Investigation of Linear Magneto-Resistance in PbSnTe Samples

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1 Introduction

2 Laboratory Set-Up

There are several important machines that are used in both the cleanroom and the transport laboratory. Here, we will focus on the cryostat set-ups that we use in the transport laboratories. The cryostat that we use, nicknamed King Louie, is a Helium-4 fridge that has a base temperature of 4.2K and can be cooled below 2K when pumped on.

The concepts behind the cryostat are simple. Liquid helium is pumped into the sample chamber and thermally coupled to the sample. This can either be done by putting the liquid in contact with the sample or its holder or by having a gas, primarily gaseous helium, act as a medium between the liquid and the sample holder.

Regardless of this, it is important that the helium stays liquid for a suitable amount of time in the cryostat. To make sure that we can keep the cryostat at a low enough temperature, we create buffers between the outside laboratory and the inner liquid helium chamber. In the King Louie cryostat we achieve this with a vacuum chamber in between the helium chamber and the exterior shielding. However, in other cryostats, we also have a liquid nitrogen shield followed by a secondary vacuum chamber shield around the helium chamber.

The lifetime of our helium can further be extended by separating the chamber with the sample from the main supply of helium. We connect this sample chamber with the helium bath using a needle value that limits the flow of helium between the two sections. This ensures that when loading and removing our sample, the main helium bath is not heated up quickly and the sample is not cooled down too quickly. Thus, not as much helium is used when cooling our samples and the is a lower chance that our sample is damaged in the process.

Of course, we can't keep an infinite supply of helium in the cryostat. Thus, there must be a filling and recovery system. Filling requires moving helium from an exterior tank by exerting a pressure on the fluid in the can. The liquid helium moves through a siphon into the main bath of the cryostat. In the King Louie cryostat, this process is automated. However, other cryostats require pressure to be created through manual pumping of an attached balloon.

As the helium evaporates naturally in the can and the cryostat, it begins to build up pressure. Thus, it is imperative to also release this pressure in both places, while conserving the gaseous helium for future uses. We connect the main bath, sample chamber, and exterior helium tank to a recovery pipe. This recovery pipe takes the used helium gas to a compressor to be turned back into liquid helium. The liquid is stored until it is used once again to fill these exterior helium cans once again.

When working in low temperatures, we must also maintain vacuums in the buffer

chambers and prevent air from entering our system. In such an event, ice could form at important junctions and cause machines to break or parts to get stuck. To prevent this from happening, we ensure that every junction between two pieces of piping is sealed using rubber o-rings and either metal or plastic clamps.

In parallel with the cryostat, we have electronic measurement equipment used to conduct our hall measurements on our samples. The equipment we use include lock-in amplifiers, voltmeters, and a variety of resistors and voltage dividers. The exact set up differs based on the sample that is being measured at the time. However, there are quite a number of features that are constant throughout all of our measurements. Here, we won't record the details of the equipment but will focus on the set-up that we create.

In general we use three lock-in amplifiers, each attached to a separate voltmeter. These devices are each used for a separate voltage measurement, corresponding to the reference, longitudinal, and hall resistances of the sample. The lock-in amplifiers are all synchronized to give the same reference output. This reference output is then moved through a voltage divider and a reference resistors before pass through the sample. In between our reference resistor and our sample, we place a grounding box that allows us to ground the sample without having to remove it from the cryostat. These grounding boxes have a separate BNC connector for each of the eighteen pins on our chip carriers.

Using the grounding box and the reference resistor, we take our voltages from across each our resistance points and input them into the lock-in amplifiers. The lock-in amplifiers then pass the DC output into a voltmeter to be read using the computer program.

3 Micro-Structure Fabrication Process

The work that I have done at the University of Würzburg can easily be split into two parts. Once of which involves the work in the cleanroom and microfabrication. The other part consists of hall measurements of the microfabricated samples.

In the cleanroom, we perform lithography. Our material is grown by MBE in various forms. The more recent material stacks consists of an insulating GaAs substrate followed by the PbSnTe layer. Older samples that we have worked with have a slightly different stack. These older samples consist of a thin indium layer followed by the GaAs substrate, a CdAs buffer layer, and then our PbSnTe layer. To begin, we must cut our MBE-grown material to an appropriate size, approximately a centimeter by five millimeters. This size is large enough to contain our hall bar structure and small enough to fit into our chip carrier. The sample of the material is the cleaned and dried using acetone and isopropanol.

