Probing Nanoscale Magnetism in 2D van der Waals Ferromagnet Fe5GeTe$_2$ with Magneto-Thermal Microscopy

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Primary CNF Tools Used: GCA 6300 DSW 5X g-line Wafer Stepper, AJA Orion Sputtering Systems, DISCO Dicing Saw, Heidelberg Mask Writer – DWL2000, Westbond 7400A Ultrasonic Wire Bonder

Abstract:

The relevant length and time scales of magnetic phenomena are typified by the width of domain walls, ranging over 10-1000 nm, and the time scale of ferromagnetic resonance and spin waves, ranging over 10-1000 ps. Currently, synchrotron x-ray techniques are the only reliable methods capable of simultaneously resolving both spatial and temporal scales. However, they are facility techniques that impose a limit on its accessibility and throughput. Here, we present a table-top method called magneto-thermal microscopy [1], to study magnetism with a spatial resolution of 650 nm (≤ 100 nm with near-field methods [2]) and a temporal resolution of 10-100 ps. This technique is based on the magneto-thermoelectric anomalous Nernst effect for conducting magnetic materials. The spatial resolution is limited only by the area of the thermal excitation, and it possesses no fundamental limit due to diffraction. We present a study of the recently discovered two-dimensional ferromagnetic van der Waals metal Fe_5GeTe_2 [3] using magneto-thermal microscopy to image the static magnetization at low temperatures. This work is part of an ongoing effort using magneto-thermal interactions to probe the competition between spin and charge ordered phases of this material, along with associated changes in band structure [4].

Summary of Research:

Two-dimensional (2D) magnets are interesting for applications in spintronics, in part because of their low-energy switching of spin states through various gating methods and ability to create heterostructures with engineered properties [5]. They are also interesting for their exotic quantum phenomena such as topological states, anomalous Hall effect, quantum spin hall effect, and skyrmions [5]. However, most 2D ferromagnetic materials have Curie temperatures well below room temperature, which limits their commercial applications.

A new material, Fe_5GeTe_2 (F5GT), has recently emerged [3] with a Curie temperature as high as 332 K in bulk [6] and 280K in exfoliated thin flakes (10 nm) [3]. Unlike most other 2D ferromagnets, F5GT has magnetic easy-plane anisotropy, and the magnetization vs. temperature plots across many different studies exhibit exotic phase transitions [3-4, 6-7]. In particular, it shows a ferro- to ferri-magnetic transition at 275 K [6], suspected competition between spin and charge order at 180 K, and a transition caused by the fading of charge order at 110 K [4] (the exact transition temperatures depends on the experiment).

Our research utilizes a unique experimental technique called “magneto-thermal microscopy” [1] to study the magnetic behaviors of thin F5GT flakes (Figure 1). We can determine the in-plane local magnetic moment $\vec{M}$ of a material via the anomalous Nernst effect (ANE) by applying an out-of-plane thermal gradient $\vec{\nabla}T$, as given by the equation $\vec{E}_{ANE} = -N\vec{M} \times \vec{\nabla}T$, and measuring the anomalous Nernst voltage V_{ANE} created by the ANE electric field $\vec{E}_{ANE}$. A schematic is shown in Figure 2.

A spatially localized and short-lived thermal gradient creates an $\vec{E}_{ANE}$ that is also spatially localized and short-lived, hence the spatial resolution depends only on the size of the thermal excitation and is not inherently limited (e.g., by diffraction). The temporal resolution depends on how long it takes the thermal gradient to equilibrize. With this, we obtain a sub-micron spatial resolution of 0.65 µm and a temporal resolution of typically < 30 ps.

Fabrication:

The F5GT nanoflake, provided by our collaborator, was placed on top of electrical contact pads fabricated via photolithography at CNF. The photomask was created with the Heidelberg Mask Writer – DWL2000, and the substrate was exposed using the GCA 6300 DSW 5X g-line Wafer Stepper. Ti/Pt was sputtered using AJA Orion Sputtering Systems to form conducting pads. The resulting wafer was diced into 5 mm × 5 mm pieces using the DISCO Dicing Saw.

