Thin Film Multilayer Systems with interfacial Dzyaloshinskii-Moriya Interaction [1]

Our research on skyrmions profits from our profound understanding of sputter deposition methods and from decades of experience in design, development and application of quantitative magnetic force microscopy methods [2,3,4].

The Dzyaloshinskii-Moriya interaction (DMI) induced by the interfaces of thin-film structures has been shown to support the existence of skyrmions at room temperature [5]. Provided that the exchange stiffness A and the anisotropy K_u are known, the average DMI can be extracted from MFM data of the domain structure obtained after different demagnetization procedures (Figure 1) [6].

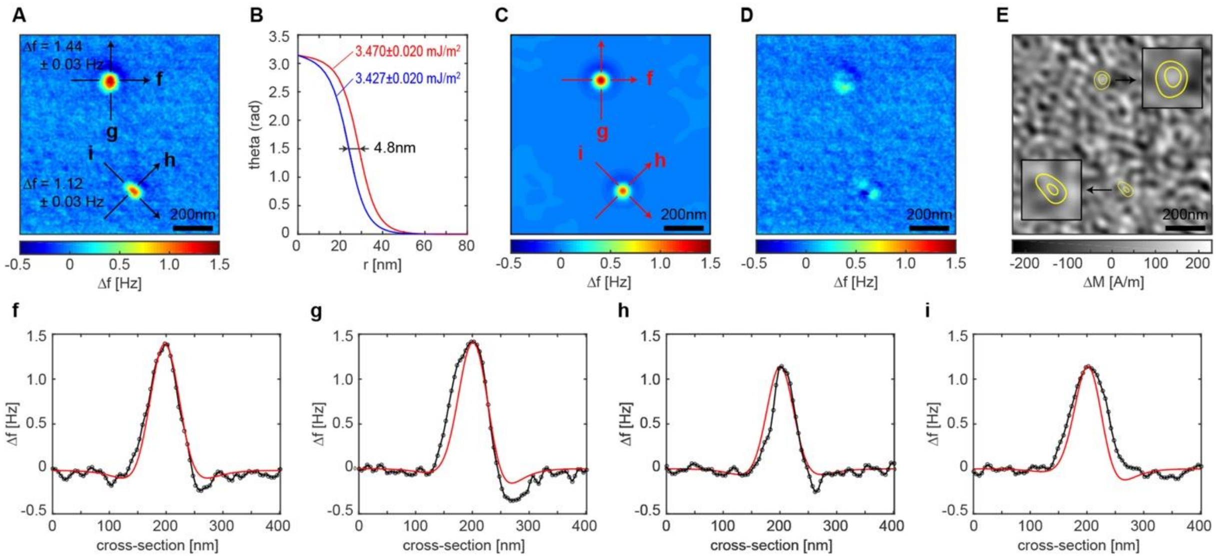

Figure 1: skyrmion measured and simulated profiles. **A** Background (i.e. same area in saturation) subtracted high resolution image of two skyrmions measured at 1.14 mT. Sections f−i are reproduced in the corresponding black trace of Figures f−i. **B** Calculated skyrmion profiles for the values of the Dzyaloshinskii-Moriya interaction, D, corresponding to the maximum contrast of top and bottom skyrmions. **C** Calculated measurement contrast maps for the skyrmion profiles of **B**. The sections f−i are reproduced in the corresponding red trace of Figures f−i. **D** Point by point map difference **A** and **C**. **E** Magnetization pattern which repeated on each Co layer reproduces the measured contrast in saturation, i.e. a measure of the local thickness' departure from the average 0.6 nm.

Also, we have recently shown that even the sign of D can be measured by exploiting Halbach effect at nanoscale. The magnetic field distribution above (and below) a thin film with a chiral magnetization structure depends on the sense of rotation of the magnetic moments inside the Néel walls (Figure 2), which alters the strength of the stray field on the surface depending the position, e.g., above or below [7].

