Physics 111B Lab 2
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SHE-Hall Effect in a Semiconductor

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Abstract

Semiconductors have revolutionized modern society, and can be found in most electronics. This lab focuses on studying the Hall Effect in a semiconductor between temperatures 95K-350K. By following Van Der Pauw technique we were are able to measure the electrical properties of the Al doped Germanium slab along with the carrier type and mobility of the sample.

Introduction

Solids can be categorized as a conductor, insulator, or semiconductor depending on the materials atomic structure. A conductor is a material that easily conducts electricity due to the materials low resistivity. The electrons in a conductor are weakly bounded together such that small potential differences throughout the material is enough to free the electrons and thus conduct electricity. The amount of potential needed to free the electrons from their bounded atoms depends on the materials energy bands. For conductors, the Fermi Energy which describes which the lowest energy state of the electrons in a solid at zero temperature is in an allowed energy band [1] such that the electrons are weakly bounded. While an insulator typically has higher resistivity which makes it harder to conduct electricity. As oppose to conductors, insulators have a large energy gap between the Fermi energy and the conduction bad as seen in *Figure 1.* The material requires a higher potential difference to free the few free electrons within the material from their bounded atoms, classifying it as an insulator.

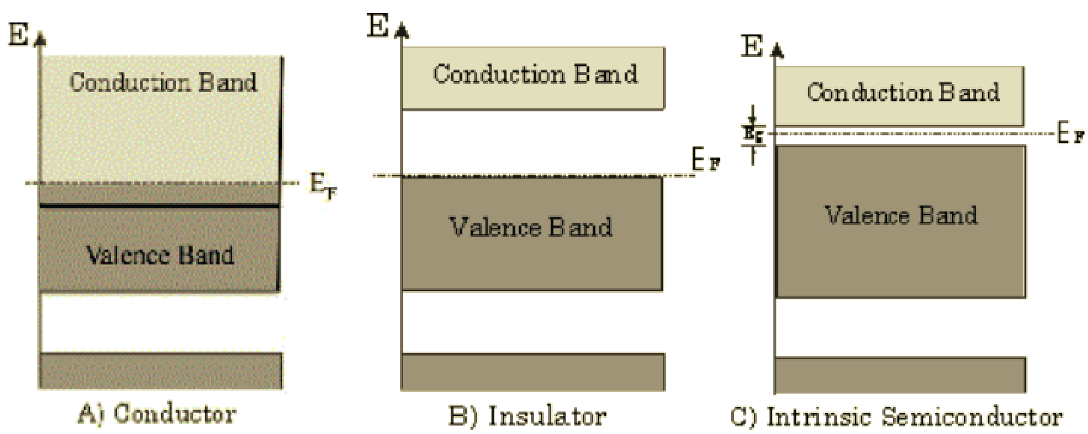

Figure 1 Fermi Energy (Got this image from lab [1])

A semiconductor, on the other hand lies in in between a conductor and an insulator such that there is a small energy gap separating the Fermi Energy from the valance and conduction band. The lab report [1], describes the energy gap in a semiconductor to be *in the order of the thermal energy* $k_b T$ making the materials electrical properties susceptible to temperature.

The electrical properties in a semiconductor can be manipulated by introducing impurities i.e. non semiconductor material into the semiconductor to change the materials conductivity. The process of introducing impurities into a pure semiconductor (i.e. intrinsic semiconductor) is known as doping, and a semiconductor can either be positively or negatively doped converting the material into either a P type or N type semiconductor known as extrinsic semiconductors. When a material is P doped then the material has an excess amount of *holes* which can be regarded as positive charge since the electrons in the material is attracted to the holes. On the other hand, a N doped semiconductor is filled with an excess amount of electrons such the amount of free electrons increase.

Scientist have designed different techniques to extract the electrical properties of semiconductor material. By studying the Hall effect in a semiconductor slab we are able to extract the electrical properties of the semiconductor. This lab focuses on implementing the Van Der Pauw technique on a 1.25mm thick slab of Al doped germanium to study the electrical properties of a semiconductor slab of germanium and determine the type and density of the doping between the temperature 95K-350K.

Theory

As aforementioned the Hall effect studies the induced Hall voltage created by an externally applied magnetic field that's perpendicular to the flow of charge within the material. The Hall voltage is an effect of the Lorentz force law *[Equation 1], [2]* which describes the magnetic force applied by the external magnetic field on a moving particle. We were then able to use the Hall effect to study the parameters of the semiconductor sample.

$$\vec{F} = q(\vec{v} \times \vec{B})$$

Equation 1 Lorentz Force Law.

