Vanadium Modulation Doping in Topological Insulators to Induce Ferromagnetism

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Abstract

Topological insulators (TI), discovered in 2004, are structures with an insulating bulk and conducting surface states that contain novel topological features, providing a path for the realization of fault-tolerant quantum computing. By breaking the time reversal symmetry of TI, the Quantum Anomalous Hall Effect (QAHE), without an external magnetic field, is expected to emerge in the two-dimensional TI and forms a dissipation-less chiral edge state. Previous efforts have utilized homogenous doping of $(Bi,Sb)_2Te_3$ with Cr or V in order to induce ferromagnetism and observe the QAHE at ultra-low temperatures. By modulation doping, the anomalous Hall effect is observed in our penta-layer structure samples, which indicates that ferromagnetism has been introduced into the films. Additionally, magnetic field dependent longitudinal and Hall resistivity measurements were carried out on the penta-layer samples by varying the chemical potential with gate voltages. Although the anomalous Hall resistance only displayed a maximum of 36 Ω, robust ferromagnetism shows the effectiveness of this approach for future exploration.

Introduction

What is a Topological Insulator?

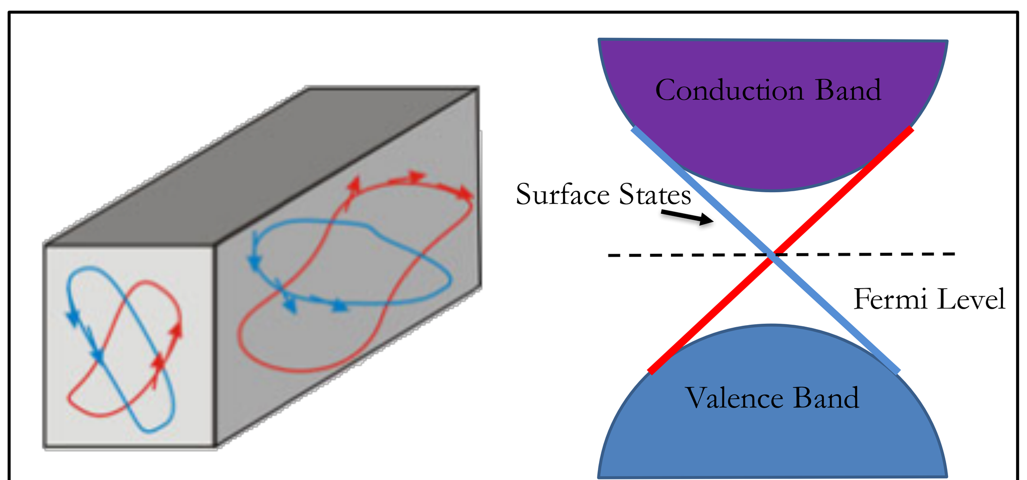


Figure 1: Schematic image and band structure of TI. The surface state as shown gives rise to novel properties of this system such as high mobility on the surface whereas in the bulk, it is nearly insulating. The surface transport is immune to scattering.

What is QAHE?

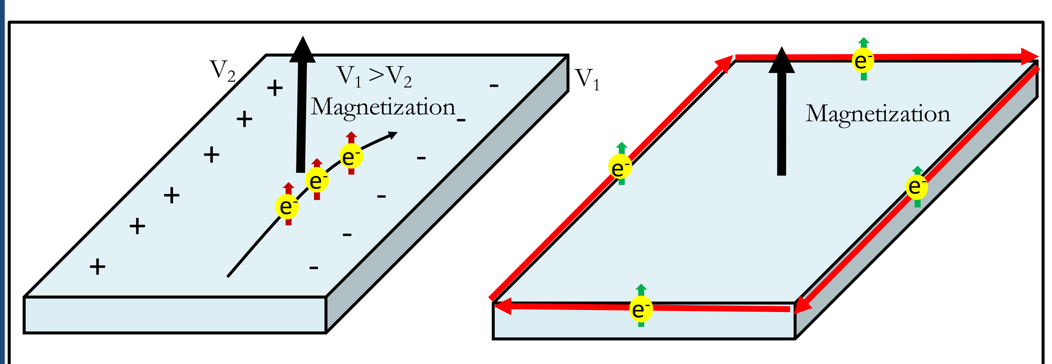


Figure 2: AHE and QAHE.

