Magnetic Force Microscopy: a Unique Tool

The sophisticated method allows investigating magnetic hosts for antiskyrmions.

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In an ever-growing digitalized world, recent estimations suggest that we already produce dozens of exabytes of data on a single day [1]. This staggering amount of data calls for new storage technologies to stem the tide of expanding information.

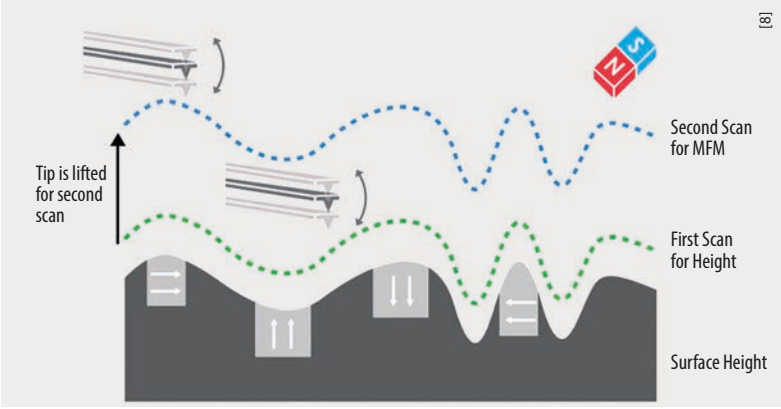


Fig. 1 Magnetic Force Microscopy detects the sample topography in the first pass and the magnetic structure in the second pass [8].

Here, skyrmions and antiskyrmions could provide novel solutions for smaller and faster data storage with improved energy efficiency [2]. Skyrmions are topological spin structures, arranged in small vortices, that act as quasiparticles in the magnetic texture of certain host materials [3]. Their size can vary between 100 µm and 1 nm [4]. Due to their size, stability, and response to external electric or magnetic fields, the application of skyrmions and antiskyrmions in spintronics is studied for high-density data storage and transfer as well as neuromorphic computing [5, 6].

Antiskyrmions have been observed in so-called tetragonal Heusler compounds, including $Mn_{1.4}PtSn$. However, resolving such magnetic patterns is not an easy task, since a microscopy method providing nanoscale spatial resolution and high magnetic sensitivity is required. Here, Magnetic Force Microscopy (MFM), a variant of Atomic Force Microscopy (AFM), allows for the investigation of such magnetic spin structures and the study of their dependence on the sample geometry by enabling real-space imaging of surface topography and magnetic structure of the same sample area.

During an AFM measurement, the sample topography is scanned with a probe consisting of a sharp tip with a nanometer-sized apex attached at the end of a µm-long cantilever. Meanwhile, a laser beam is focused on the backside of the cantilever and reflected onto a position-sensitive photodiode (PSPD). At close distance, the cantilever bends due to tip-sample interactions and the laser reflection moves accordingly across the PSPD. If the cantilever is mechanically excited at resonance, one can track the lever oscillating amplitude via the PSPD. A feedback loop detects changes in the amplitude induced by any variation of the tip-sample interaction strength and adjusts the relative tip-sample distance in

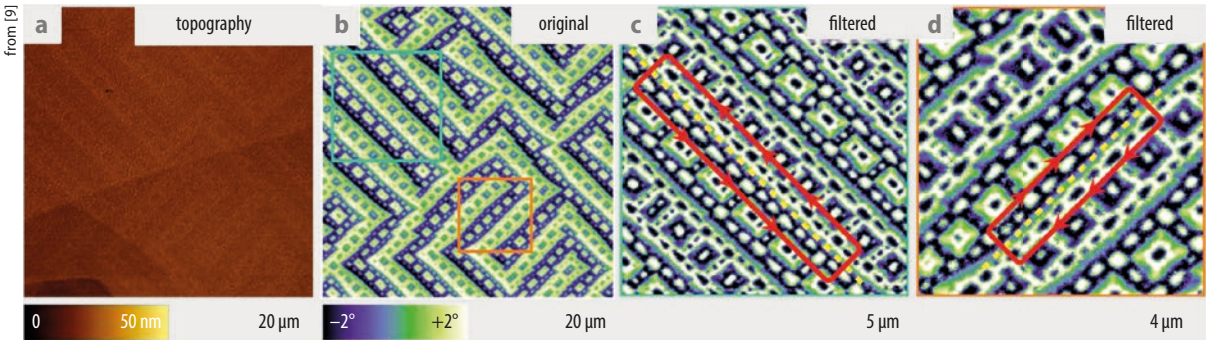
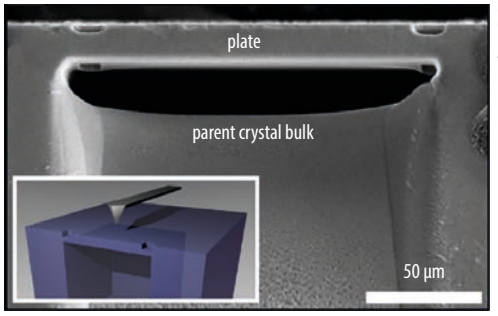


Fig. 2 The sample topography (a) shows a smooth surface. MFM measurements reveal more and more details with increasing magnification (b to d).



from [11]

Fig. 3 Thin plates of $Mn_{1.4}PtSn$ with defined thickness were extracted from a single crystal.