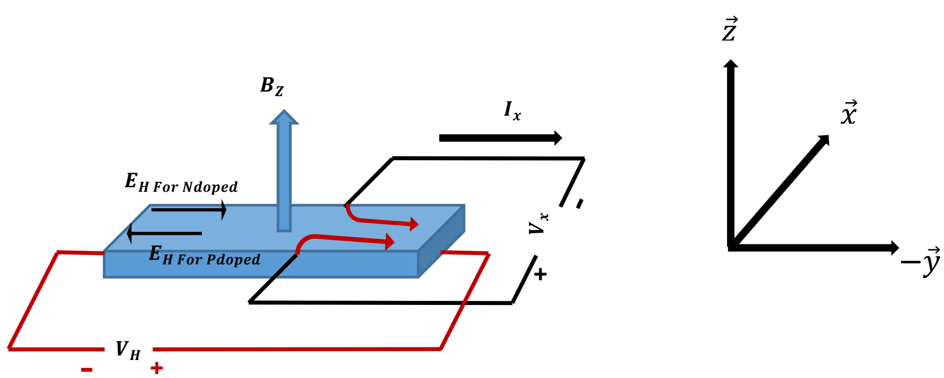

Figure 2 Hall Effect on a semiconductor sample

Figure 2 shoes that by applying an external magnetic field to our Al doped sample of germanium with a current flowing in the x direction across the sample then electrons in the semiconductor will start building up at the right end of the sample, in the –y direction as seen in *Figure 2* creating a potential difference across the sample knowns as the Hall voltage, which in turn induces an electric field in the y direction with a voltage difference of $V_H = sE_H$ (s is the width of the sample) [2]. The force applied by the magnetic field and the induced electric cancel each other out such *Equation 1* can be written as *Equation 2*.

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) = 0$$
$$qE_y = qv_xB_z$$
$$E_H = v_xB_z$$

Equation 2 Calculation of the Induced electric field

We are able to find a relationship between the hall coefficient and the charge carriers. For our example we will consider the case where the sample is P type since our sample of germanium was P doped as I will explain later on. To find total current we simply need to multiply the current density $J = epv_x$ with the cross sectional area of the sample, $A = sd$, where d is the thickness of the sample and s is the area.

$$I = JA = epv_xsd$$
$$E_H = v_xB_z$$
$$V_H = sE_H = sv_xB_z$$

We are able to rearrange our calculation for total current to calculate v_x

$$\frac{I}{epsd} = v_x$$

Such that we are now able to solve for the Hall Voltage

$$V_H = sv_xB_z = \frac{I_xsB_z}{epsd} = \frac{I_xB_z}{epd}$$

The Hall coefficient for a p type semiconductor is then given by

$$R_H = \frac{1}{ep}$$

The Hall coefficient for a n type semiconductor is then given by

$$R_H = \frac{-1}{en}$$

Equation 3 Calculation for hall coefficient and voltage along with the carrier density [1,2]

As seen from my calculation the carrier type depends on the sign of the hall coefficient which we measured using the Van Der Pauw technique. Another important electrical property is the resistivity of the semiconductor sample, which tells us the materials ability to resist electricity or the ability to conduct electricity because the inverse of resistivity is conductivity. [3] gives us the formula for resistivity of the sample based on the Van Der Pauw theorem of sheet resistance as seen in equation 4. The full deviation is beyond the scope of the lab but it is shown in [4].

$$\rho = \frac{\pi d}{\ln(2)} \times \frac{R_{12,34}+R_{23,41}}{2} \times \frac{1}{\cosh\left(\frac{\ln\left(\frac{R_{12,34}}{R_{23,41}}\right)}{2.403}\right)}$$
$$\sigma_{conductivity} = \frac{1}{\rho_{resistivity}}$$

Equation 4 Resistivity and conductivity calculation

We are also able to calculate the carrier mobility using *equation 5* which is a measurement on the charge carriers due to an applied magnetic field.

$$\mu = \frac{d\Delta R_{24,13}}{B * g} = R_H * \sigma_{conductivity}$$

$$\mu = mobility$$

d = thickness

$$\Delta R_{24,13} = change\ in\ transresistance$$

B = magnetic field

Equation 5 Carrier mobility

Apparatus and Procedure

The Van Der Pauw technique allows us to measure the hall coefficient to extract important parameters found in the semiconductor sample as it changes in temperature. We mount a 10mm x 10mm +/- 0.01mm slab of Al doped germanium with thickness 1.25mm +/- 0.01mm inside a cryostat which uses liquid nitrogen to cool the sample down to about 95K. Once at 95K the cryostat uses a *brass-copper rod containing a 50-watt maximum heating coil [1],* in order to heat up sample which uses a silicon diode temperature sensor to measure the temperature of the sample. The square slab has four leads A, B, C, D, *Figure 3*, two of which are for current and the other two leads are to measure the voltage. In order to get the Hall effect, we use a 5000 Gauss electromagnet to apply an external magnetic field into our sample.

