

Spatiotemporal Imaging of Magnetization Dynamics of Van der Waals Ferromagnet Fe_5GeTe_2

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Abstract:

Two-dimensional (2D) magnetic materials offer a rich landscape for exploring spin dynamics and topological textures, with tunable properties and compatibility with heterostructure engineering. Among these, a 2D ferromagnet Fe_5GeTe_2 (F5GT) has emerged as a promising candidate due to its high Curie temperature (T_c). However, the magnetism of F5GT is highly sensitive to thermal history and sample inhomogeneity, making per-flake characterization necessary. Here, we present a scanning diamond nitrogen-vacancy (NV) magnetometry study where the flakes are transferred onto a patterned loop antenna. We observe near- T_c magnetic domain formation and stabilization for both furnace-cooled and quench-cooled flakes. Furthermore, we observe distinct magnetic domain features between the two samples: the quench-cooled flake develops fine-scale magnetic domains elongated predominantly in a single direction, whereas the furnace-cooled flake exhibits multiple nematic domain directions. This work can offer new insights into the nanoscale magnetism and local magnetic configurations of van der Waals ferromagnets.

Summary of Research:

Two-dimensional (2D) magnets have garnered significant attention for hosting exotic magnetic phenomena and topological spin textures, arising from strongly enhanced intrinsic spin fluctuations [1]. Their magnetic properties are readily tunable through external fields, strain, or

chemical modifications, and their cleavable nature enables seamless integration into engineered heterostructures [1]. These features position 2D magnets as versatile platforms for probing fundamental spin interactions and developing multifunctional devices that integrate electronic, optical, and magnetic properties. Despite their intriguing properties, many two-dimensional ferromagnetic materials exhibit Curie temperatures (T_c) significantly below room temperature, restricting their practical use. F5GT has been identified as a promising candidate demonstrating a T_c of up to 332 K in bulk and 280 K in exfoliated thin flakes (~ 10 nm) [2]. Additionally, a recent photoemission electron microscopy (PEEM) study reported possible sample inhomogeneity in F5GT crystals, revealing a coexistence of out-of-plane and in-plane magnetic domains likely tied to chemical inhomogeneities such as Fe vacancies [3]. Understanding the single flake magnetic properties will be key to future applications.

To better assess per-flake magnetic properties, we perform scanning NV measurements using exfoliated F5GT flakes from two crystals: a quench-cooled F5GT crystal and a furnace-cooled F5GT crystal. For this purpose, we design and fabricate loop antennas and transfer exfoliated F5GT flakes onto them, enabling imaging of their nanoscale magnetic domains.

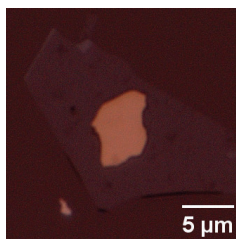


Figure 1: F5GT flake transferred onto the patterned loop antenna. A larger, close-to-transparent flake is the hBN flake capping the F5GT flake.

Fabrication:

Loop antennas were fabricated by patterning loop antenna onto a 2-inch sapphire (single-side-polished) wafer with the Heidelberg MLA 150 Maskless Aligner, followed by cleaning with Oxford 81/82, and sputtering Ti (10 nm)/Pt (150 nm) films. The patterned wafers were subsequently diced using a DISCO Dicing Saw. A nanoflake of F5GT, capped with hexagonal boron nitride (hBN), was transferred onto the center of the loop antenna (Fig. 1). For scanning NV measurements, the Westbond 7400A Ultrasonic Wire Bonder was used to wirebond the antenna to a rf circuit component.

Conclusions and Future Steps:

Using our variable-temperature scanning NV setup, we were able to capture the near- T_c ferromagnetic domain stabilization of the exfoliated flakes. Figure 2 shows the representative scanning NV images for variable temperatures, for a representative flake (28 nm thick furnace-cooled flake), taken with a probe-to-sample distance of 100 nm. As the temperature decreases, magnetic contrast becomes more pronounced and domain features nucleate, reaching a stray field contrast of approximately 10 G at 280 K, indicating the stabilization of ferromagnetic order.

Furthermore, we observe that the furnace-cooled flake and quench-cooled flake show different magnetic domain features at 280 K. Figure 3 shows scanning NV images of the furnace-cooled flake, measured at a probe-to-sample distance of 100 nm, and the quench-cooled flake, measured at a probe-to-sample distance of 200 nm. At this temperature, the 90 nm thick quench-cooled flake exhibits magnetic domain features that are elongated in an almost single direction (along the y-direction).

In contrast, the 28 nm thick furnace-cooled flake displays multiple nematic domain directions.

To further investigate the magnetic properties of F5GT flakes, we are planning to measure scanning NV images with varying bias magnetic field, which can allow us to further resolve the evolution of magnetic domain features and the underlying magnetic anisotropy.

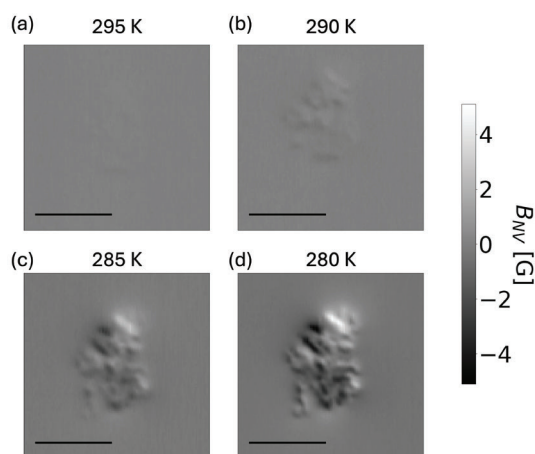


Figure 2: Stray magnetic field imaging of 28 nm thick, furnace-cooled F5GT flake at (a) 295 K, (b) 290 K, (c) 285 K, and (d) 280 K. The images were taken with a probe-to-sample distance of 100 nm. The scale bar represents 5 μm .

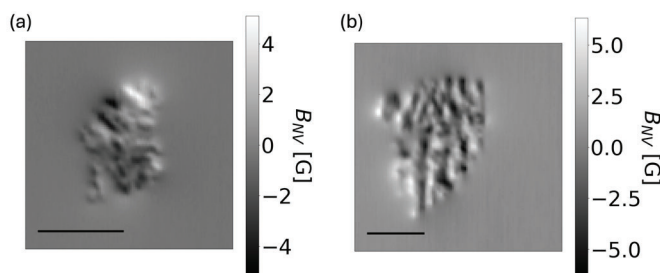


Figure 3: Stray magnetic field imaging of F5GT flakes at 280 K: (a) 28 nm thick, furnace-cooled F5GT flake, and (b) 90 nm thick, quench-cooled F5GT flake. The images were taken with a probe-to-sample distance of 100 nm for the furnace-cooled flake and 200 nm for the quench-cooled flake.

References:

- [1] K. S. Burch, D. Mandrus, and J.-G. Park, *Nature*, 563, 47-52 (2018).
- [2] A. F. May et al., *ACS Nano*, 13, 4436 (2019).
- [3] M. Ghidini et al., *ACS Nano* 19, 26193 (2025).