Temperature-driven transition from Meron-type spin textures to stripe domains and revealing the nanosecond dynamics of antiferromagnetic quasiparticles through sublattice-resolved x-ray microscopy

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ABSTRACT

Magnetic topologically non-trivial quasi-particles, such as skyrmions, hopfions, merons, and bimerons that are stabilized by the Dzyaloshinskii–Moriya interaction, have garnered significant interest in recent years. Here, we demonstrate a temperature-driven transition from meron-type textures to out-of-plane stripe domains by continuously tuning the effective anisotropy across the spin reorientation transition. Combined magnetic force microscopy and SQUID magnetometry reveal the temperature-induced evolution of spin structure and anisotropy. Our results establish temperature as a key control parameter for reconfigurable topological states in SyAFM multilayers.

Keywords: Skymrion, meron, bimeron, synthetic antiferromagnet

1. INTRODUCTION

Topologically non-trivial spin textures such as skyrmions,[1–4] merons,[5] and bimerons[6] represent metastable, particle-like excitations characterized by non-trivial topology and complex internal spin structures. Skyrmions and bimerons both carry a topological charge of unity ($Q = \pm 1$), yet they differ in their symmetry, magnetization profiles, and stabilization mechanisms. Skyrmions are typically stabilized in systems with perpendicular magnetic anisotropy (PMA), where the magnetization undergoes a continuous rotation from a central out-of-plane (OOP) core to an oppositely aligned periphery. The resulting spin texture forms either a radial Néel-type or a tangential Bloch-type domain wall, depending on the symmetry of the Dzyaloshinskii–Moriya interaction (DMI)[7,8] or the nature of the stabilizing mechanism.[9] Bimerons, in contrast, emerge in systems with easy-plane magnetic anisotropy and consist of a bound pair of meron-type textures, a meron and an antimeron, with oppositely oriented OOP cores[10,11] enclosed within an in-plane magnetized background. When embedded in antiferromagnetic (AFM) systems, these textures acquire additional advantageous properties arising from the compensated spin structure. These include the suppression of external stray fields, enhanced resistance to external magnetic perturbations, and cancellation of gyrotropic forces.[12–16]

Synthetic antiferromagnets (SyAFMs), composed of ferromagnetic layers, antiferromagnetically coupled through nonmagnetic spacers, offer a tunable platform for stabilizing topological spin textures in magnetically compensated environments.[17–19] The cancellation of net magnetization and spin angular momentum suppresses dipolar fields and gyrotropic forces, enabling purely longitudinal, current-driven motion. Recently, Néel-type antiferromagnetic skyrmions have been observed in SyAFMs, exhibiting dynamics free from transverse deflection.[20,21] In addition, in-plane textures such as merons, antimerons, and bimerons have been realized

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through controlled tuning of interfacial DMI, magnetic anisotropy, and the compensation ratio.[6] However, a direct transformation between out-of-plane spin textures and bimerons within SyAFM system, driven by continuous tuning of external parameters such as temperature, has remained elusive.