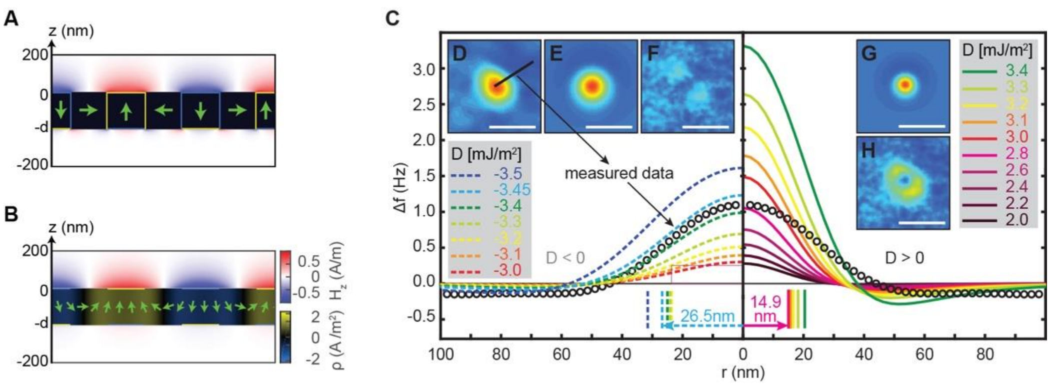

Figure 2: **A** Halbach array showing larger fields above and smaller fields below the magnet array consisting of 200 nm square magnets with a magnetization of 1 A/m (center band, black). **B** Perpendicular domain pattern in a film of 200 nm thickness with chiral Néel walls with a wall width of 150 nm. The

unique chirality for the Néel walls is necessary to establish spin textures with the same topology as panel **A**. **C** main panel: Simulated MFM frequency shift profiles of skyrmions with negative (left, dotted lines) and positive *D* (right, solid lines) values. The half-width at half-maximum values are indicated by the vertical segments below the abscissa. The black circles depict an experimental cross-section. *D* Measured skyrmion. **E** Simulated skyrmion for *D* < 0 chosen to match the experimental peak contrast. F Pointwise difference between panels **D** and **E**. Panels **G** and **H** are the same as **E** and **F** for *D* > 0. Scale bars **D−H**: 100 nm.

Similar methods were also applied to determine the chirality of the Néel domain walls and Néel-type skyrmions in $SrIrO_3/SrRuO_3$ (SIO/SRO) bilayers [8]. These samples were grown in laboratories of Prof. Dr. Fengyuan Yang , Ohio State University. The SIO/SRO bilayers exhibit a remarkable topological hall (TH) effect, which is up to 200% larger than the anomalous Hall (AH) effect at 5 K, and zero-field TH effect at 90 K. Using variable-temperature, high-field magnetic force microscopy (MFM), we imaged skyrmions as small as 10 nm (Figure 3), which emerge in the same field range as the TH effect. In this system, imaging skyrmions require a careful disentanglement of the different contributions to the measured MFM contrast. These results reveal a rich space for skyrmion exploration and tunability in oxide heterostructures.

