

Magnetotransport of Topological Insulators: Bismuth Selenide and Bismuth Telluride

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Abstract

Topological insulators are recent and exciting discovery in the field of condensed matter physics. In this paper, we measure some of the properties of two topological insulators: Bismuth Selenide (Bi_2Se_3) and Bismuth Telluride (Bi_2Te_3). Using a cryostat and a super conducting magnet, we are able subject the samples to a variety of magnetic fields and temperatures. We then measure the magnetoresistance and hall resistance of the samples. Each sample type varied in size and thickness, and was tested at multiple fields, temperatures, and angles.

The samples show interesting effects when subjected to the magnetic fields. In several of the samples, the magnetoresistance is proportional to square of the B field. The Hall Resistance has several features of interest that are explained in more depth in this paper. Low-Field Weak Anti-Localization also manifested itself in nearly every trial we did. We found that at high fields, the magnetoresistance of many samples would oscillate slightly. This ends up being the result of the Shubnikov-de Haas Effect.

Introduction

Topological insulators (TI) are an exciting, new topic in condensed matter physics.

The discovery of TIs was unusual for the field of condensed matter, in that they were predicted theoretically before they were observed in the lab. Several papers were published in 2005 and 2006 that predicted the existence of a type of material that would permit the movement of electrons only on its surface^{[1],[2]}, and TIs were observed later in 2007^[3].

We in the field are interested in Topological Insulators because of their unique conductive properties. The bulk of a TI acts as an insulator, while the surface allows the flow of electrons^[4]. You can therefore think of a TI as a piece of rubber or plastic with a thin layer of metal, only it achieves this conductive behavior by itself. You can achieve a similar effect through the Quantum Hall Effect. The (non-quantum) Hall Effect states that when you subject an electron current to a magnetic field, the carriers will tend toward one side of the

conductor, creating a potential difference laterally within the material. In high quality samples at low temperatures, you can start to measure quantum effects on the carriers. The Quantum Hall Effect states that, due to quantum effects, the carriers that have collected along the edge will move along the surface. This is similar to the behavior in TIs, but they are able to do this without the use of an external magnetic field.

TIs also have a unique effect on electron spin. The carriers that move along the surface of a TI are spin-locked^[4]. This means that the spin of each electron is perpendicular to its momentum. Figure 1a shows this as compared to a conventional insulator, and Figure 1b shows the band structure of a topological insulator.

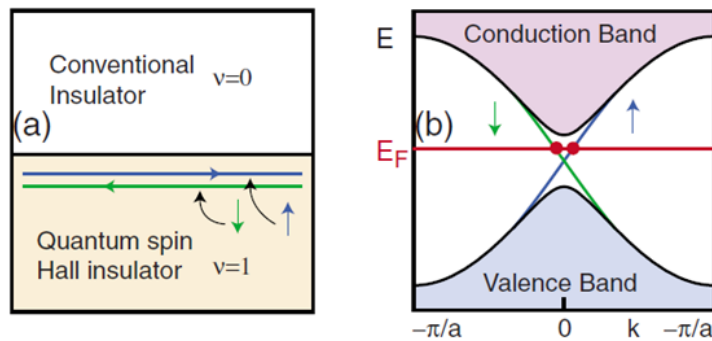


Figure 1 – a) A visual representation of the quantum hall effect b) the band structure of a topological insulator

As the electrons move to the right at the top of the material, their spins must be directed upwards. Those that move left have their spins reversed. These velocity-spin relationships would be switched for electrons at the bottom surface of the material. One effect of being spin-locked is that the electrons have a very high mobility, because scattering the carriers would require flipping their spin. This is impossible to do because that state is simply not available. These unique properties of TIs make them promising materials for research; there is great interest for applications in spintronics and quantum computing^[4].

Experimental Setup

In order to learn some of the basic properties of our TIs, which were grown in the MBE lab at Notre Dame, we performed magnetotransport on Bi_2Se_3 , Bi_2Te_3 , and $\text{Bi}_2(\text{TeSe})_3$. We accomplished this by soldering samples of various materials, size, and thickness to a sample holder. The sample holder was wired to instrumentation that would measure the magnetoresistance and the hall resistance of each sample. The sample holder, inserted to the top of the cryostat, was placed right next to a super conducting magnet. Using liquid helium and liquid nitrogen to cool the magnet, we were able to subject the samples to magnetic fields anywhere between 6 and -6 Tesla. By controlling the flow of liquid helium through the sample space, along with the help automatic internal heater, we were able to stabilize the temperature of the samples within a range of 2 K to about 200 K. The angle of the samples with respect to the magnetic field was easily adjusted by twisting the top of the sample holder. Thus for every sample we tested we measured a full sweep of the magnetic field for an assortment of angles and temperatures.

