetic properties of the nanorods, high-resolution MFM measurements were carried out using a small region of interest. The topography of the individual structures is shown in the first row of Figure 5, with the corresponding lift phase presented in the corresponding column of the second row. All structures display a change in the magnetic signal at the vertices of the nanorods, where the stray field gradients are largest, as expected.

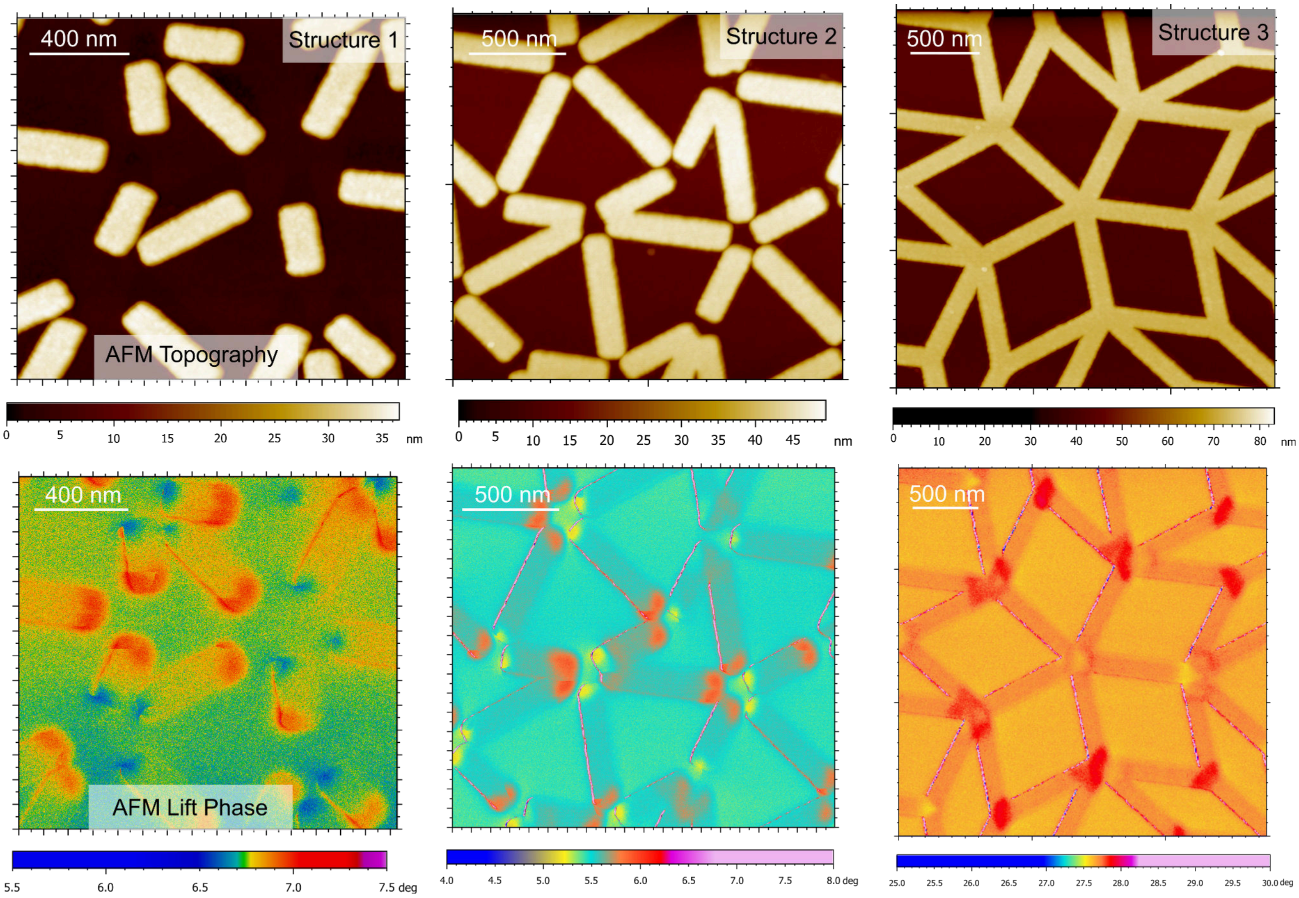


Figure 5: *In the first row, a high-resolution AFM topography of the three different structures is displayed. The corresponding lift phase signal is shown in the second row, which indicates the magnetic signal. The signal intensity differs most strongly at each of the vertices where the stray field gradients are largest.*

FIB-Patterned Cobalt Film

In the final example, the magnetic structure of a focused ion beam (FIB)-patterned cobalt layer is examined **[4]**. As with the prior example, the lithographically defined regions are relatively small, and the SEM guided Profile View enabled by FusionScope allows for precise placement of the MFM tip (Figure 6d). Upon patterning, a clear cross-shaped domain pattern is visible in the lift phase (Figure 6b) and the 3D representation of the topography (Figure 6a) with overlaid lift phase (Figure 6, central image) which is not apparent in the nearby continuous film. This is expected as the energy balance has shifted to minimize stray field energy by creating magnetic domains at the cost of additional domain wall energy.

