Probing Ferromagnetism in van der Waals Iron Germanium Telluride

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The developing material class of van der Waals (vdW) magnets has attracted great interest due to their novel properties such as gate and strain tunable magnetism.[1] Magnetism at the atomic limit remains difficult to explore however due to the air instability of most vdW ferromagnets. Commonly studied 2D magnets such as Fe_3GeTe_2 (FGT) and $Cr_2Ge_2Te_6$ (CGT) rapidly oxidize under ambient conditions,[2,3] making it difficult to use processes such as photolithography and electron beam lithography to deposit electrodes on a flake without exposing it to the atmosphere. Even momentary exposure (i.e. when moving a sample from a glovebox to a sputtering chamber) can significantly affect the flake's surface.[4] In this work, we show that pre-patterned electrode arrays can offer a simple means of probing 2D magnetism using electrical transport while minimizing exposure to air and eliminating the risk of damaging the material surface during metal deposition. Using this device structure, we systematically characterized the anomalous Hall effect in FGT flakes.

Arrays of Ti/Au Hall bar electrodes were formed on 90 nm SiO_2 using photolithography and metal deposition. The electrodes consist of 10 nm Ti/100 nm Au. FGT flakes were then transferred on top of electrodes using Polydimethylsiloxane (PDMS) or gel-films. Flakes were exfoliated and transferred in both the air as well as a nitrogen glovebox. Illustrations of a typical device as viewed from the top and side and shown in Figs. 1a and 1b, respectively. The FGT flakes are flexible enough to bend over the electrodes and prevent further oxidation to the underside of the flake. The topography and height profile of an FGT Hall bar device are shown in Fig. 1c and 1d respectively. The thickness of the FGT flake is ~42 nm. When transferred and exfoliated in air, the FGT flake demonstrated ferromagnetic switching via the anomalous Hall effect (AHE) as shown in Fig. 1e. For a magnetic conductor, the Hall voltage can be decomposed into two parts $V_{xy} = V_{NH} + V_{AH}$, where $V_{NH} = R_0 BI$ is normal Hall voltage, and $V_{AH} = R_s M$ is anomalous Hall voltage. R_0 and R_s are coefficients characterizing the strength of V_{NH} and V_{AH}, respectively. B and M are the applied magnetic field and the sample magnetization perpendicular to the sample surface, respectively. I is the current flow along the channel. As FGT is a metallic ferromagnetic material, the normal Hall resistance is negligible compared with the anomalous Hall resistance in the magnetic field range of interest. Hence, the shape of the V_{xy} vs B loop is the same as that of the M vs B loop. The coercive field can be obtained from the V_{xy} (B) curve. For the flake transferred in air, the hysteresis window is very narrow, which can be attributed to degradation of the flake in air. When transferred in a <10 ppm O_2 nitrogen glovebox, the quality of the AHE measurements improved significantly as shown in Fig. 1f. A large hysteresis window was observed at 40 K. As the temperature increases, the hysteresis window gradually reduces as indicated in Fig. 1g. At 200 K, the ferromagnetic switching was still apparent, which is consistent with the material's bulk Curie temperature of 220 K.[2] Note that transferring of the flake directly onto the electrodes eliminates the risk of the contacts being degraded from the damage during metal deposition and minimizing the oxidation of the FGT flake during the photolithography process, which facilitates the experimental observation of AHE in these FGT flakes.

In summary, we demonstrate that pre-fabricated Hall bar electrodes can be used to probe magnetism in FGT flakes via the anomalous Hall effect. Utilizing this device structure, we systematically investigated the magnetic properties of FGT. Clear ferromagnetic hysteresis windows were clearly observed at temperatures up to 200 K. These vdW Hall bar structures provides a highly efficient and damage-free strategy for metal integration, which could be used in many other 2D magnetic materials.