Magnetoresistance Data

When subjected to a magnetic field, certain materials have a tendency to change their resistivity. This property is known as magnetoresistance. From Kohler's Rule, the resistance of a material is proportional to the square of the magnetic field. This is shown in Eq. 1:

$$\frac{R(B)}{R(B=0)} \approx 1 + (\mu B)^2 \quad \text{Eq. 1}$$

By measuring the resistivity of the sample longitudinally (along the direction of the current) we are able to determine the magnetoresistance. Figure 2 shows the resistivity of $\text{Bi}_2(\text{TeSe})_3$. This sample is a particularly good example of the resistance and B^2 relationship.

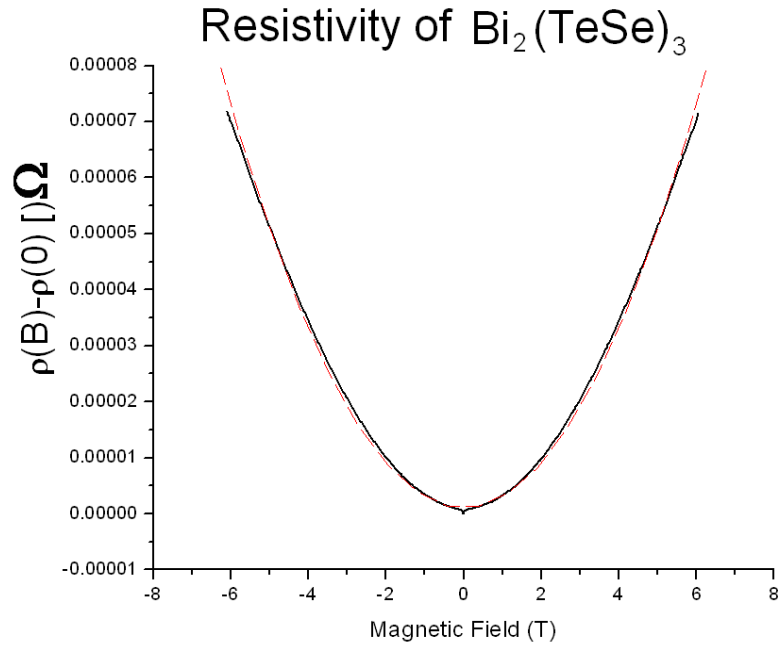


Figure 2 – The resistivity of a sample of $\text{Bi}_2(\text{TeSe})_3$ at 2.03K and its second order fit

Hall Data

As stated earlier, conductors in the presence of a magnetic field undergo the Hall Effect. Our topological insulators are no exception. Refer to Figure 3.

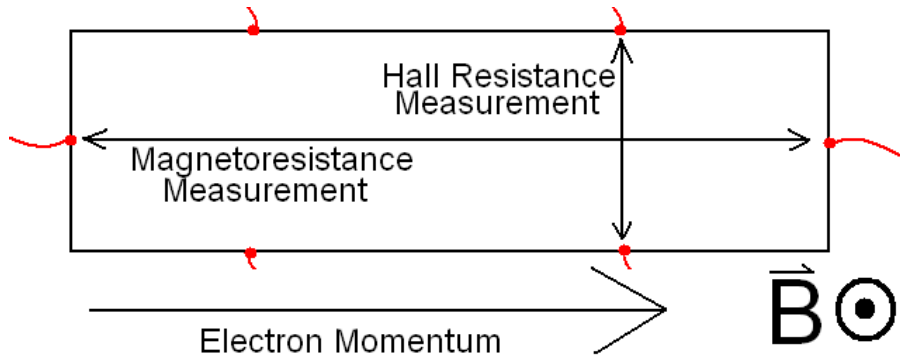


Figure 3 – A general diagram of each sample that we measured. The dots show the contact points where wires were soldered, and the arrows in the box indicate where each resistance was measured.

As the electrons flow longitudinally through the sample, they are pushed downward by the B field. This results in the expected potential difference, which in turn creates a Hall Resistivity. We measure this laterally according to the figure. For an example of a typical result, refer to Figure 4, which plots the Hall Resistivity versus the field strength for a sample of Bi_2Se_3 at various temperatures.