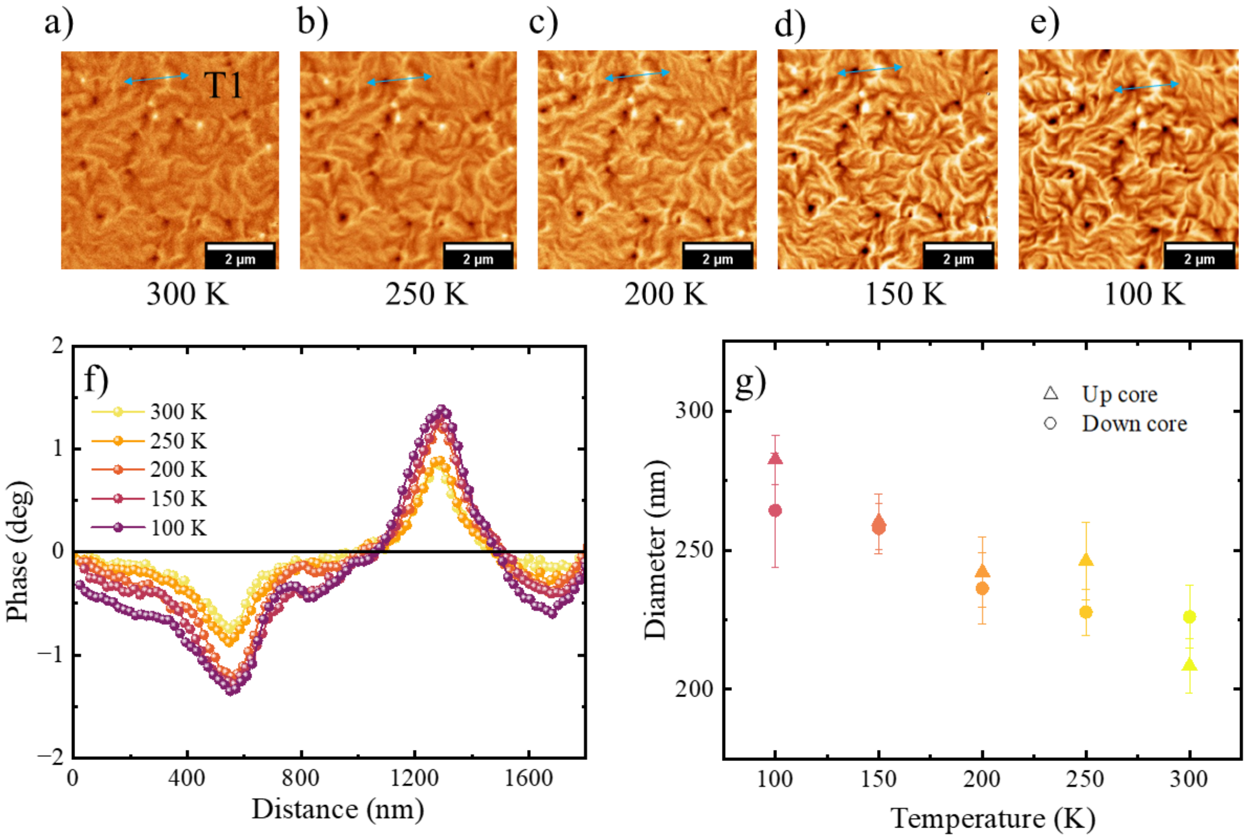

Figure 1. **Temperature-dependent evolution of (bi)merons. (a–e)** MFM phase images acquired from the same scan area at temperatures of 300 K, 250 K, 200 K, 150 K, and 100 K, respectively. A progressive enhancement in phase contrast and an apparent increase in the core size of (anti)merons are observed upon cooling. **(f)** Line profiles across an individual (bi)merons (labelled T1) at each temperature, showing a systematic increase of the phase contrast of the MFM response with decreasing temperature. **(g)** Extracted core diameters, defined as the FWHM from Gaussian fits to the line profiles, as a function of temperature.

We demonstrate that varying the temperature in a SyAFM system enables a continuous tuning of the effective magnetic anisotropy from easy-plane to easy-axis, thereby driving a topological transition from meron-type spin textures to out-of-plane stripe domains with skyrmionic character. Magnetic force microscopy (MFM) and SQUID magnetometry reveal a systematic increase in magnetic phase contrast and a widening of the core size with decreasing temperature. The multidomain stripe phases are stabilized at low temperatures due to the enhanced dominance of perpendicular anisotropy, while the meron-type spin textures are recovered upon warming, confirming the reversibility of the transition. These findings establish temperature as a robust control parameter for tuning topological spin textures in SyAFM systems.

2. TEMPERATURE-DRIVEN EVOLUTION OF (BI)MERONS

The SyAFM multilayers used in this study are deposited using a previously established sputtering protocol.[6] Each ferromagnetic sublattice of the SyAFM, $\mathrm{FM_A}$ and $\mathrm{FM_B}$, is a composite heterostructure comprising $\mathrm{Co_{0.6}Fe_{0.2}B_{0.2}}$ (CFB) and $\mathrm{Fe_{0.6}Co_{0.2}B_{0.2}}$ (FCB), respectively. The ferromagnetic sublattices are antiferromagnetically exchange-coupled through an Ir spacer of thickness $d_{\mathrm{Ir}} = 0.4$ nm. The adjacent Pt and Ir interfaces break inversion symmetry and induce interfacial DMI, which facilitates the stabilization of chiral Néel-type configurations. By tailoring the relative thicknesses of the CFB and FCB layers within a fixed total ferromagnetic thickness of $d_{\mathrm{FM}} = 0.9$ nm, the effective magnetic anisotropy (K_{eff}) can be tuned to the spin reorientation transition (SRT). Temperature serves as an additional parameter for dynamically controlling K_{eff}. 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.[22] 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.

