Application Note

Revealing complex antiferromagnetic spin textures

temperature- and field-dependent MFM in closed-cycle cryostat attoDRY2200

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Abstract

Topological spin textures in synthetic antiferromagnet (SAF) systems hold great promise for next-generation spintronic devices due to their unique advantages such as ultrafast spin dynamics, substantially higher frugality in comparison to ferromagnetic systems, as well as robustness against external parasitic magnetic fields. However, imaging these nanoscale magnetic structures presents significant experimental challenge, particularly due to their weak stray fields and compensated magnetization. In this application note, we leverage the capabilities of attocube cryogenic MFM platform to address this challenge and investigate antiferromagntic spin textures in a specially designed multilayer SAF system. Utilizing the attoAFM I microscope inside an attoDRY2200 closed-cycle cryostat, we explore the evolution of exotic bimerons across a broad temperature range and under varying magnetic fields. We observe a reversible transformation from in-plane bimeronic textures at room temperature to out-of-plane, skyrmion-like domains at low temperatures, driven by a temperature-induced change in magnetic anisotropy. Magnetic field-dependent measurements further reveal the tunability and stability of these topological states. These results demonstrate how varying temperature and magnetic field is indispensable in the nanoscale exploration and manipulation of complex magnetic phenomena in SAF systems.

1. Introduction

Synthetic antiferromagnets (SAF) are promising candidates for next-generation spintronic devices due to their ultrafast spin dynamics, intrinsic robustness against external magnetic fields, and capacity to host a wide range of topological spin textures [1–3]. Among these, in-plane chiral textures such as *merons* and *antimerons* have attracted growing attention. These topological objects can form stacked 3D configurations in racetrack memory architectures, offering a pathway toward high-density, low-energy data storage and fast processing [4–7].

Topologically, merons represent half-skyrmion configurations where magnetization rotates from an out-of-plane core to an in-plane periphery. When paired as meron–antimeron doublets, they form *bimerons*, which retain a topological charge equivalent to a skyrmion but maintain in-plane spin symmetry. The schematic in Fig. 1 visualizes this relationship: skyrmions exhibit full 360° spin rotations, while merons show partial wrapping, offering a distinct symmetry and topological character. These structures are stabilized in SAFs via interfacial Dzyaloshinskii–Moriya interaction (DMI), combined with antiferromagnetic interlayer coupling that suppresses net magnetization.

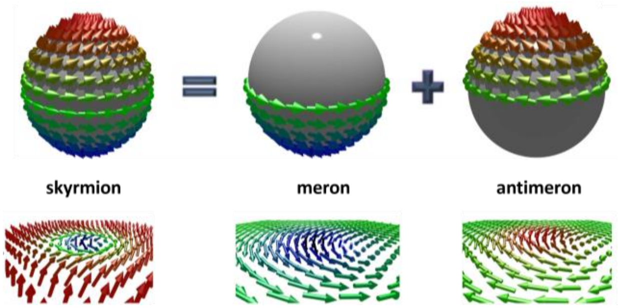

Fig 1: Schematic illustration of the relationship between a skyrmion and a meron (antimeron). The upper spheres show spin orientations, with spins pointing up or down at the center and aligning in-plane at the periphery to form nontrivial windings. The lower part depicts the corresponding spin textures, emphasizing their topological structure. Adapted from [9].

However, imaging these nanoscale textures in SAFs remains challenging. The antiferromagnetic coupling suppresses net magnetization and stray fields, rendering conventional magnetic microscopy techniques less effective [8]. While synchrotron-based X-ray magnetic imaging or SPLEEM can provide spin-resolved contrast, they require specialized environments and limited accessibility. An alternative approach is to use magnetic force microscopy (MFM) to probe the weak stray fields arising from Néel-order uncompensated moments—provided the system offers high sensitivity, cryogenic compatibility, and spatial resolution.

In this application note, we demonstrate how attocube cryogenic MFM platform enables the real-space study of spin textures in a multilayer SAF across a wide temperature and field range. By tracking the evolution of spin textures in a multilayer SAF across a thermally induced spin reorientation transition (SRT), we capture a reversible transformation from in-plane (anti)merons to out-of-plane (OOP) skyrmion-like stripe domain phase. We further explore their field response and stability, providing insight into the tunability of these chiral spin textures.