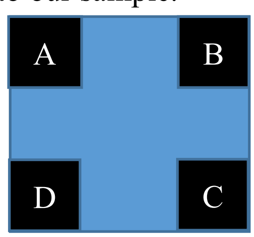

Figure 3 Germanium Sample

When conducting a run of our experiment we must first apply liquid nitrogen to our cryostat to cool the system down to 95K any lower could have broken the equipment we were using. Once the cryostat reached about 240K we quickly had to apply more cryogen into the cryostat as the liquid nitrogen was reaching its boiling point. We then set the magnetic field in the computer to 3500 Gauss which is what was recommended by the lab. For our experiment we studied five different sample currents ranging from 1uA to 900uA. Once the sample reached 95K the LabVIEW program starts to source and measure the current and voltage across the sample.

In the end the LabVIEW program is designed to collect 16 different measurements of current and voltage as the temperature increase in the presence of a zero magnetic field or a positive or negative 3500 gauss magnetic field. Such that we are left with four positive and negative sample currents: $I_{AB}, I_{AD}, I_{AC}, I_{BD}$ along with four positive and negative voltages $V_{CD}, V_{BC}, V_{BD}, V_{AC}$. Using Ohms law, we are able to calculate the average trance-resistance of the sample such that the two currents applied between non-adjacent points allow us to calculate the Hall voltage while the currents applied to the adjacent points is used to calculate the resistivity of the sample as in *Equation 4*.

Analysis

Do to the time constraint with this lab we only measured 5 sample currents ranging from 1uA to 900uA, we used geometric sequencing to evenly space out the sample currents and obtain a plot for 1uA, 225uA, 450uA, 675uA, and 900uA. We set up the LabVIEW program to apply a positive and negative magnetic field of 3500 Gauss in order to observe the Hall effect. However, after analyzing each individual file I noticed that the actual positive and negative magnetic field was consistently greater than what we had set it too as seen in *Figure 4*. *Figure 4* shows that the 900uA file has a large standard deviation of about 1183.370 Gauss which as noticeably different than the others. Unfortunately, due to timing we did not have time to redo the measurement to account for the strange variation in applied magnetic fields.

	1uA	225 uA	450 uA	675 uA	900 uA
No B Field	122.010	121.990	121.800	121.990	122.400
No B Field STD	0.120	0.150	0.110	0.130	25.300
Pos B Field	4164.920	4164.890	4164.960	4161.125	4084.875
Pos B Field STD	3.580	2.960	4.996	5.380	550.830
Neg B Field	-3970.357	-3970.142	-3967.286	-3966.910	-3748.000
Neg B Field STD	4.890	4.010	4.990	6.142	1183.370

Figure 4 Average Magnetic Field Applied and its standard deviation

For each sample current we plotted six different graphs describing the electrical properties of the Germanium sample we were testing along with the parameters of the Hall effect. *Figure 5* shows the data we collected for a sample current of 1uA. Which was the lowest recommended sample run. Unfortunately the 1uA file returned the sloppiest plots overall, by analyzing the dataset I have come to the conclusion that the issue comes sampling such a low current. By looking at the Hall Coefficient vs Temperature plot in *Figure 5*, it is noticeable that the no magnetic field hall coefficient is not accurate. Despite claiming to be the zero magnetic field it applied a constant magnetic field of 122Gauss which we took to be zero but this is why we still get a plot for the hall coefficient despite claiming to have no magnetic field.

1uA

We measured the Hall coefficient at room temperature for the sample run of 1uA to be -.7664 [Ohm*m/T] with a standard deviation of .119, I compared the data taken by averaging the results from the positive and negative measurements of voltage and current for each individual run. To measure the hall coefficient, I considered 295K to be room temperature and wore a python script to extrapolate the hall coefficient right above and below 295K and then I averaged out the value.

