Gate-Tunable Anomalous Hall Effect in a 3D Topological Insulator/2D Magnet van der Waals Heterostructure

CNF Project Number: 598-96

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Primary Source(s) of Research Funding: Air Force Office of Scientific Research, Department of Energy

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Primary CNF Tools Used: Zeiss Supra SEM, Nabity Nanometer Pattern Generator, AJA Sputter Deposition, CVC SC4500 Even-Hour Evaporator

Abstract:

We demonstrate advantages of samples made by mechanical stacking of exfoliated van der Waals materials for controlling the topological surface state of a 3-dimensional topological insulator (TI) via interaction with an adjacent magnet layer. We assemble bilayers with pristine interfaces using exfoliated flakes of the TI $BiSbTeSe_2$ and the magnet $Cr_2Ge_2Te_6$, thereby avoiding problems caused by interdiffusion that can affect interfaces made by top-down deposition methods. The samples exhibit an anomalous Hall effect (AHE) with abrupt hysteretic switching. For the first time in samples composed of a TI and a separate ferromagnetic layer, we demonstrate that the amplitude of the AHE can be tuned via gate voltage with a strong peak near the Dirac point. This is the signature expected for the AHE due to Berry curvature associated with an exchange gap induced by interaction between the topological surface state and an out-of-plane-oriented magnet.

Summary of Research:

Interactions between three-dimension topological insulators (TIs) and magnets can induce exotic topological phases like the quantum anomalous Hall or axion insulator states, and might be used to harness the properties of topological-insulator surface states in spintronic devices [1]. We study TI/magnet bilayers using an all-van der Waals (vdW) heterostructure, by stacking together in a glovebox exfoliated flakes of the TI $BiSbTeSe_2$ and the insulating magnet $Cr_2Ge_2Te_6$ [2].

In contrast to previous work on TI/magnet samples grown by top-down deposition methods, or made by assembling exfoliated flakes with air exposure, the use of a glovebox-assembled vdW structure ensures a defect- and diffusion-free atomically-flat interface. Further, our use of a thin insulating vdW magnet enables both spatially-uniform magnetic coupling to the topological surface state and large tunability of the electron chemical potential using electrostatic gating (see Figure 1 for device structure and gating geometry). We measure the anomalous Hall response while continuously controlling the contribution of the surface state by gating.

The out-of-plane magnetization of the CGT is expected to break time-reversal symmetry in the BSTS surface through proximity coupling and result in the opening of an exchange gap (Δ) in the adjacent Dirac surface state, as described by the following 2D Dirac Hamiltonian:

$$H(k) = \hbar v_F(k_x\sigma_y - k_y\sigma_x) + \Delta\sigma_z$$

where $\sigma_{x,y,z}$ are the Pauli spin matrices, k_x and k_y are in-plane wave vectors, and v_F is the Fermi velocity. States in the vicinity of the gap have non-zero Berry curvature, with equal and opposite values on opposite sides of the gap. Therefore when states on opposite sides of the gap have unequal occupations, the result is a nonzero Hall conductance, σ_{xy}. The peak value of the Hall conductance, when the electron chemical potential lies in the gap, should be $e^2/2h$ in the low temperature limit (3). Consequently, a peak of the Hall resistivity ($\rho_{xy} = \sigma_{xy}/(\sigma^2_{xx} + \sigma^2_{xy})$), where σ_{xx} is the longitudinal conductivity) should be found when the chemical potential is tuned through the gap.

In Figure 2a, we show the Hall resistance (R_{xy}) after subtraction of the ordinary Hall background for the measurement done at top gate voltage V_{tg} = 0V. The measurements are performed at 4.4K and under a constant bias current, with the bottom-gate voltage V_{bg} fixed at 0V. The current flows primarily through the BSTS layers since CGT is insulating at this temperature. We observe hysteretic step-like changes in V_{xy} corresponding to an anomalous Hall effect (AHE), indicative of a strong perpendicular anisotropy for the magnetism in CGT that is coupled to the BSTS surfaces.

As the chemical potential of the top surface is tuned by varying the V_{tg}, we observe a modulation in the observed AHE signal. The amplitude of the AHE response is maximum at V_{tg} = 0.55V and becomes smaller as the gate voltage is tuned on either side of this maximum.