2. Experimental Setup

The experimental setup of cryogenic MFM from attocube comprises two key parts:

- ***attoAFM I***: This versatile cantilever-based atomic force microscope is designed for high-resolution nanoscale imaging. It offers multiple scanning probe microscopy (SPM) modes, including MFM, conductive-tip AFM (ct-AFM), piezo force microscopy (PFM), and Kelvin probe force microscopy (KPFM), under demanding cryogenic and high-field conditions.
- ***attoDRY2200***: Complementing the *AFM I* microscope, this cryogen-free cryostat offers a variable temperature range of 1.7 K to 300 K and the ability to apply a high magnetic field including vector field. This cryostat is designed to provide an ultra-stable, low-vibration environment, which is critical for achieving the sensitivity and resolution necessary for SPM measurements.

The integration of these systems provides an exceptional platform for studying nanoscale spin textures under varying temperature and magnetic field conditions.

Fig 2: Experimental setup for cryogenic MFM imaging. The attoAFM I microscope, operated in MFM mode, is mounted inside the attoDRY2200 closed-cycle cryostat, which provides a vibration-damped environment with base temperatures down to 1.7 K and vector magnetic field control.

3. Measurement Results

The sample investigated in this study is a multilayer SAF thin film comprising 14 repetitions of $Co_{0.6}Fe_{0.2}B_{0.2}$ (FM_A) and $Fe_{0.6}Co_{0.2}B_{0.2}$ (FM_B) ferromagnetic layers, antiferromagnetically coupled via 0.4 nm thick nonmagnetic Ir spacers (Fig. 3a). The combination of these alternating ferromagnetic layers with adjacent Pt and Ir interfaces breaks inversion symmetry and induces DMI, stabilizing chiral Néel-type topological spin textures, including merons and antimerons.

MFM imaging at room temperature (Fig. 3b) reveals a distinct phase of meronic textures. The merons and antimerons are distinguished by their characteristic black-and-white contrast corresponding to their core polarities, a result of their opposing out-of-plane magnetization components. Line profiles extracted from these textures (Fig. 3c) show nearly symmetric Gaussian peaks, with average lateral sizes of 137 ± 2 nm and 142 ± 2 nm for up and down cores, respectively.

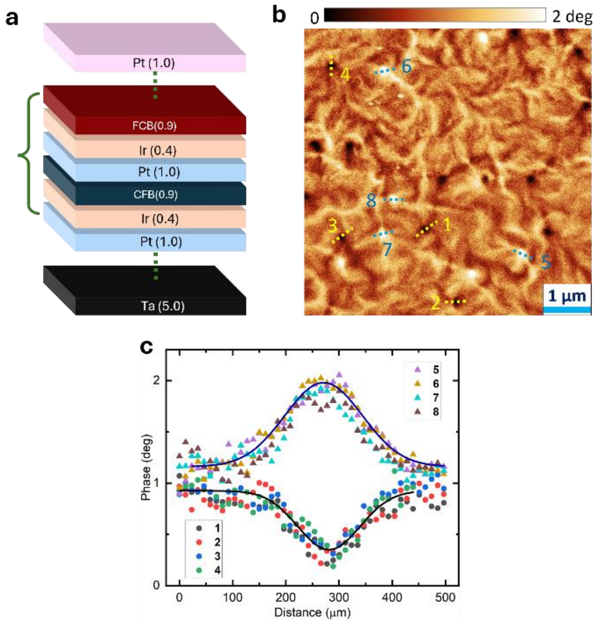

Fig 3: (a) Schematic of the multilayer SAF stack (b) Room-temperature MFM image showing merons and antimerons; dashed lines mark the positions of extracted cross-sections. (c) Corresponding Line profiles of the meron and antimeron cores, fitted with Gaussian peak functions (solid lines) to determine their core sizes.

A central factor governing the formation and evolution of these textures is the system's effective magnetic anisotropy K_{eff}. In SAF multilayers, K_{eff} arises from a competition between shape anisotropy, favoring in-plane alignment, and perpendicular magnetic anisotropy (PMA), which favors out-of-plane spin alignment. Structurally, K_{eff} can be tuned by adjusting the thickness ratio between the $\mathrm{FM_A}$ and $\mathrm{FM_B}$ layers. When this balance favors easy-plane anisotropy (i.e., negative K_{eff}), in-plane bimerons are energetically stabilized. However, an important external tuning parameter is temperature.

