Progress Report

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Recipient: Massachusetts Institute of Technology

b. Project Name: Quantum Transport in Topological Insulator Nanoelectronic Devices

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d. Accomplishments

Background

This is the final report of our research program on electronic transport experiments on Topological Insulator (TI) devices, funded by the DOE Office of Basic Energy Sciences. TI-based electronic devices are attractive as platforms for spintronic applications[1], and for detection of emergent properties such as Majorana excitations[2], electron-hole condensates[3], and the topological magneto-electric effect[4]. Most theoretical proposals envision geometries consisting of a planar TI device integrated with materials of distinctly different physical phases (such as ferromagnets and superconductors). Experimental realization of physics tied to the surface states is a challenge due to the ubiquitous presence of bulk carriers in most TI compounds as well as degradation during device fabrication.

Program Accomplishments

We initially approached these challenges by developing two alternative device fabrication approaches: the first approach is based on contacting Bi_2Se_3 flakes exfoliated from a single crystal, which we employed for establishing that the surface channel supports electronic transport[5], that its density is tunable by a gate voltage, and that the surface-state's spin-helicity allows for a polarization-dependent photocurrent[6]. The second approach is based on patterning thin-films of Bi_2Se_3 grown in an ultra-high vacuum chamber. We investigated the nature of coherent transport in the TI system[7], where weak antilocalization (WAL) emerges as a consequence of the strong spin-orbit coupling in the system. Using low carrier density films we demonstrated that the contribution of both surfaces to coherent transport phenomena can be separated from each other as the system is tuned so that the bulk is largely removed. This principle, the additivity of phase coherent phenomena, is now widely acknowledged as an intrinsic property of multi-channel transport systems and is used as a measure of surface-dominated transport in TI systems.

We then extended our efforts in surface-sensitive probes which include tunneling spectroscopy and dual-gated transport. These were implemented in exfoliated devices of Bi_2Se_3 and

$Bi_{0.5}Sb_{1.5}Te_{1.7}Se_{1.3}$ (BSTS), respectively. In both cases, we extended our development of an advanced fabrication technique based on exfoliated thin film transfer, which allows us to integrate TI layers into heterostructures including hexagonal Boron-Nitride (h-BN) and graphene. The projects we report are: (i) dual-gated transport in h-BN—TI heterostructures, through which we can begin to understand the effects of charged impurities on thin device behavior, (ii) TI-graphene junctions.

Previously in the literature, evidence for surface-dominated transport was found, but the absence of bulk states was not confirmed[8,9]. Here, we fabricated dual-gated transport devices from BSTS, and found clear evidence of transport with two surface states that are separately modulated by the top and bottom gate electrodes. For the first time, we observed independently tunable surface states on both the top and bottom surfaces. Moreover, for the first time we find that a resistance peak (associated with the surface state Dirac point) is observable at room temperature. Thin devices showed clear evidence for electric field penetration through the bulk, which we quantified by tracking the motion of the resistance peak of the upper surface charge neutrality point as a function of both gate voltages. We developed an electrostatic charging model to explain the motion and found good agreement with angle-resolved photoelectron spectroscopy (ARPES) measurements of the surface state density-of-states while also quantifying the dielectric constant of the interior of the TI material (our primary fitting parameter)[10]. For a thicker device (80nm thick) we found that there was no electric field penetration through the bulk of the sample. We can understand this from a theoretical framework developed to explain the anomalously small energy gap measured in transport of macroscopic samples of compensation-doped materials like BSTS[11]. We extended this theoretical framework to the case of a thin slab with two surface states contributing to screening, and find that surface state screening can result in true dielectric behavior even when a thicker crystal would have had bulk puddles capable of charging. Finally, we found that applying a magnetic field resulted in an increase of electric field penetration, possible originating from the creation of a gap in the surface state spectrum.

We also began a new direction for the field by studying the behavior of TI-graphene junctions. In many cases we found tunneling-like behavior in the transport characteristics of the junction – measured dI/dV curves agree strikingly well with scanning tunneling microscopy measurements of Bi_2Se_3. We found interesting dispersive features in the tunneling spectra, which are related to elastic and inelastic (phonon-assisted) tunneling into the charge neutrality point in the bilayer graphene. We related such patterns to observations in STM studies on back-gated graphene, in which the dispersive and non-dispersive features are associated with plasmons[12] and phonons[12,13], respectively. Based on the energies of the non-dispersive features, we have identified many of the features to be associated with inelastic tunneling via graphene phonons[14]. This generates questions about the nature of momentum-conserving tunneling between systems with mismatched Brillouin zones, a potentially fruitful direction of future research.

In our work on TI thin films, coupling to ferromagnetic insulator was achieved by epitaxial growth of EuS onto Bi_2Se_3. We found, via a collaboration to perform polarized neutron reflectivity measurements on the films, that signatures of magnetism persist up to nearly room temperature, which is much larger than observed in a bare EuS film itself. The technique also allows fo a depth-dependence measurement, finding that the induced magnetism penetrates about two nanometers into the TI film. This strong interfacial magnetism is surprising in itself, and moreover paves the way towards local breaking of time reveral symmetry on TI surfaces[15]. We also investigated Cr-doped Bi_2Se_3 thin films, finding clear signatures ferromagnetism in both electronic transport and magnetometry measurements[16].

