

# Topological insulators: transport measurements in $\text{Bi}_2\text{Te}_2\text{Se}$ and capacitance probe construction

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University of Michigan REU 2014

## Introduction

In recent years, a new classification of materials called topological insulators (TIs) has moved from theory to reality, opening up an exciting field of new physics. TIs are materials that are electrically insulating in the bulk but exhibit conductive surface states as  $T \rightarrow 0$ . The conductive surface is topologically protected,<sup>2</sup> meaning that it is present even on the new surfaces if a TI crystal cut in half.

Band theory also provides an illustration of the surface and bulk states. In pure conductors, the valence band is completely occupied and the leftover electrons are free to move in the conduction band.<sup>4</sup> In insulators or semiconductors, only states in the valence band are filled, so the conduction band is inaccessible.<sup>2</sup> Like insulators, TIs are characterized primarily by distinct valence and conduction bands, but topologically protected surface states span the energy gap to allow some conduction<sup>1</sup> (Fig. 1). While theoretical predictions of TIs model their behavior in this way, many TIs may in practice have impurities in the bulk that cause them to be moderately conductive throughout, more like doped semiconductors.<sup>1</sup>

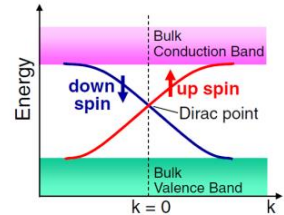


Fig. 1: Idealized TI band structure. The blue & red lines represent surface states.

Because TIs are new and unique, an understanding of their electronic properties is crucial. To do this, electronic transport properties were tested with varying temperature. The results of this measurement also prompted an exploration of capacitance in TIs, leading to the construction of a probe designed particularly for capacitance measurements.

## Transport measurements in $\text{Bi}_2\text{Te}_2\text{Se}$ (BTS)

Transport measurements were used to explore the emergence of surface states as  $T \rightarrow 0$  in  $\text{Bi}_2\text{Te}_2\text{Se}$  (BTS), a known TI. The BTS was grown in a rod of varying purity. Each sample was cut in a thin slice to expose the surface. Each slice was connected to a “dipstick” probe using gold wire and silver paste. The probe was lowered into a helium Dewar and then raised again over about 3 hours. Measurements were taken over a range of about 6-196K, with the upper limit due to a 200K range on the temperature sensor and the lower limit due to the liquid level in the Dewar.

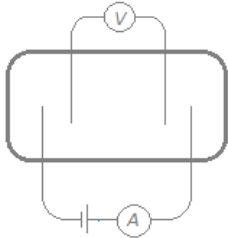


Figure 2: four-probe method

To reduce error, the four-probe method was used to test resistance (via voltage). The standard method of making this measurement is to attach a lead to each end of the sample and directly measure voltage. In the four-probe method, however, the current is sent through the sample using one set of wires, and voltage is measured separately (Fig. 2). This means that any internal resistance in the current source or wires does not affect the result.

The BTS samples showed typical metallic behavior; that is, resistance decreased with temperature (Fig. 3). TI surface states, however, are indicated by a sharp increase in

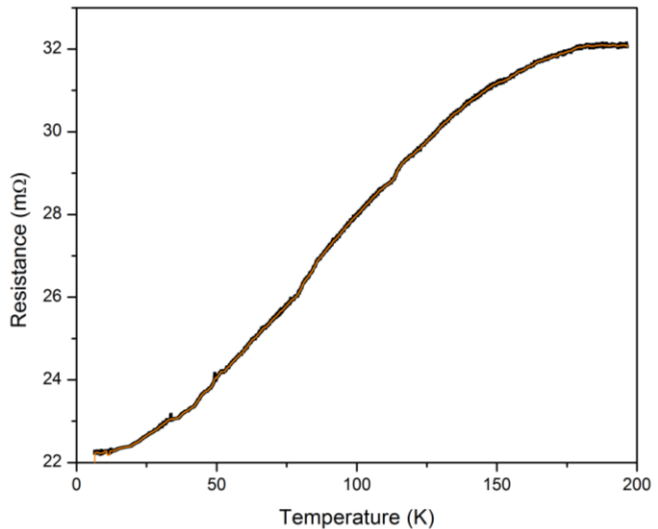


Figure 3: BTS heating curve, measured with 500  $\mu\text{A}$  at 29.333 Hz. The run showed typical metallic behavior.

resistance below 10K.<sup>5</sup> While the results were unexpected, they suggest the presence of impurities in the bulk that caused BTS to behave like a regular metal even though it is a known TI.