As the system is cooled, the saturation magnetization M_s increases, and the anisotropy K increases nonlinearly with M_s, following $K \propto M_s^X$ with $x > 1$, due to Cullen–Cullen scaling. This enhances the interfacial PMA, primarily arising from Co–Pt hybridization, which eventually overcomes the demagnetizing energy. As a result, the system toward an easy-axis regime, promoting a gradual realignment of the magnetization from in-plane to out-of-plane and resulting in a transition from meron-type spin textures to OOP stripe domains. As a result, K_{eff} transitions from negative to positive, driving the system through a spin reorientation transition (SRT) — a shift from an easy-plane to an easy-axis anisotropy regime. This transition is expected to alter the topology and symmetry of the spin textures, promoting the transformation from in-plane bimerons to out-of-plane skyrmion-like textures.

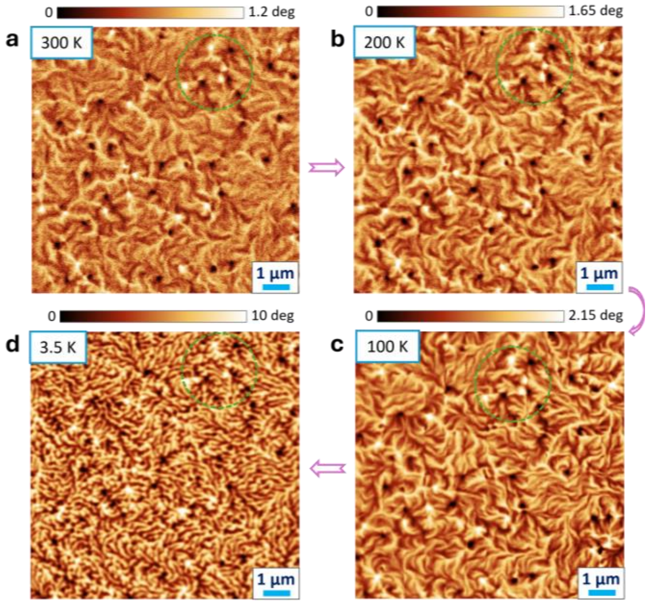

Fig 4: (a–d) MFM images acquired at 300 K, 200 K, 100 K, and 3.5 K, respectively, showing the temperature-driven evolution of spin textures in the SAF sample. The marked circles highlight the same region across all images, allowing direct tracking of individual merons and antimerons during the transition.

To capture this evolution in real space, MFM measurements were performed across a wide temperature range, from 300 K down to 3.5 K, using the same scan region throughout (Fig. 4). Since MFM is primarily sensitive to the vertical component of the stray field, it is particularly well suited to detecting changes in out-of-plane magnetization. A progressive increase in phase contrast is observed with decreasing temperature, indicating an enhancement of the OOP magnetization component. As the PMA becomes more dominant at low temperature, the OOP component of the magnetization within each core spin textures intensifies, leading to both a stronger MFM signal and an increase in lateral core diameters. These observations provide strong evidence for a continuous, topologically driven transformation of the spin textures, from meronic to skyrmion-like.

To validate and quantify the evolution of anisotropy, SQUID magnetometry was performed over the same temperature range (Fig. 5a). At higher temperatures (200 K to 100 K), the out-of-plane hysteresis loops remain narrow, nearly linear, and non-hysteretic — characteristics of an easy-plane regime. As the temperature decreases below 80 K, the loops begin to open, signaling the onset of finite coercivity. By 50 K, a clear and stable hysteresis loop appears, confirming the emergence of an easy-axis magnetic configuration. This magnetic transition correlates well with the enhanced MFM contrast and growing core size observed in the imaging data, verifying the occurrence of a spin reorientation transition.

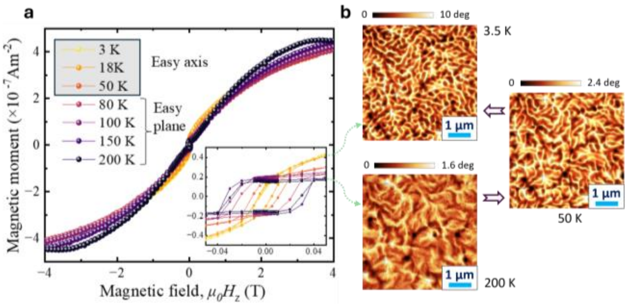

Fig 5: Temperature-induced transition from merons to out-of-plane stripe domains (a) Out-of-plane magnetic hysteresis loops measured at different temperatures reveal a SRT around 50 K. The inset zooms into the coercivity region, showing the emergence of remanent magnetization as the temperature decreases. (b) Corresponding MFM images recorded at 200 K, 50 K, and 3 K illustrate the thermal evolution of spin textures across the SRT. At 200 K, sample exhibits (anti)meron structures, consistent with in-plane magnetization. At 3.5 K, the system enters an OOP anisotropy regime, where these isolated textures are replaced by labyrinthine stripe domains.