We have also had successful collaborative efforts between the Gedik and Jarillo-Herrero groups. First we studied potential spintronic applications in TIs by expanding its notion to include helicity induced photocurrents, which we dubbed "optospintronics". An experiment was designed specifically to search for such photocurrents in electronic devices fabricated using exfoliated crystals of low bulk density Bi_2Se_3. A photocurrent was discovered that reverses direction upon changing the light polarization from left- to right-circularly polarized. These results are consistent with the surface state spin-distribution revealed by ARPES, confirming the surface nature of these currents[6]. In a second collaboration, Floquet-Bloch states of TI surface states were discovered by using pump-probe time-resolved ARPES[17]. Finally, we have also collaborated to do a second-harmonic generation study on the previously discussed EuS-Bi_2Se_3 bilayer epitaxial films to understand their in- and out-of-plane magnetic behaviors[18].

Finally, we investigated a potentially new 2D Topological Insulator: monolayer WTe_2. This material has already displayed remarkable properties in the bulk, particularly including an exceptionally large magnetoresistance phenomenon[19,20]. In ultra-thin films, however, the samples are prone to chemical degradation[21,22]. As such, in our first study on 2D samples, we developed a fabrication methodology that enables preservation of the WTe_2 flake throughout the fabrication process. We showed that few-layer WTe_2 displays similar magnetoresistance phenomena to the bulk material, with the additional capability to electrostatically turn the magnetoresistance off by tuning the system out of the semimetallic regime. The magnetoresistance itself was found to be sub-quadratic, with a gate-independent power-law exponent[23]. These results paved the way towards ongoing monolayer WTe_2 experiments that will aim to confirm that it is a topological system.

e. List of Papers (all published)

1. J. W. McIver, D. Hsieh, H. Steinberg, P. Jarillo-Herrero, N. Gedik. "Photon helicity dependent currents in an optically driven topological insulator" Nature Nanotechnology **7**, 96 (2012).

2. Y. H. Wang, D. Hsieh, E. J. Sie, H. Steinberg, D. R. Gardner, Y. S. Lee, P. Jarillo-Herrero, N. Gedik. "Measurement of Intrinsic Dirac Fermion Cooling on the Surface of the Topological Insulator Bi_2Se_3 Using Time-Resolved and Angle-Resolved Photoemission Spectroscopy" Physical Review Letters **109**, 127401 (2012).

3. P. P. J. Haazen, J.-B. Laloe, T. J. Nummy, H. J. M. Swagten, P. Jarillo-Herrero, D. Heiman, J. S. Moodera. "Ferromagnetism in thin-film Cr-doped topological insulator Bi_2Se_3" Applied Physics Letters **100**, 082404 (2012).

4. Y. H. Wang, H. Steinberg, P. Jarillo-Herrero, N. Gedik, "Observation of Floquet-Bloch States on the Surface of a Topological Insulator" Science **342**, 453 (2013).

5. V. Fatemi, B. Hunt, H. Steinberg, S.L. Eltinge, F. Mahmood, N.P. Butch, K. Watanabe, T. Taniguchi, N. Gedik, R.C. Ashoori, P. Jarillo-Herrero. "Electrostatic Coupling between Two Surfaces of a Topological Insulator Nanodevice." Physical Review Letters **113**, 206801 (2014).

6. H. Steinberg, L. A. Orona, V. Fatemi, J. D. Sanchez-Yamagishi, K. Watanabe, T. Taniguchi, P. Jarillo-Herrero. "Tunneling in graphene-topological insulator hybrid devices" Physical Review B **92**, 241409(R) (2015).

7. F. Katmis, V. Lauter, F. S. Nogueira, B. Assaf, M. Jamer, P. Wei, B. Satpati, J. W. Freeland, I. Eremin, D. Heiman, P. Jarillo-Herrero, J. S. Moodera. "Achieving high-temperature ferromagnetic topological insulating phase by proximity coupling" Nature **533**, 513–516 (2016).

8. C. Lee, F. Katmis, P. Jarillo-Herrero, J. S. Moodera, N. Gedik. "Direct measurement of proximity-induced magnetism at the interface between a topological insulator and a ferromagnet" Nature Communications **7**, 12014 (2016)

9. V. Fatemi, Q. D. Gibson, K. Watanabe, T. Taniguchi, R. J. Cava, P. Jarillo-Herrero. "Magnetoresistance and quantum oscillations of an electrostatically tuned semimetal-to-metal transition in ultrathin WTe_2" Physical Review B **95**, 041410(R) (2017).

f. People Working on the Project

Hadar Steinberg, Postdoc. Full Support.

Ferhat Katmis, Postdoc. Partial support (30%).

Valla Fatemi, Graduate Student. Partial support (30%).

Lucas Orona, Undergraduate Student. Partial support (10%)

Stephen Eltinge, Undergraduate Student. Partial support (10%)

g. Estimate of the unexpended funds at the end of the budget period

None

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19. Ali, M. N. *et al.* Large, non-saturating magnetoresistance in WTe2. *Nature* **514,** 205–208 (2014).
20. Ali, M. N. *et al.* Correlation of crystal quality and extreme magnetoresistance of WTe 2. *EPL* **110,** 67002 (2015).
21. Wang, L. *et al.* Tuning magnetotransport in a compensated semimetal at the atomic scale. *Nat Commun* **6,** 8892 (2015).
22. Ye, F. *et al.* Environmental Instability and Degradation of Single- and Few-Layer WTe2 Nanosheets in Ambient Conditions. *Small* **12,** 5802–5808 (2016).

23. Fatemi, V. *et al.* Magnetoresistance and quantum oscillations of an electrostatically tuned semimetal-to-metal transition in ultrathin ${\mathrm{WTe}}_{2}$. *Phys. Rev. B* **95,** 041410 (2017).