Once we have an acceptably clean sample free of large particles, we can begin the lithography process. The sample is taken to a spin-coater and coated with a positive photoresist. The coater simple rotates the sample quickly moving the liquid photoresist in an even coat across the sample.

The photoresist covered sample is then taken to a mask aligner. This device is used to line up our structure pattern with our sample. The pattern is made from a thin film of chromium that prevents UV rays from passing through. When the pattern is aligned with the sample, we expose the sample with the pattern on top to a UV light for a certain amount of time depending on the resist. The UV light changes the properties of the resist based on whether it is negative or positive. For the positive resist that we

use, the UV causes the the exposed resist to break down more easily than the hidden resist.

There are two different masks that we use in this process. The first is a mask for two six-terminal hall bars, one of size 200 micrometers by 600 micrometers and another of size 10 micrometers by 20 micrometers. These hall bars allow for two current contacts and four resistance contacts on each bar. The second newer hall bar is an eight-terminal hall bar. This eight-terminal design has two current contacts but six resistance contacts that can be used. Once again, the hall bar, like the two six-terminals, have a length to width ratio of three.

The processed resist-coated sample is then taken to a developer to dissolve the exposed positive resist. The remaining sample is the positive resist in the pattern of the mask on top of our material. With this, we can begin to etch the surface of the material to make our pattern. For our materials, we use a wet etch solution to carve into our material to the insulating substrate or buffer. This solution is made in the cleanroom by dissolving potassium-iodide and pure iodine in hydrobromic acid and diluting with water. We are left with a mesa of PbSnTe on the substrate.

When we reach the substrate, which we can confirm using a stylus profiler to measure the surface, we can remove the remaining resist and check the sample under the microscope. If the sample looks unscratched and clean, we can move on to the contact deposition. To begin the contact deposition, we must once again spin-coat the sample, but now with negative resist. This negative resist now will preserve the negative of the pattern that we have above. We apply the chromium pattern for the contacts, expose, and develop the sample. The sample is now ready for deposition. We move the chip to a high vacuum deposition chamber. Using physical vapor deposition, we evaporate fifty nanometers of AuGe followed by a hundred nanometers of Au onto our material.

Finally, we can remove the resist and lift-off any remaining gold that we have on our sample. Once we have our contacts set up and extra gold removed, we can attach our sample to a chip carrier and have it bonded for electrical contact. We record the connections that we make with the gold bonding wire and move the sample to the transport lab for measurement.

The microfabrication process does however face some challenges as we saw with thicker samples. When moving to samples of thickness 800nm, we encountered large amounts of under-etching into the mesa, due to the isotropic nature of the wet etch solution. This produced a small overhang by the mesa that prevented electrical contact created by the gold. While we never found a solution to this in my time at the university, we believe that we could purposely collapse the mesa on the under-etch parts. By sonicating a sample in acetone and cleaning with isopropanol, there is a chance that the mesa could be collapsed and the sides could remain straight and particle free, and electrical contacts could be made.

4 Hall Measurement Process

The second set of responsibilities at my job here were mainly in the transport laboratories. These involved the characterizing samples and performing and analyzing hall measurements. In order to do this, we make use of the cryostat set-up described in section two. Using the cryostat, we performed two different measurements. The first sets were standard out of plane hall measurements that were used to characterize the mobility and carrier density of the grown materials. The second set of measurements dealt with the angle-dependence of magnetoresistance in our samples.

In our characterization measurements, we cooled our samples to below two Kelvin. At this temperature, we can attach our reference resistors and lock-in amplifiers and begin our measurement by sweeping the magnetic field inside the cryostat between negative fourteen tesla and positive fourteen tesla. When we perform this, we must make sure that we sweep the magnetic field at an acceptable rate. If we sweep the magnetic field too fast, we are at risk of quenching the magnet, causing typically superconducting parts to overheat, damage the magnet, and evaporate helium. Thus, we set our magnet to sweep at at rate of 0.1 teslas per minute.