MFM images taken at intermediate and low temperatures reflect this evolution in real space. At 300 K and 200 K, we observe a dense distribution of low-contrast, in-plane bimeronic textures (Fig. 5b). As the system cools toward 50 K, the textures exhibit enhanced contrast and broadened cores —

a signature of increased out-of-plane anisotropy. At 3.5 K, the system undergoes a full topological transition to an out-of-plane, stripe-like domain phase. These labyrinthine structures are skyrmion-like in topology, consistent with chiral Néel-type domain wall textures stabilized by strong interfacial DMI and positive K_{eff}.

To further assess the tunability and robustness of these textures, we performed field-dependent MFM measurements at 3.5 K by applying an external magnetic field along the out-of-plane (z) axis (Fig. 6). At zero field, the sample exhibits a labyrinthine OOP domain state stabilized by positive anisotropy. As the magnetic field increases, the domains begin to align with the field direction, leading to a suppression of the MFM contrast. At sufficiently high fields, the contrast saturates, indicating a field-polarized state.

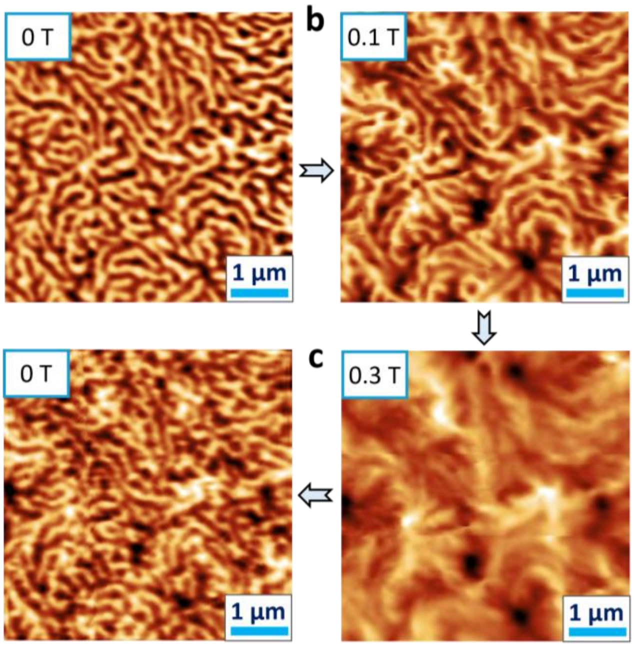

Fig 6: Magnetic field evolution of spin textures at 3.5 K. (a-d) MFM images acquired at 0 T, 0.1 T, 0.3 T, and after returning to 0 T.

Crucially, when the field is reduced back to zero, the original stripe domain pattern is restored, indicating that the spin texture evolution is reversible and robust under field cycling. These observations emphasize the dual role of temperature and magnetic field in controlling the magnetic anisotropy and topology of spin textures in SAF.

4. Conclusion

This study reveals how variable temperature, and variable magnetic field can be used to reversibly tune the topology of spin textures in synthetic antiferromagnets. Starting from a room-temperature state dominated by in-plane bimerons, the system undergoes a gradual transformation into a low-temperature regime characterized by out-of-plane labyrinthine domains. This transition is driven by a thermally induced change in effective magnetic anisotropy. Field-dependent MFM imaging at low temperatures shows that these textures are not only thermally stable but also dynamically responsive to external magnetic fields, exhibiting reversible transitions between meronic and stripe-like states. These results emphasize the delicate balance between interfacial DMI, magnetic anisotropy, and Zeeman energy in shaping complex spin textures.

The ability to resolve and track such nanoscale spin structures across varying experimental conditions underscores the precision and stability of attocube cryogenic MFM product for probing emergent magnetic phenomena and phase transitions in advanced spintronic materials.

References

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