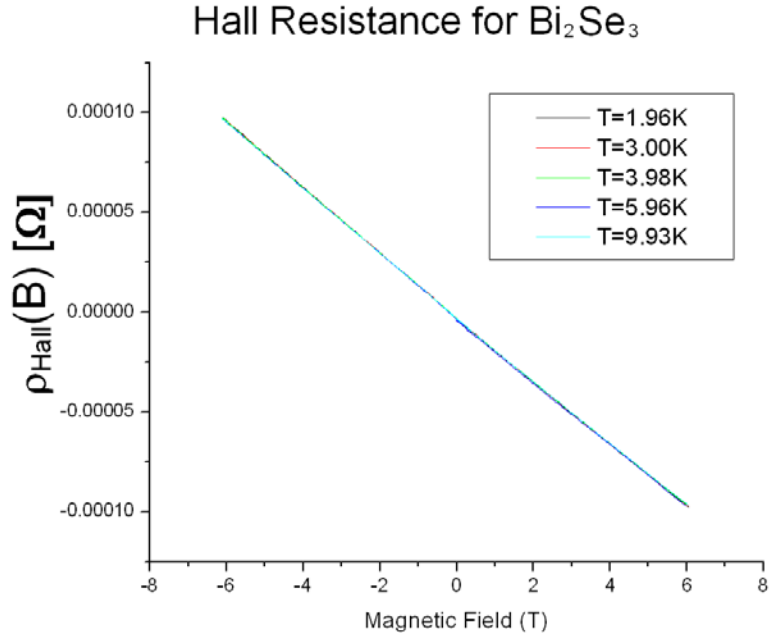


Figure 4 – Hall resistance for Bi_2Se_3 at various low temperatures

The equation for Hall Resistivity is listed in Eq. 2.

$$\rho = \frac{B}{nq} \quad \text{Eq. 2}$$

This equation predicts a linear function, which matches our shown results. However, linearity is not always the case. If an anomalous Hall Resistivity is introduced, then there will be a B^3 term present. Notice too, the slope of the Hall Resistivity. The fact that it is a negative slope confirms that the carriers are electrons, as opposed to electron holes which have positive charge. From this data, it is possible to calculate the carrier concentrations and mobility in the sample. The carrier concentration is result of linear regression. The program we used calculated the concentration and mobility for each, and results are listed in Table 1.

Temp (K)	Carrier Concentration (cm ⁻³)	Mobility (cm ² /V*s)
1.96	-3.89E+19	-270
3.00	-3.89E+19	-270
3.98	-3.90E+19	-269
5.96	-3.89E+19	-270
9.93	-3.92E+19	-268

Table 1 – Carrier concentration and Mobility for Bi₂Se₃ at various temperatures

Low Field Weak Anti-localization

Most if not all of the trials we did had an interesting dip in the graph near the zero Tesla mark. Sometimes these “features” were so small that you had to zoom in to see them, other times they dominated nearly the entire B field range. Figure 5 has an example of a sample with moderately sized features (Figure 2 also has an example of a very small feature).

Examples of WAL in Bi₂Se₃

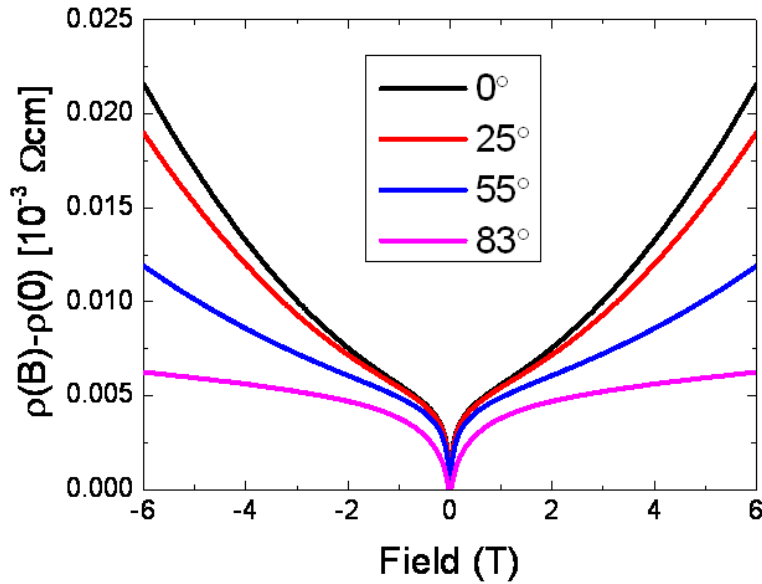


Figure 5 – Bi₂Se₃ at several different angles. This graph shows an interesting “feature” that is the result of the Low Field Weak Anti-Localization