Throughout the magnetic sweep, the computer polls the voltmeters and take voltage drop measurements for each of the resistors (i.e. reference, longitudinal, and hall). Once we have these voltage drops, we can calculate the resistances of each section from the size of the reference resistor. This data is then plotted and curve-fitted. With the results from the curve-fit we can get the carrier density and mobility of the sample. The details of this curve-fitting is explained in the following section.

Secondly, we have the measurements that explored the angle-dependence of the magneto-resistance. For the most part, this set up is fairly similar to the characterization measurements. However, due to the rotation, we require a special insert for the cryostat that allows us to turn our sample in the sample chamber. When we have this stick set up, we perform this magnetic sweep measurements at different angles between out of plane and in plane. Depending on the hall bar design that is being used, the direction that current points with respect to the magnetic field changes. In the six-terminal hall bars, we move to an in-plane parallel-current magnetic field. Meanwhile, the eight-terminal hall bars move to an in-plane perpendicular-current magnetic field. We conduct at total of seven different angle measurements to analyze the angle-dependence at every fifteen degree angle and move to analyze the data.

Of course, there were many problems with the equipment that we used. Most of the problems were easily solved as loose connections or small problems in code. However, there was a major problem that we had towards the end of my term. That is, we noticed a continuous introduction of air into the cryostat system. After some investigation, we found this to be coming from the rotation stick that we had been constantly using. After replacing the rubber o-rings and clamps on the stick, we passed it to the workshop for further inspection.

5 Analysis

In this report, we will summarize two different analysis that we performed over the past eight months. In this section, we will look at our results of characterization. We looked at four new samples, two of which using both the eight-terminal and six-terminal hall bars. In addition, we also reviewed several older samples. With the older sample, we simply reconfirmed the values that we had recorded before reviewing the samples for linear magneto-resistance.

The four new samples that we analyzed have a variety of different properties and are labeled PST 236, 380, 441, and 442. Sample PST 441 is in a {100} configuration. It has a thickness of ninety nanometers and a tin content of 60%. Similarly, PST 442 has a thickness of ninety nanometers and a tin content of 60%, but is in the {111} configuration. PST 380 is a thinner sample with thickness of twenty nanometers and a tin content of 60%. Additionally it is once again in the {100} configuration. PST 236 is in the {100} configuration with a thickness of nine hundred nanometers and a tin content of 60%.

The analysis of the hall measurements conducted with these samples took place with

a personally constructed python code. The majority of the data processing consisted of conducting curve fitting. Each data file, which contains a series of data points from each of the connect instruments, is loaded into the python script after having been adapted to only have the data in it. Generally, all the data files are observed to see if the data should be used or not. Once the data has been manually confirmed, the headers and comments are taken out and the raw data is saved into a different file. This file can then be loaded as a numerical array and used to perform our data analysis.

We begin our curve fitting by looking at the Rxy values. When we have a single dominating carrier type, we should see a mostly linear response to an external magnetic field in out Rxy graph. The slope of this linear response is inversely proportional to the two-dimensional carrier density, or the carrier density of the material if it were compressed into a two-dimensional sheet. The just as important three-dimensional carrier density can be found easily by dividing the two-dimensional carrier density by the thickness of the sample. Note that this is simply the thickness of the material and not the material along with any buffer layer or substrate.

Once we have our carrier density, we can find our mobility. The mobility can be derived from the Rxx value at zero magnetic field if the weak anti-localization did not exist. In order to find this value, we approximate the Rxx value as being parabolic, although we will later see that this is not the best. Once we have the zero-field Rxx value, we can calculate the conductivity of the material and derive the mobility.

These are not, however, the best approximations that we can make for our carrier density and mobility. Instead, we can add some corrections to our Rxy and Rxx values so as to get a better approximation on our two values. The Rxy values should pass through zero ohm resistance at zero magnetic field. However, some amount of Rxx can bleed through into this reading if the contacts are not perfectly aligned. Thus, we must subtract out this response as to see the final values of Rxy. Once we have subtracted out the Rxx response, we can once again calculate the two-dimensional and three-dimensional carrier densities.

Let us not stop there. We can also curve-fit the Rxx data to a better curve than a parabola. Instead, we can model the data as two linear portions joined by a parabolic portion. This will later be explored in the linear magneto-resistance section. Regardless, we attempt to optimize the transition field between the linear and parabolic sections to better approximate the mobility values that we receive. Once we have optimized this, we also once again add a correction onto the Rxy values to get our final two-dimensional and three-dimensional carrier densities.