In Figure 2b, we plot the extracted signal size of the anomalous Hall resistance response as a function of V_{tg} (black trace). This trend tracks approximately with the gating behaviour of the longitudinal resistance R_{xx} shown by the dotted blue trace. We therefore identify the maximum in the AHE response as due to tuning of the electron chemical potential within the exchange gap, as expected from the Berry curvature picture.

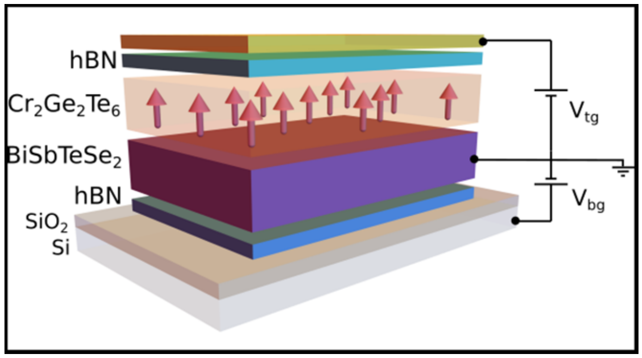

Figure 1: Schematic of the device geometry and electrostatic gating geometry. TI and 2D magnet flakes with few-layer thickness are double-encapsulated between h-BN layers on a Si/SiO_2 substrate.

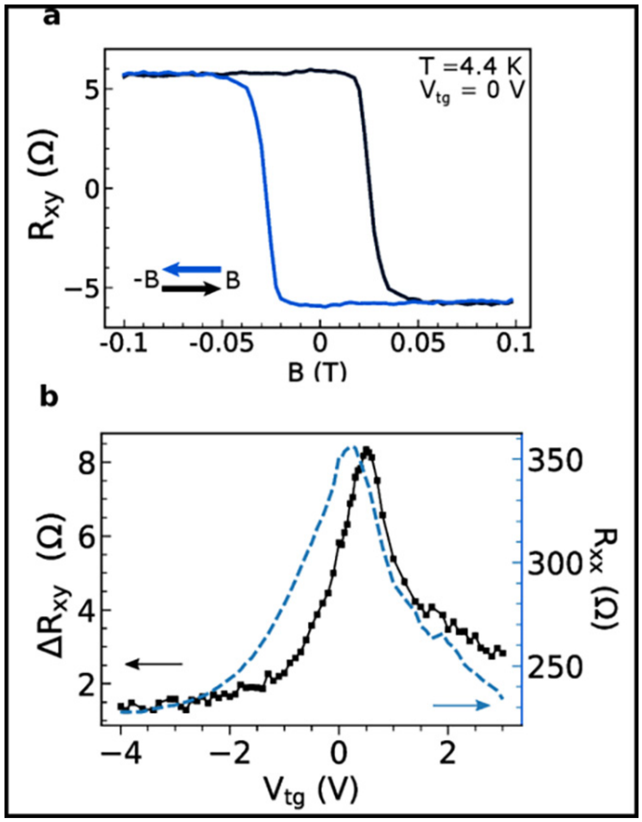

Figure 2: (a) AHE contribution to R_{xy} at V_{tg} = 0 after subtraction of linear background. (b) Size of AHE signal (black solid line) ΔR_{xy} as a function of top-gate voltage. The trend matches closely with the observed top-gate dependence of R_{xx} (blue dashed line) measured at zero magnetic field.

Conclusions and Future Directions:

We have demonstrated that the use of mechanical assembly of van der Waals materials to form a pristine interface provides a strategy that avoids materials challenges which have inhibited research progress in studying topological insulator/magnet heterostructures grown by molecular beam epitaxy or other deposition techniques. The high quality of mechanically-assembled van der Waals structures provides a platform for future studies of the quantum anomalous Hall and axion insulator states, and the rich phenomenology of topological magneto-electric phenomena predicted for these states.

References:

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[3] Xiao, D., Chang, M.-C. and Niu, Q. Berry phase effects on electronic properties. Rev. Mod. Phys. 82, 1959 (2010).