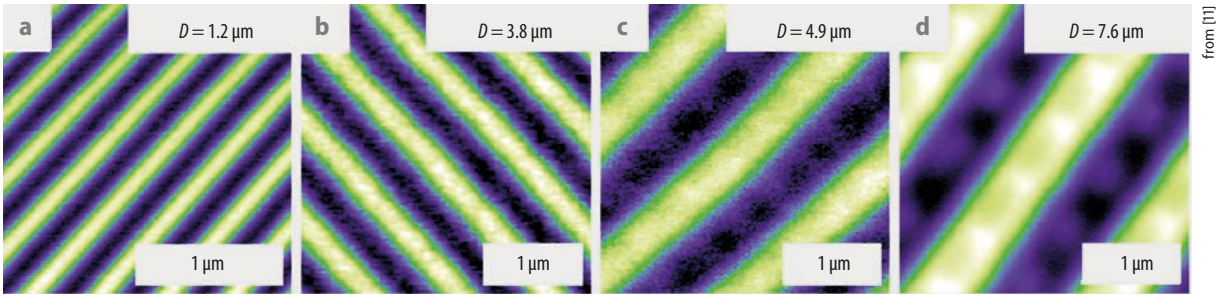
order to keep the amplitude at a given setpoint. Thus, when shifting the tip position over the sample, the scanner will move accordingly following the surface profile and hence providing a measure of the sample topography. For additional MFM measurements, the cantilever also needs to be covered with a magnetic coating that interacts with any magnetic moment originating from the sample surface.

To disentangle the contributions of the surface and the magnetic moment on the lever dynamics, MFM uses the different distance dependence of the forces acting on the cantilever [7]. At close proximity, van-der-Waals interactions and Pauli repulsion dominate the tip-sample forces. At distances larger than a few tens of nm, the short-range van-der-Waals and Pauli interactions become negligible and magnetic forces govern the tip-sample interaction. Therefore in MFM, each line is scanned twice: the first pass images the sample topography and the second pass pictures the magnetic texture of a sample (**Fig. 1**). To keep the tip-sample distance constant during the second pass, the cantilever follows the previously recorded topographical profile. The cantilever amplitude and phase shifts provide information on the local magnetic polarization and moment, thereby resolving magnetic structures present in the sample.

Such MFM measurements have been conducted by Aleksandr Sukhanov and colleagues to investigate the magnetic properties of a single crystal and thin lamellas of $Mn_{1.4}PtSn$ using a Park Systems NX10 AFM in ambient conditions [9]. In this study, the sample was mounted on a non-magnetic sample holder to avoid magnetic crosstalk. For MFM, a cantilever with a magnetic coating (PPP-MFMR, Nanosensors) was magnetized prior to the measurement and used for all experiments. MFM measurements were conducted in dual-pass scanning mode (**Fig. 1**). In the first pass, the topography was imaged in Park's True Non-Contact™ Mode. Subsequently, the cantilever was lifted by 100 to 150 nm and the magnetic distribution was detected while retracing the topographic profile.

Single crystals of $Mn_{1.4}PtSn$ were grown by flux method and polished along the ab plane with a focused xenon ion beam to create smooth surfaces (**Fig. 2**) on $Mn_{1.4}PtSn$ that have shown the existence of antiskyrmions in thin layers of the material [10]. These room temperature MFM measurements reveal the formation of a fractal ferromagnetic domain structure consisting of a lamellar striped pattern with widths of up to 3 µm (**Fig. 2b**). Further magnifications (**Fig. 2c, d**) display additional smaller nested domains with an arrowhead shape and opposite orientation around domain walls, thus, introducing a chirality. This chirality around the domain walls is indicative of the presence of the Dzyaloshinskii-Moriya interactions (DMI) – an anisotropic magnetic exchange interaction, fundamental for the formation of skyrmions and antiskyrmions. Thus, Sukhanov and co-workers showed that bulk $Mn_{1.4}PtSn$ single crystals favor the formation of ferromagnetic domain patterns over antiskyrmion lattices [9].

A subsequent study used a Park Systems NX10 microscope in MFM mode to resolve the thickness dependence of the magnetic structure of $Mn_{1.4}PtSn$ crystals [11]. To do so, suspended lamellae with different thicknesses ranging from 400 nm to 10 µm were created by cutting a 100 × 100 µm² wide groove into the side of an appropriate crystal (**Fig. 3**). The measurements revealed a transition from the fractal ferromagnetic domain structure in bulk $Mn_{1.4}PtSn$ to a simple pattern with single rows of nested domains, as the thickness decreased to less than 4.4 µm (**Fig. 4**). Below this threshold thickness, the nested domains disappeared to form uniform sinusoidal stripes that originate from the



from [11]

Fig. 4 With decreasing thickness (a to d), samples of $Mn_{1.4}PtSn$ show simple patterns of nested magnetic domains.

nucleation of spin helices instead of striped ferromagnetic domains due to DMI (**Fig. 4**). This magnetic pattern based on spin helices can act as a prototype for the antiskyrmion formation under the application of external magnetic fields.

In conclusion, room temperature MFM measurements on Park Systems NX10 AFM revealed that bulk $Mn_{1.4}PtSn$ features anisotropic fractal ferromagnetic domains, indicating the presence of DMI as a prerequisite of antiskyrmion formation [9]. By decreasing the layer thickness of $Mn_{1.4}PtSn$ to below 4.4 µm, a sinusoidal stripe pattern appears that originates from the nucleation of spin helices caused by DMI. Under applied magnetic fields, this pattern can act as a template for antiskyrmion nucleation [11]. These two examples illustrate Magnetic Force Microscopy as a unique tool to further our understanding of magnetic textures on a nanoscale that might pave the way for future spintronic applications.

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