6 Linear Magneto-Resistance Analysis

The largest part of this project dealt with the observed linear magneto-resistance that can be found in the lead tin telluride samples. We dealt with this in two stages. The first bit of analysis that we had performed focused on finding what physical properties of the material affected the change in resistance that we had been seeing. The second portion of the analysis looked at the effect of angle to the magnetic field to the change in resistance.

The analysis of this was taken in conjunction with the general analysis we had applied previously. From this, we can get the value of the magnetic field that indicates the change in power. When we had conducted this first bit of analysis, we plotted these transition magnetic fields with various prop-

erties of the materials to see how it evolved with each of them.

Our results didn't show anything completely concrete, but leaned to showing that the magneto-resistance had certain dependencies. We found that with our samples, the transition points depended on the thickness of the sample. Furthermore, it didn't seem to be affected by the carrier density of the material. These results are compared to the data reported in other papers and other materials. With these results, we attempted to find a model to describe the linear magneto-resistance.

7 Linear Magneto-Resistance Model

The final part of my duties consisted of creating or reanalyzing magneto-resistance models. While we have looked at a variety of models, including but not limited to those published by A. Abrikosov and C. Wang and X. Lei, there are two that we focused on. The first was a model of our own creation. It involved the idea that the material could be divided into layers between which the carrier density fluctuates. The layers then followed the standard and known model for parabolic magneto-resistance.

When we consider the layers to be similar to parallel resistors and to not interact with each other, we can recover this linear magneto-resistance behavior when adding up the magneto-resistance of each layer. However, there are two main problems that we see with this model.

Firstly, the model eventually saturates with a high enough magnetic field. While we see no evidence of this happening in our samples, others have reported seeing no saturation when applying magnetic fields on the order of 60 Teslas or greater. The second problem is more pressing. When plugging in our numbers for various samples, it seems that the mobility in each layer does not fluctuate as highly as the carrier density. Thus, we see that the linear magneto-resistance is not activated until magnetic fields of the order of 60 to 100 Teslas are applied.

With the roadblock in the model, we continued to another classical model, the Parish-Littlewood model. This model describes the material as a network of unit disc conductors. Each conductor then has a varying carrier density and mobility and subsequently when added, it should produce an effect that mimics the linear magneto-resistance.

The last weeks of my stay, I had attempted to recreate this model from base principles provided in the paper. While it was simple to rederive the impedance matrix of a single unit cell resistor, it was harder to find a pattern in a network of resistors, of which I made seemingly small steps towards completing. The following is a list of patterns that I had discovered and confirmed:

1. For a N by M network with $2N-1$ longitudinal components and $2M$ hall components, the full impedance matrix can be divided into a $2M$ by $2M$ hall-hall (HH) matrix, $2M$ by $2N-1$ hall-longitudinal (HL) matrix, $2N-1$ by $2M$ longitudinal-hall (LH) matrix, and a $2N-1$ by $2N-1$ longitudinal-longitudinal (LL) matrix.

2. Unique cases appear for $N=1$ and $M=1$.

3. The remainder of impedance matrices can be split into three groups: $N>M$, $N=M$, and $N<M$.

For my work, I focused on the HH matrix, attempting to deduce any patterns in the matrix. The following is seemingly true:

1. For any N by M network, the HH matrix can be split into four matrices. We will name these based on the contributing factors, similarly to

how we have named the four matrix components of the complete impedance matrix. We define the left side as the hall side ninety degree counter-clockwise from the ground side. Alternatively, the right side is the hall side ninety degree clockwise from the ground side. Thus, we have four matrices (LL, LR, RL, RR) that compose the HH matrix, each of size M by M.

2. When $N = 1$, the LR and RL matrices are symmetric along their diagonals. When $N < M$, the LR and RL matrices consist of $d - b$ and $c - b$, and $a - c$ and $a - d$, respectively.

3. The remaining matrices (LL and RR) are trickier. They have complex formula but revolve around and steadily increasing and reliable diagonal and the remaining components simply being minor additions and subtractions from this.

Finding the remaining patterns is complex and will require time not only to find by to confirm as well.