To take electrical measurements (i.e., V_{ANE}), the Westbond 7400A Ultrasonic Wire Bonder was used to wirebond the contact pads to an electrical circuit component.

Conclusions and Future Steps:

While magneto-thermal microscopy has been used in the past to study various ferromagnetic and antiferromagnetic metals and insulators, this study is the first to apply it to 2D materials. Our preliminary results confirm that we can use magneto-thermal microscopy to study and image magnetization of 2D ferromagnets as shown in Figure 3. Magnetic domains are visible at an applied field of 67 G at 77 K, and we can characterize its magnetic properties by varying the field and temperature, alongside taking magnetic hysteresis measurements. With this, we would like to further investigate the exotic phase transitions at 180K and 110K, which Wu, et al. (2021) proposed is due to the competing charge and spin orders [4]. We would like to expand upon this topic by probing the magnetization vs. temperature behavior at different field cooling to help elucidate the energy barriers between the competing orders, as well as magnetic imaging to illustrate the spatial extent of the different phases. In addition, our magneto-thermal microscopy can not only measure magnetization via ANE, but it is also capable of current imaging, which can give different signatures of the charge and spin order.

References:

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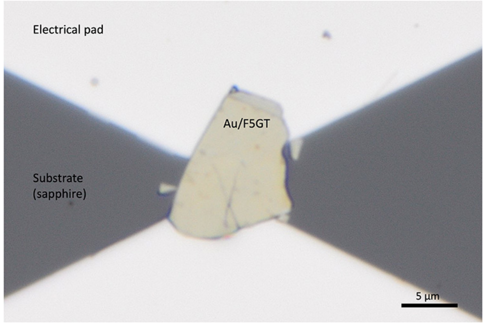

Figure 1: Optical image of a F5GT sample, Au coated to prevent degradation.

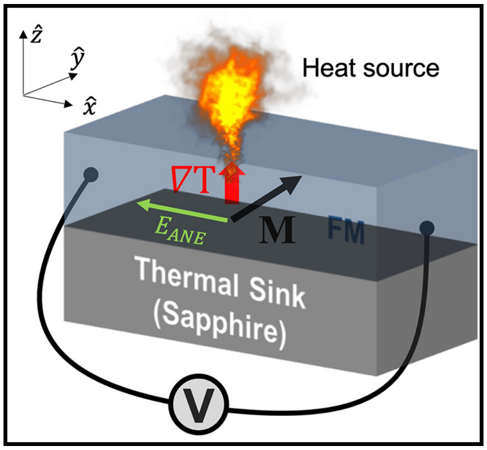

Figure 2: Schematic of the magneto-thermal microscopy technique, which exploits the anomalous Nernst effect to extract the local magnetic moment of a material.

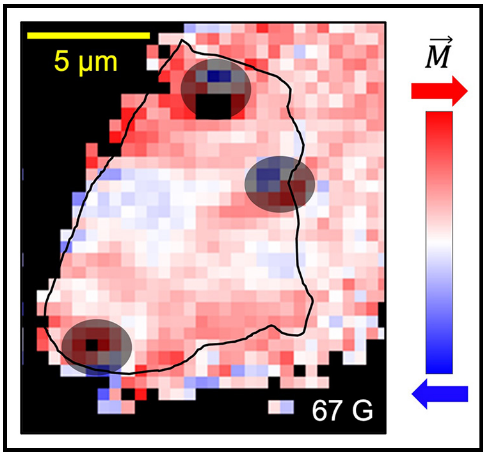

Figure 3: Magnetization image of F5GT sample shown in Figure 1 (outlined here) taken with magneto-thermal microscopy. The sample was cooled to 77 K then an external field of 67 G was applied. Magnetic domains are visible. Highly noisy parts are blacked out or shaded.