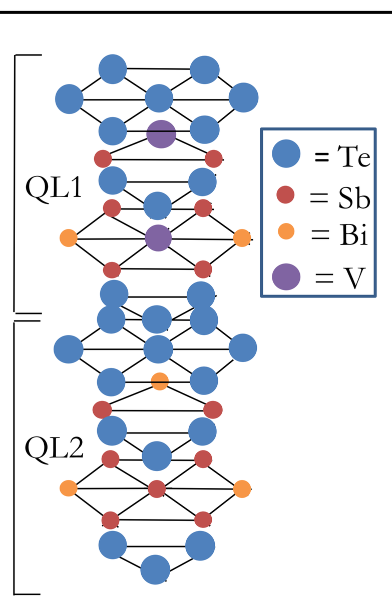
Anomalous Hall Effect (AHE)

- Spontaneous magnetization causes internal magnetization.
- Electron drift to one side of the material.

Quantum Anomalous Hall Effect (QAHE)

- Spontaneous magnetization causes internal magnetization.
- Insulating bulk.
- Conducting chiral edge state.
- Quantized Hall resistance (h/e^2).

Creating Ferromagnetism in TI



- **In-layer interactions:**
  - RKKY interaction
  - Van Vleck interaction:
- **Interlayer interactions:**
  - Magnetic exchange interaction

Figure 3: Structure of modulation doped $(Bi,Sb)_2Te_3$ with magnetic dopant Vanadium.

Objectives

- The primary objective is to synthesis thin films that are able to show robust ferromagnetism and the Quantum Anomalous Hall effect by modulation doping of Vanadium in $(Bi,Sb)_2Te_3$.
- Decrease impurity scattering and synthesize clean samples with Molecular Beam Epitaxy through modulation doping.
- Find the optimal doping level and thin film structure to increase the anomalous Hall resistance.

Methods

Make magnetic TI films and characterize them

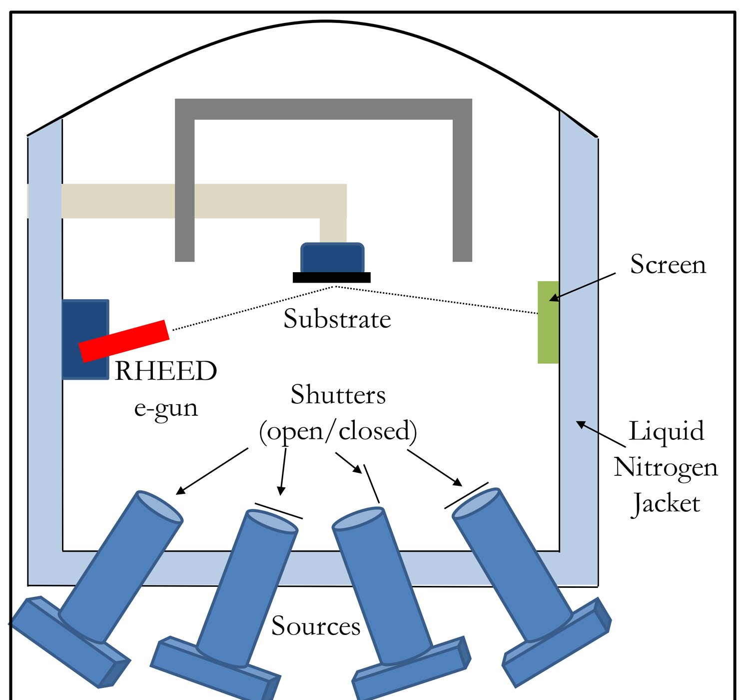


Figure 4: Film growth setup in an MBE

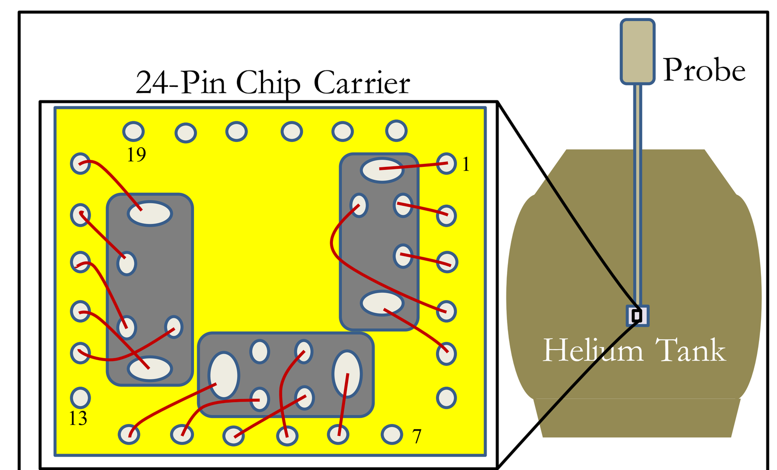


Figure 5: Transport measurement setup: three samples were mounted and gated onto a chip carrier and placed in a Helium Dewar at 4.2K. The carrier can withstand up to ~5.7T.

