Probing Spin Dynamics in Exfoliated van der Waals Ferromagnet Fe_5GeTe_2 Using Superconducting Resonators

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Primary CNF Tools Used: AJA Orion Sputtering Systems, Heidelberg MLA 150 Maskless Aligner, Oxford 81/82, PT770 Etcher, DISCO Dicing Saw, Westbond 7400A Ultrasonic Wire Bonder

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 and low Gilbert damping. However, bulk measurements are often limited by structural inhomogeneities. Here, we present a single-flake ferromagnetic resonance (FMR) study of exfoliated F5GT nanoflakes using high-Q superconducting resonators ($Q > 10^4$) to probe intrinsic damping properties with enhanced sensitivity. We observed ferromagnetic resonance in an F5GT flake transferred onto a 4 GHz superconducting resonator, demonstrating magnetic coupling between the flake and the resonator. The extracted upper bound for the Gilbert damping parameter is slightly lower than bulk values, indicating reduced damping in exfoliated samples. To further resolve damping contributions, we have also fabricated quarter-wavelength resonators with overtone modes and Q-factors exceeding 10^6, enabling frequency-resolved separation of viscous and inhomogeneous linewidth broadening. This work can offer new insights into the dynamical properties of van der Waals magnets.

Experimental Procedure:

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 significantly below room temperature, restricting their practical use. Recently, a promising candidate—Fe_5GeTe_2 (F5GT)—has been identified [2], demonstrating a Curie temperature of up to 332 K in bulk [3] and 280 K in exfoliated thin flakes (~10 nm) [2]. A recent ferromagnetic resonance (FMR) study reported that bulk F5GT crystals exhibit effective Gilbert damping coefficient of $\alpha \approx 0.01$—comparable to permalloy (NiFe)—although the measurements revealed substantial inhomogeneous linewidth broadening beyond viscous (Gilbert) damping contributions [3].

To better assess the intrinsic damping properties, we perform FMR measurements at the single- flake level using exfoliated F5GT, which are expected to be more structurally pristine. For this purpose, we design and fabricate high-Q superconducting resonators ($Q > 10^4$) and transfer exfoliated F5GT flakes onto them, enabling sensitive detection of their dynamic magnetic response (Fig. 1).

Fabrication:

Niobium (Nb) films were sputtered onto high-resistivity Si (100) wafers using AJA Orion Sputtering Systems. Superconducting resonators were fabricated by patterning the Nb layer with the Heidelberg MLA 150 Maskless Aligner, followed by cleaning with Oxford 81/82 and dry etching using a PT770 Etcher. The patterned wafers were subsequently diced using a

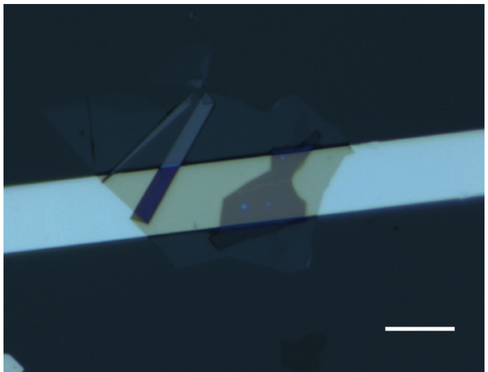

Figure 1: F5GT flake transferred onto the patterned inductor line of the 4 GHz superconducting resonator. A larger, close-to-transparent flake is the hBN flake capping the F5GT flake. The scale bar represents 10 µm.

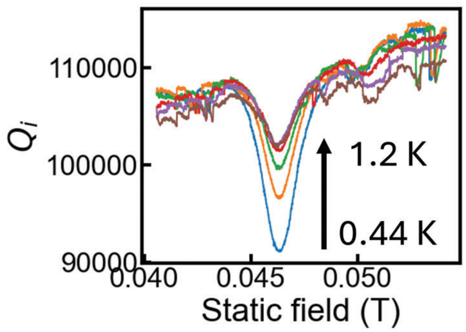

Figure 2: Ferromagnetic resonance (FMR) line at various temperatures.

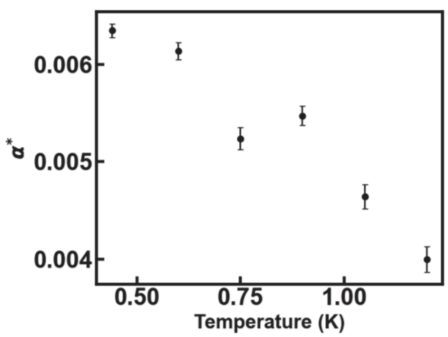

Figure 3: Estimated upper limit in Gilbert damping α at various temperatures..*

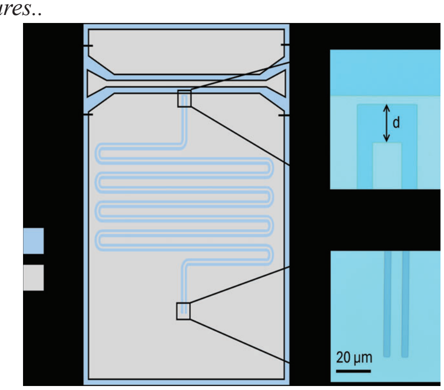

Figure 4: Schematic of the quarter-wavelength superconducting resonator. The zoomed-in optical images show the capacitive end and the inductive end of the resonator. The gap distance d in the capacitive end is 20 µm.

DISCO Dicing Saw. A nanoflake of Fe_5GeTe_2 (F5GT), capped with hexagonal boron nitride (hBN), was transferred onto the inductor line of the superconducting resonator (Fig. 1). For ferromagnetic resonance (FMR) measurements, the Westbond 7400A Ultrasonic Wire Bonder was used to wirebond the resonator to an electrical circuit component.

Conclusions and Future Steps:

We performed ferromagnetic resonance (FMR) measurements on a 25 nm F5GT flake capped with a 10 nm hBN flake that is transferred onto a 4 GHz lumped-element superconducting resonator. As shown in Fig. 2, we observe a decrease in the intrinsic Q-factor (Qi) at a static magnetic field of 0.046 T. This reflects that as the F5GT flake comes into resonance, it is drawing energy out of the superconducting resonator, which results in an apparent decrease in Qi. This measurement confirms the coupling between the flake and the resonator and demonstrates successful single- flake FMR detection.

To estimate an upper bound for the Gilbert damping parameter (α*), we analyze the FMR linewidth under the assumption of negligible inhomogeneous broadening. The extracted α* values are slightly lower but comparable to bulk values reported at 10 K ($\alpha \approx 0.007$), suggesting reduced damping in the exfoliated sample (Fig. 3). Interestingly, we observe that α decreases with temperature in the range of 0.4 – 1.2 K. To further investigate damping properties at the single-flake level, we have designed and fabricated quarter-wavelength superconducting resonators with optimized Q-factors, targeting values exceeding 106 (Fig. 4). A key advantage of this approach is that we will use the many overtone resonances, each as a separate frequency probe, which will allow us to distinguish viscous Gilbert damping from inhomogeneous linewidth broadening. The zoomed-in optical images show one representative device from a set of resonators we fabricated with varied gap distances, all of which are ready for FMR characterization. We plan to measure each resonator's Q-factor, transfer F5GT nanoflakes, and utilize overtone modes to extract the intrinsic damping parameters of F5GT with enhanced spectral resolution.

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