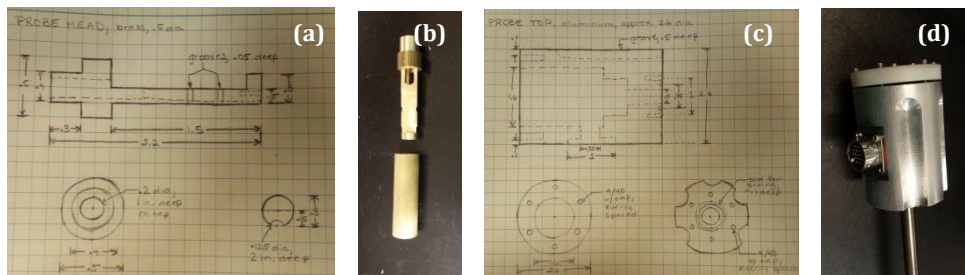
### Capacitance probe construction

Although the transport measurements did not exhibit characteristic TI behavior, it is possible that a study of capacitance might yield something new, prompting the construction of another “dipstick” to do this. Capacitance is also useful because it is versatile. One possible measurement is of quantum capacitance, which for a TI is the capacitance between the conductive surface layer and an external sheet.

The first part of the probe that was built was the brass head, where the sample is attached (Fig. 4(a), (b)), made from a cylindrical stock piece. The ends were cut to the appropriate size on the lathe and a section was milled to create a flat surface for the sample. Grooves were added on the rounded underside and on the sides leading to the flat surface to allow the cables to wrap around and attach to the sample. A brass cap to cover the head was also constructed by drilling a hole of the appropriate length in another piece of stock material.

The opposite end of the probe included an aluminum head, nylon cap, and brass connector. The aluminum head (Fig. 4(c)) was made of a large cylinder of stock material. Holes were drilled through the center on the lathe to accommodate the wires. A piece of the curved side of the cylinder was milled to be flat for placement of a 19-pin connector. The nylon cap, which was attached to one end of the aluminum head (Fig. 4(d)), was machined by the professionals. This was necessary because the D-shaped holes needed for a specific brass connector in this part could not be machined in the student shop. On the other end of the aluminum head, a small brass cylinder was attached. This cylinder was hard soldered to the stainless steel tube that formed the body of the dipstick. The brass head was hard soldered to the other end of the tube to complete the body.

Then the wiring was completed. Two types of wires were used, stainless steel coaxial cables and copper twisted pairs. On one end, the coaxial cables attached to the sample, and the grooves on the brass head were required because they are quite thick. The other ends of these cables were attached to the D-shaped brass connectors in the nylon cap. Copper twisted pairs were also used in the wiring. On the brass head, they attached to the temperature sensor. The opposite ends were soldered to the 19-pin connector.



**Fig. 4: Capacitance probe design and completed parts. (a) Brass head shop drawing. (b) Brass head and cap. (c) Aluminum head shop drawing. (d) Aluminum head with nylon cap and 19-pin connector.**

### Conclusion

The study of topological insulators is a fascinating new subfield in condensed matter physics. By exploring their electronic properties such as resistance and capacitance, this new classification of materials can be understood in greater depth. Future studies can take these measurements even further; for example, measuring the capacitance between the surface and bulk states of a TI would increase the understanding of the characteristics of this boundary state that defines a TI.

## **Acknowledgements**

I would like to thank the University of Michigan and the National Science Foundation for making this REU program possible. At the University of Michigan, I would like to thank my adviser Lu Li and his group, especially Fan Yu.

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