- 4 Sources are Vanadium, Bismuth, Antimony, and Tellurium.
- Molecular Beam Epitaxy: High vacuum ($<3.7\times10^{-10}$ Torr) for clean samples.
- concentration controllable and thin films and hetero-structures feasible.

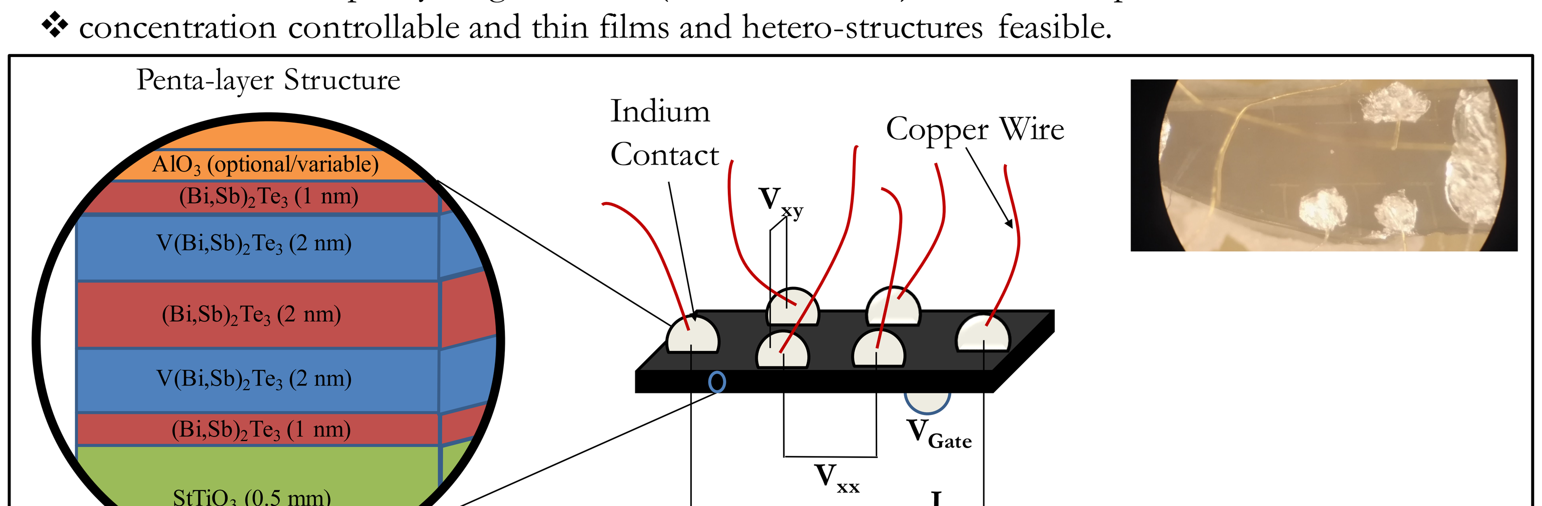
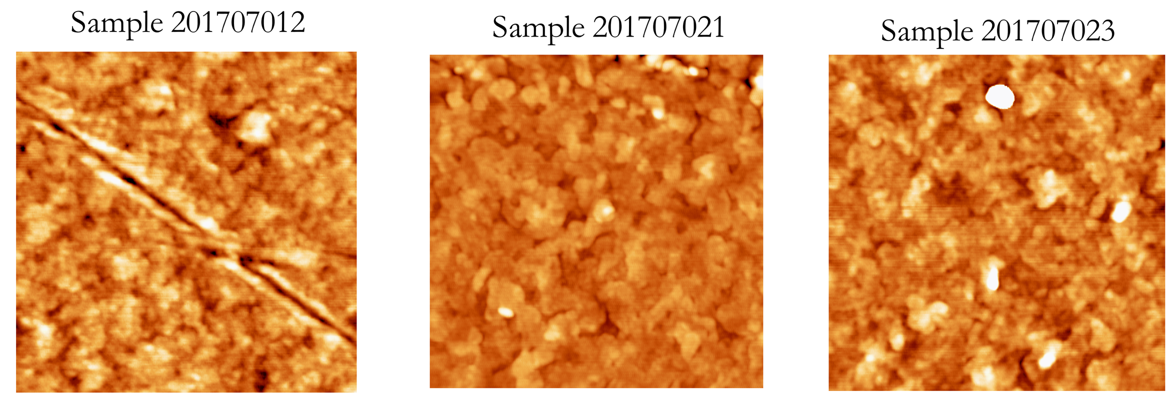


Figure 6: Hetero-structure and devices: The penta-layer structure of the thin film was fabricated and Vanadium-doped layers are indicated in blue.