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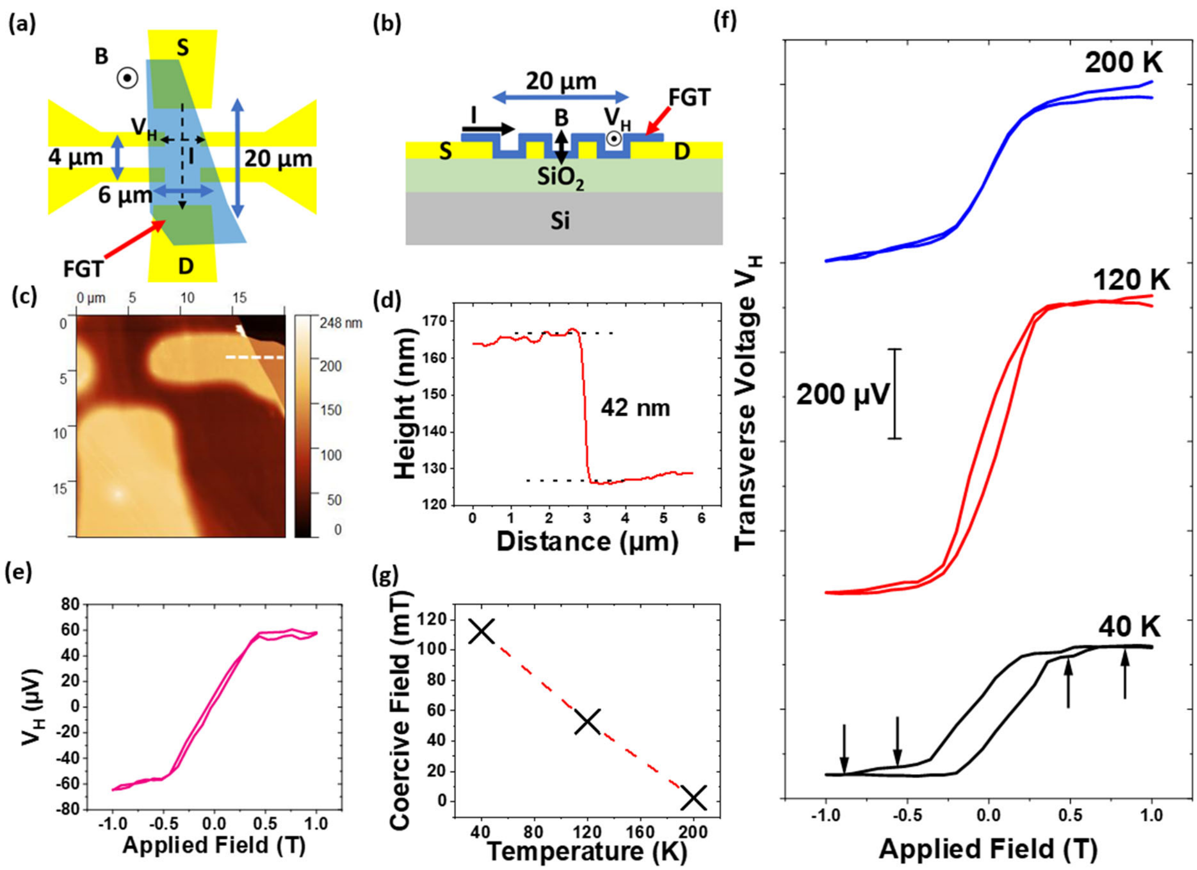

Figure 1: (a) Top and (b) side views of device. The blue region represents the FGT flake. (c) AFM image of FGT flake and electrode. (d) Height profile of the FGT flake and electrode along dashed line in (c), showing a typical thickness. (e) Transverse voltage measurements of FGT flake transferred in air at 40 K. (g) Extracted coercive field of FGT flake vs temperature. (f) Transverse measurements of flake transferred in nitrogen glovebox. Steps in the hysteresis loop at lower temperatures (highlighted by arrows) indicate large domain formation in the FGT flake.