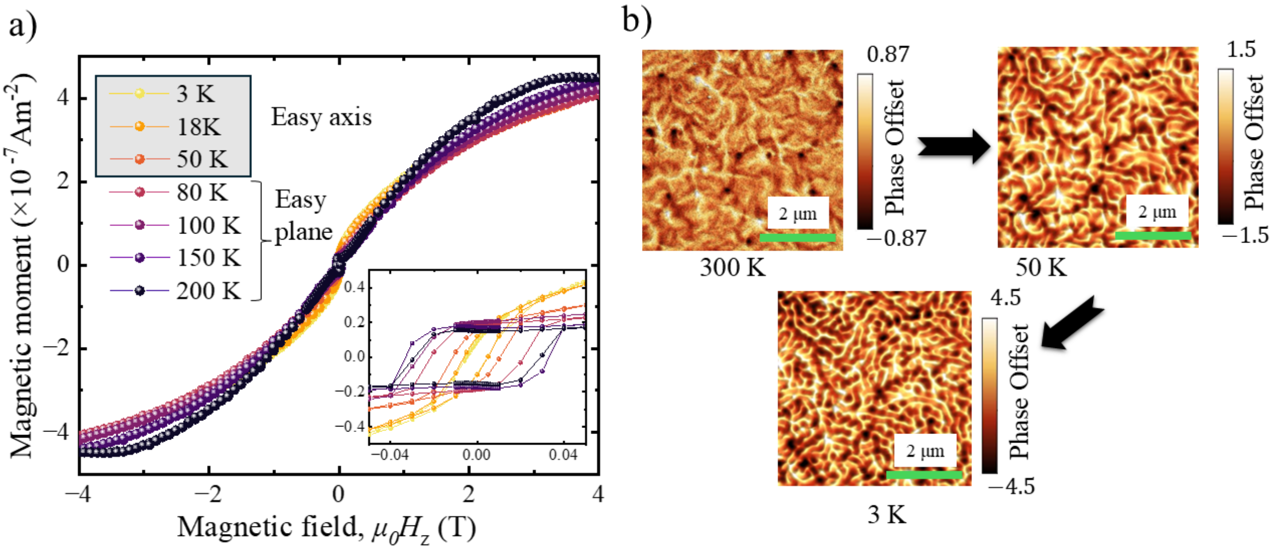

Figure 2. **Temperature-driven transition of a (bi)meron texture to OOP stripe domains (a)** OOP magnetic hysteresis loops measured at various temperatures reveal a spin reorientation transition near 50 K. A detailed view of the low field regime where the coercive field is visible is shown in the inset. **(b)** Corresponding MFM images acquired at 300 K, 50 K, and 3 K, demonstrating the transition of spin textures across the SRT. At 300 K, the sample exhibits dense (anti)meron-like textures, characteristic of in-plane magnetized systems. At 3 K, the system transitions into a fully OOP multidomain state, with labyrinthine stripe domains replacing isolated meron-type textures.

To directly visualize this evolution, the SyAFM stack is imaged using MFM over a temperature range from 300 K to 100 K (Fig. 1(a–e)). All scans are acquired on the same region of the sample, enabling temperature-resolved tracking of individual spin textures. MFM selectively probes the OOP component of the local stray field, making it ideally suited for detecting magnetization contrast associated with (bi)meron-type cores. 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. To quantitatively assess these changes, line profiles were extracted from a representative bimeron-type texture (marked by black arrows in Fig. 1(a–e)) and plotted in Fig. 1(f). Each profile was fit using a Gaussian function, with the core diameter defined as the full width at half maximum (FWHM) of the fit. As summarized in Fig. 1(g), both up and down cores exhibit a monotonic increase in size, from approximately 220 nm ± 20 nm at 300 K to 260 nm ± 22 nm at 100 K, corroborating the temperature driven evolution of the spin structure.

To quantitatively probe the anisotropy landscape in the SyAFM stack, we perform temperature-dependent SQUID magnetometry measurements of the OOP hysteresis loops (Fig. 2(a)). At temperatures above 100 K, the magnetization response remains linear with negligible coercivity and remanence, consistent with a prevailing easy-plane anisotropy. A spin reorientation transition occurs below 50 K, driving the system from easy-plane to easy-axis anisotropy. Below this point, the effective anisotropy becomes positive and sufficiently strong to reorient the net magnetization toward the film normal. This evolution in anisotropy is mirrored in the spatial spin texture, as revealed by MFM imaging at 300 K, 50 K, and 3 K (Fig. 2(b)). At room temperature, the images display a dense distribution of in-plane (anti)merons. At 50K, the contrast increases, indicating the emergence of a stronger out-of-plane component, consistent with nearing the SRT. At 3 K, the system exhibits a fully reoriented magnetization, forming a labyrinthine stripe domain pattern characteristic of an OOP multidomain state. These measurements confirm that temperature serves as an effective tuning knob to drive the system through the SRT, enabling a transition from stabilized bimeron-type textures to out-of-plane magnetic ordering in the absence of any external field.

3. CONCLUSION

We have experimentally demonstrated a temperature-driven topological reconfiguration from antiferromagnetic meron-type spin textures to stripe domains in SyAFM. These findings provide direct evidence of thermal control over topological states in SyAFMs and establish temperature as a key parameter for accessing multiple spin configurations within a single material platform. Future investigations could explore the dynamical behavior of these excitations across the SRT, their mutual interactions, etc. Integrating temperature control with additional stimuli such as electric current or strain may further enable multiaxial tuning of topological phase transitions, advancing the design of functional antiferromagnetic spintronic systems.

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