- STO (111): high dielectric constant for changing chemical potential.
- Devices: mechanical etching through microscope.
- Contacts: mechanically press indium
- Real-life samples of Vanadium-doped thin films on STO (rightmost)

Results

Figure 7: Atomic Force Microscope Topographic Images (1000nm x 1000nm)



AFM images shows the films grew in two-dimensional way. Small roughness (<0.55 nm) shows a well-controlled growth.)

Figure 8: Magnetoresistance and Hall Resistance at 4.2K

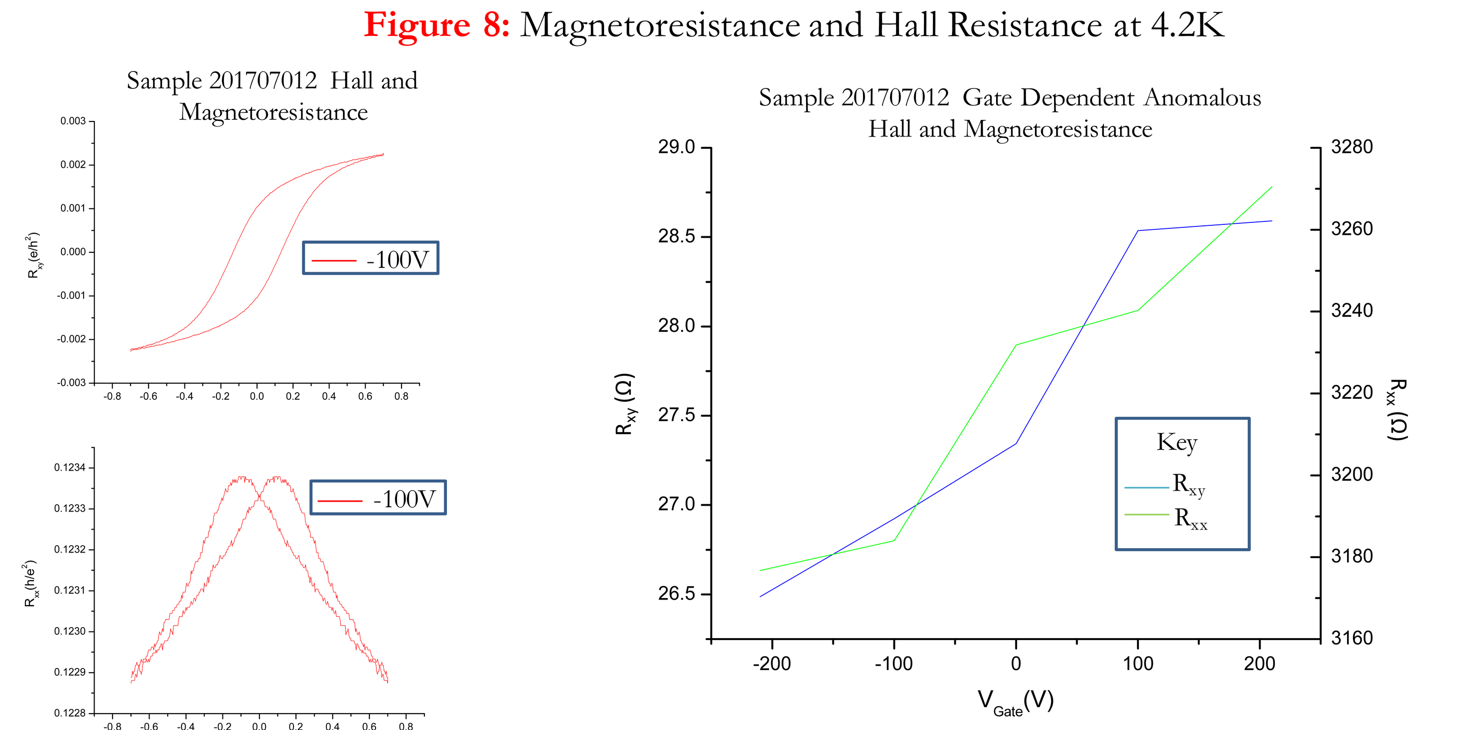
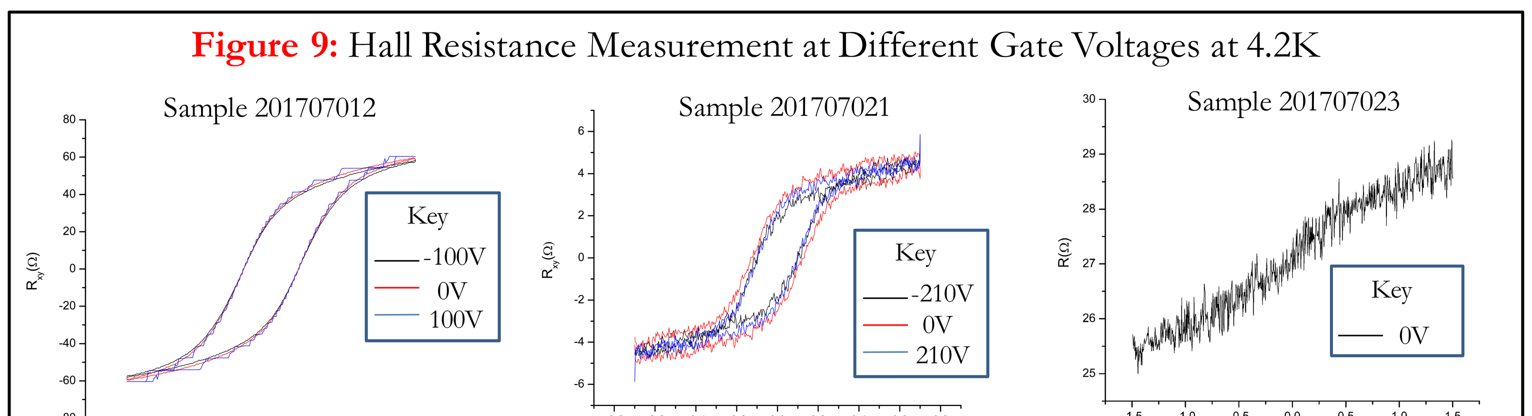