These artifacts in the resistivity can be attributed to a phenomenon called Weak Anti-Localization (WAL) Effect. WAL is the suppression of backscattering due to impurities^[5]. Less backscattering means more mobility, and less resistivity. This effect mainly manifests in the low field, which is why the features of low resistivity always center on the zero field point. Eq. 3 characterizes the WAL Effect.

$$\begin{aligned} \Delta\sigma_{2D} &= \sigma_{2D}(B) - \sigma_{2D}(0) \\ &= -\frac{\alpha e^2}{2\pi^2\hbar} \left[\ln \frac{\hbar}{4Bel_\phi^2} - \psi \left(\frac{1}{2} + \frac{\hbar}{4Bel_\phi^2} \right) \right] \end{aligned} \quad \text{Eq. 3}^{[5]}$$

Shubnikov-de Haas Effect

If you were to zoom in on the graph in Figure 2, you would notice that the line does not follow a perfectly parabolic line, but instead wavers around it. Though it would be very easy to attribute this to slight error or imprecision, it is actually due to a phenomenon called the Shubnikov-de Haas Effect. Figure 6a shows the same data as in Figure 2, but limited to the range of 1T to 6T.

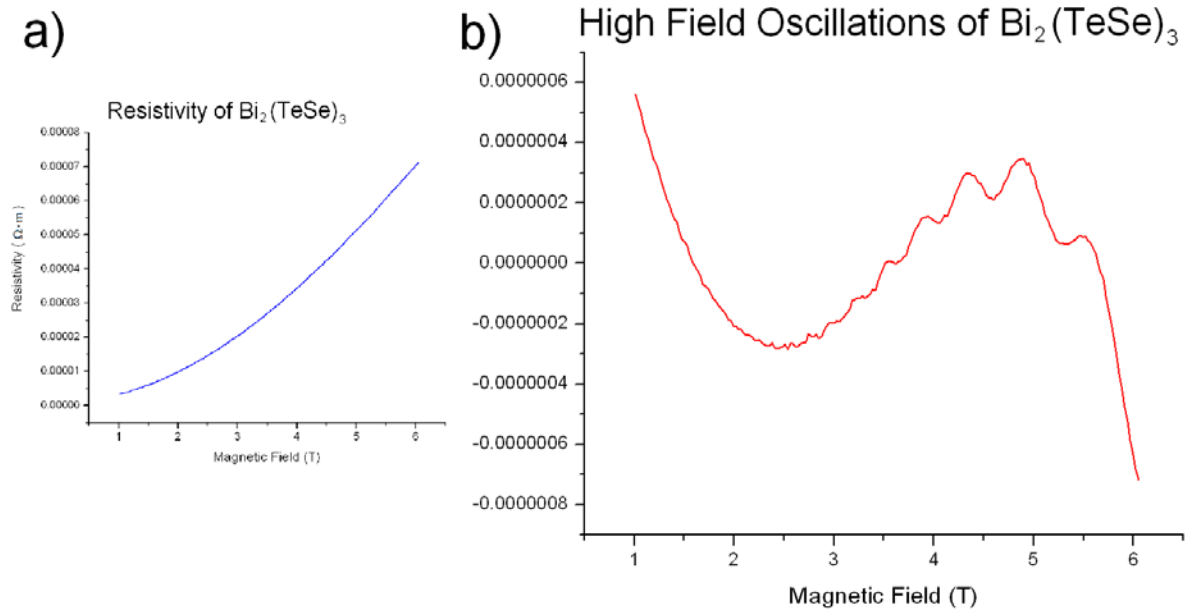


Figure 6 – An example of high field oscillations. a) A segment from Figure 2 b) The data from Figure 6a minus Figure 6a's second order fit

By taking a second order fit of that data, and subtracting that fit from the original data, we get Figure 6b. These oscillations, are not the result of error, but instead are the manifestation of the Shubnikov-de Haas Effect^[6]. This effect, which only occurs at low temperatures and high magnetic fields, is the manifestation of quantum mechanics at the macroscopic level. The peaks in these oscillations occur at quantized Landau levels.

Conclusion

In this experiment we set out to measure the magnetoresistance and hall resistance of our Bismuth Selenide and Bismuth Telluride samples. In doing so we were able to confirm properties that are expected in TIs. For example, our hall resistance data supported the idea that electrons were the carriers involved and not holes. We were also able to identify several interesting (though already known) phenomena in our samples. These include the oscillations caused by the Shubnikov-de Haas Effect in some of our samples, and the features created by the Weak Anti-Localization Effect in nearly all of our samples. Overall, we've collected a lot of data for various sample sizes, temperatures, and angles which we think will be beneficial as research on Topological Insulators progresses.

References

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