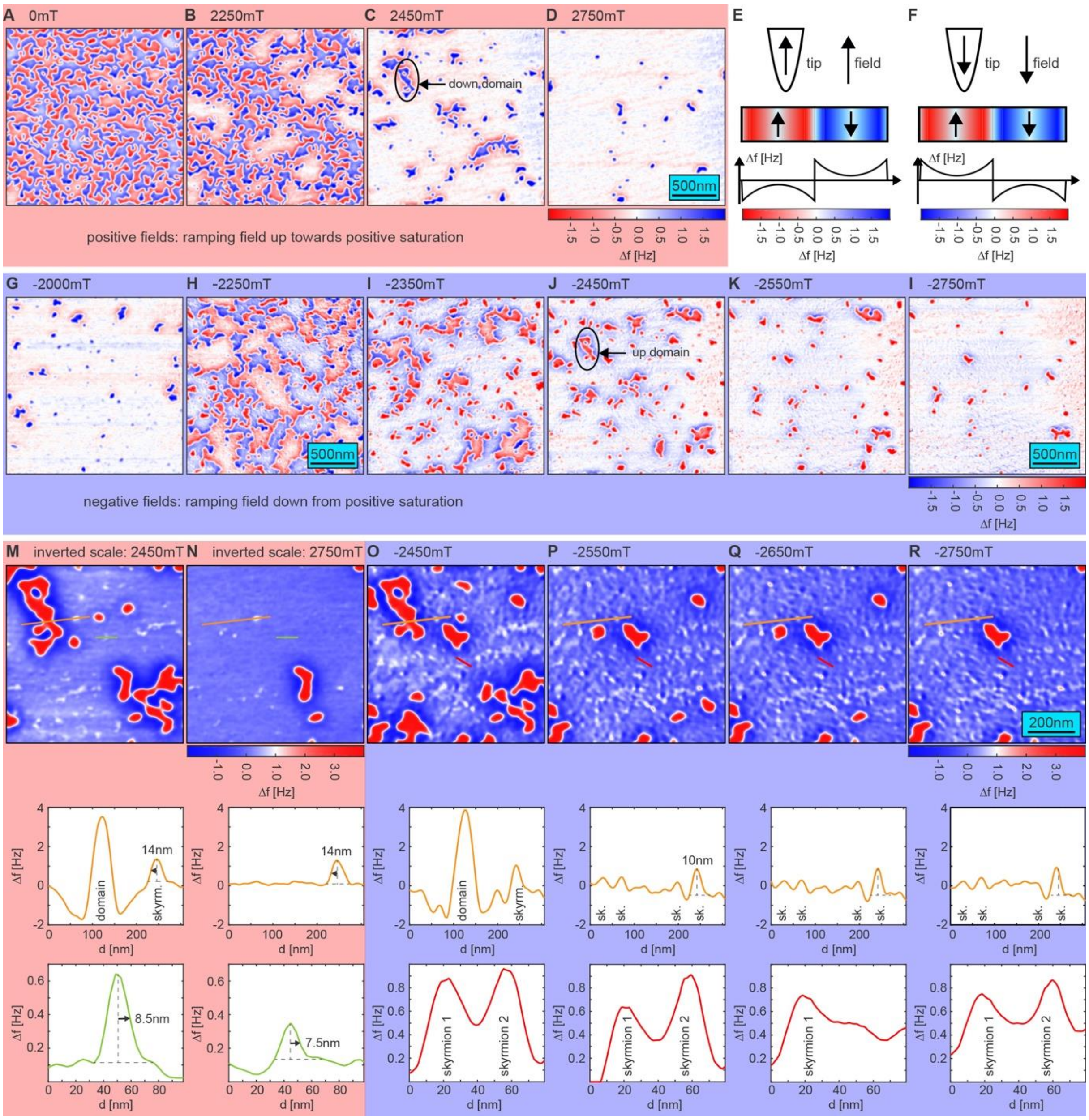

Figure 3: Background-subtracted MFM data recorded at 10 K at different fields for the SIO (2 uc)/SRO (10 uc) bilayer. (**A−D**) Evolution of the as-grown domain structure at 0, 2250, 2450, and 2750 mT. Schematics illustrating that, in panel E, red/blue domains have an up/down magnetization and generate a negative/positive frequency shift because the initial tip magnetization is up, and **F** after application of negative fields, the tip magnetization is down. **G−L** MFM images acquired at negative fields from −2000 to −2750 mT. Note that because the tip magnetization is flipped to the down direction, red/blue colors now denote domains with a down/up magnetization direction. This change of contrast becomes apparent at the location of the domain highlighted by the ellipse in panel **C** taken at +2250 mT and **J** taken at −2250 mT that appears with almost the same shape on the up and down branches of the hysteresis loop. **M**, **N** High-magnification views of the MFM images taken at positive fields [inverted scales of panels **C** and **D**], which are compared to the corresponding images taken at negative fields **O** and **Q**. **P**, **R** Additional negative field data taken at −2550 and −2750 mT. The bottom rows of panels **M**-**R** display cross sections taken at the location marked by the orange, green, and red lines plotted into the images above.

Skyrmions have been proposed as information carriers for magnetic storage for example for racetrack memory applications [9]. In a racetrack memory device, a chain of skyrmions needs to be moved between pre-defined pinning centers, i.e. defined by notches. The information in the skyrmion chain is coded by the distance between the skyrmions. This requires that the skyrmions are stable against annihilation, and that the inter-skyrmion distances are kept constant when a current pulse is applied to shift the skyrmion chain between different predefined positions in the racetrack device. However, distributions of the pinning energies, intrinsic pinning cites in the racetrack material, and the envisioned device operation at room temperature lead to a distribution in the depinning currents, times and velocities of the skyrmions that will consequently lead to bit errors in device applications [10]. To reduce the bit error rates significantly to a level required for data storage applications, Suess et al., [11] have suggested a racetrack device consisting of an artificial double layer structure in which the physical properties of one of the layers is tuned to support a linear skyrmion lattice with a well-defined inter-skyrmion distance and is magnetostatically coupled to a second layer that may contain a skyrmion or not, representing a logic 1 or 0, respectively. Based on our background on magnetic rare-earth-transition metal alloy thin films we apply such materials for improved systems supporting skyrmions at room temperature, i.e. to support two different skyrmion phases [12]. The experimental work performed by high-resolution and quantitative magnetic force microscopy is supported by micromagnetic calculations performed by the group of Prof. Giovanni Finocchio of the University of Messina and Prof. Dieter Süss of the University of Vienna.

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[1] This project was financially supported by an Empa-internal research project, and partially by SNF projects 200021_147084/2, 200021E-160637, and CRSII2_154410

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