Figure 9: Hall Resistance Measurement at Different Gate Voltages at 4.2K



Analysis & Discussion

Table 1: Concentration of elements in layers of Vanadium-doped Samples

$(Bi_xSb_{1-x})_{2-y}V_yTe_3$	X	Y
Sample 201707017	0.27	0.54
Sample 201707021	0.36	0.92
Sample 201707023	0.30	1.00

- By MBE, we fabricated V-modulation doping $(Bi,Sb)_2Te_3$ films. The AFM images shows the films grew in two-dimensional way. Small roughness (<0.55 nm) shows a well-controlled growth.
- Butterfly magnetoresistivity and hysteresis loops were observed in the samples with 1/2/2/2/1 structure rather than 1/1/4/1/1 structure, which illustrates that 2 QL V doped layer is easier to deduce ferromagnetism rather than 1 QL. Only one coercivity in the curves demonstrates that the ferromagnetism of these two doped layers are coupled and the non-doped layer is affected by the doped layer.
- Changing the gate voltage showed changes in the longitudinal and Hall resistances, indicating shifting of the chemical potential. The longitudinal resistivity and anomalous Hall resistance increase with increase of gate voltage. Increase of longitudinal resistivity indicates that we are approaching the band gap. Meanwhile, the increase of anomalous Hall resistance illustrates that the weakening of RKKY interaction.
- By increasing the doping level of V, anomalous Hall resistance decreases. This indicates the bulk conduction is increasing likely through the introduction of defects. Further studies are needed to optimize the doping level for better properties.

Conclusions

- V-modulation doped $(Bi,Sb)_2Te_3$ films were successfully grown.
- Ferromagnetism is observed in our penta-layer thick TI films.
- Lower doping level shows better anomalous Hall effect with the anomalous Hall resistance of 36 Ω compared to h/e^2 value of quantized anomalous Hall resistance.

Future Work

- More experiments should be carried out to optimize modulation doping and keeping the sample quality high.
- Modulation doping of V, a new technique, could potentially be a stepping stone to future use in the fields of spintronics and quantum computing.

References

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