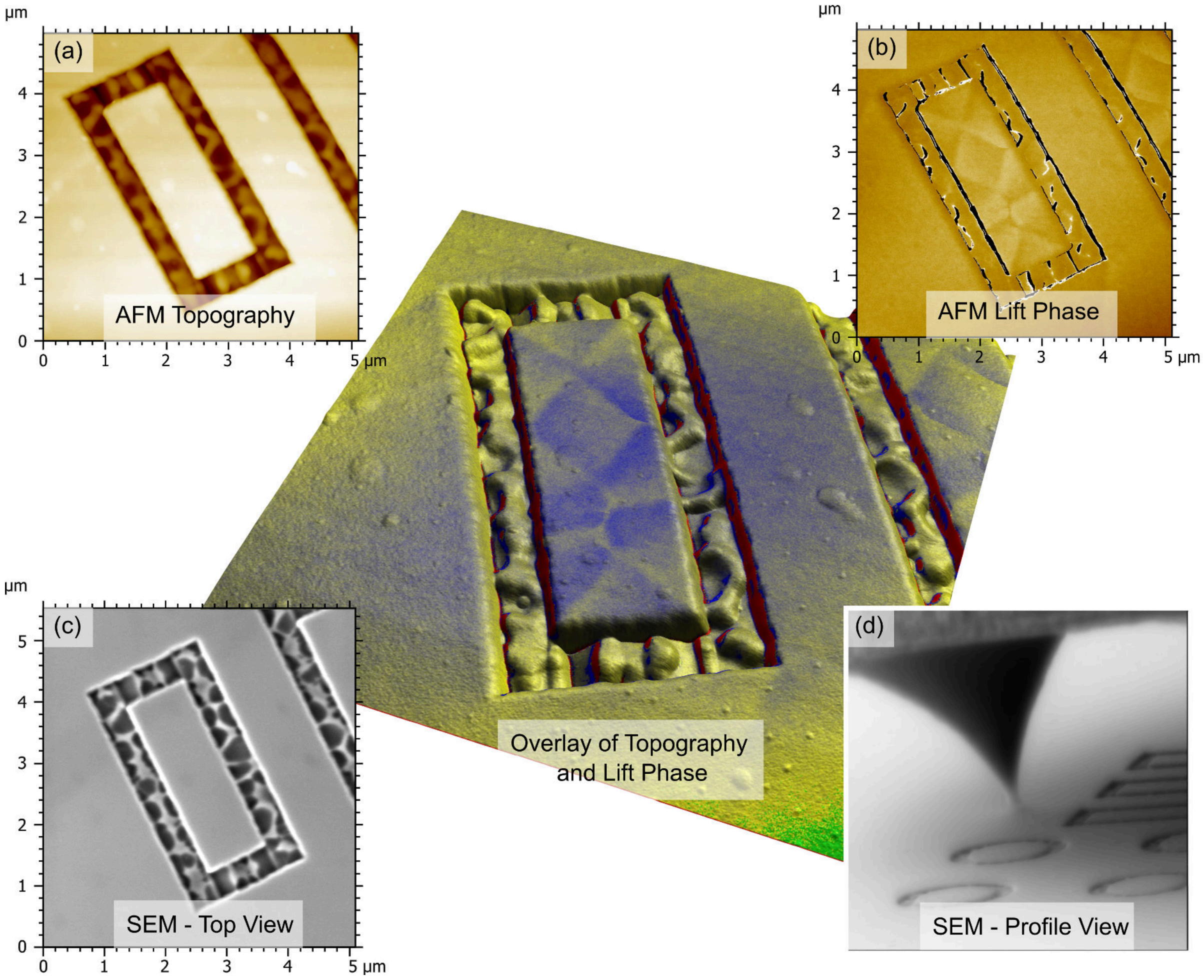


Figure 6: *3D representation of the topography and the lift phase (color-coded) is displayed in the middle of the image revealing a cross-shaped MFM signal. The topography* ***(a)****, lift phase* ***(b)*** *and SEM top view image* ***(c)*** *of the FIB-patterned cobalt sample are also included. In* ***(d)*** *the SEM profile view of the tip engaging the small structure is visible.*

Summary

- Performing MFM in FusionScope's high-vacuum environment enables increased sensitivity and reduces imaging artifacts due to electrostatic and humidity related effects.
- The MFM tip can be easily positioned on specific locations of the desired magnetic micro- or nanostructure using FusionScope's SEM observational capabilities.
- FusionScope's Profile View allows for various analyses of magnetic micro- and nanostructures to be performed at these precise locations, correlatively.

References

[1] Winkler et al., *Nanomaterials* **2023**, 13 (7), 1217.

[2] Quantum Design. "3D-Printed Nanoprobes in AFM: Transforming Surface Analysis with Multifunctional Nanoscale Precision." *Application Note 1081-211*. https://fusionscope.com/siteDocs/app_notes/1081-211.pdf.

[3] Nanorod samples were kindly supplied by Prof. Georg Fantner, EPFL Lausanne.

[4] The sample was kindly provided by Prof. Amalio Fernandez-Pacheco, TU Vienna.