We also measured the resistivity at room temperature to be -8.03 [Ohm*m] with a standard deviation of .167 [Ohm*m], I used this by plotting the best fit line using the power fit function and extrapolating what the resistivity would be at room temperature. However, due to the low current sample I noticed that the resistivity was incorrect. I also found that the Hall coefficient is zero at approximately 223.74K (Standard deviation of 1.41K), by averaging the temperature of the two hall coefficients that were right above and below 0 [Ohm*m/T]. This is called the inversion point where the semiconductor transitions from intrinsic to extrinsic if cooled down or vice versa, if heated up. Specifically, Germanium is an intrinsic semiconductor but the sample we got has been doped to have impurities. In our case we know that we have a P type semiconductor because the Hall Coefficient is not negative for a positive magnetic field as explained in the analysis. However, the semiconductor can be treated as intrinsic at high temperatures meaning the electrons and hole densities in the material are equal, and extrinsic at lower temperatures once the impurities increase.

Furthermore, we were able to plot the Hall Mobility vs Temperature for the holes, using *Equation 5* but only in the extrinsic region. Once the semiconductor temperature passes the inversion point it becomes intrinsic once again and there is the same number of holes as electrons. Therefore in order to measure the Hall Mobility I took the average of the hall mobility in the extrinsic region which remained roughly constant at low temperatures and got a hall mobility of 2.404[m$_2$/V*s]. I was unable to calculate the hall mobility easily for this sample and had to remove a lot of values that had returned –infinity. Luckily this was the only run where we faced this issue.

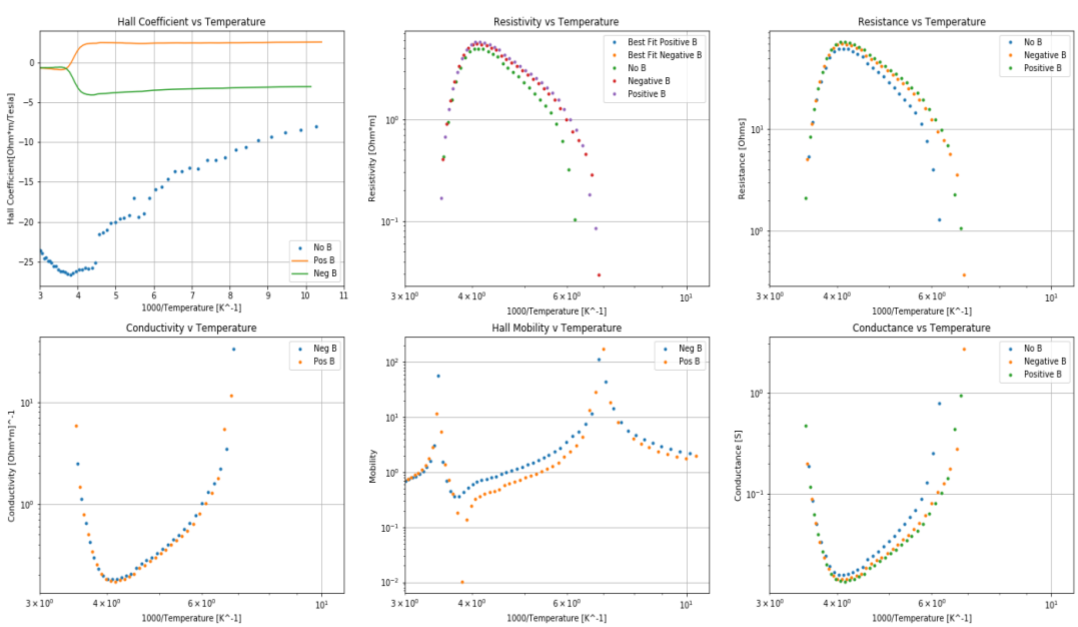

Figure 5 Plots from our First run. Using a sample current of 1uA. This is for the data using positive voltage and current

225uA

Our second run came out more successful due to the higher current sample of 225uA *Figure 6,* as one can tell the no B field measurement of the hall coefficient still returns a measurement of the hall coefficient because there is a small B field of about 121 Gauss applied for all runs with no magnetic field. I found that the Hall coefficient at room temperature increase to -.023 [Ohm-m/T] with a standard deviation of .08 [Ohm-m/T]. It makes sense that our Hall Coefficient is changing since we are sampling different current and we are using the trance-resistance to calculate the hall coefficient as aforementioned. The resistivity of the sample at room temperature appears to be 1.01 [Ohm-m] (Standard deviation of .007) which makes more sense than the -8 [Ohm-m] resistivity we measured at 1uA. Using the same methods as before I found that the hall coefficient is zero at about 222.98K (Standard deviation of 1.401). Which is what we approximately got for the 1uA run. Therefore, the inversion point occurs at around 222.98K. Once we reach lower temperatures I found that the average Hall mobility is 1.31[m_2/V*s] with a standard deviation of .198[m_2/V*s].

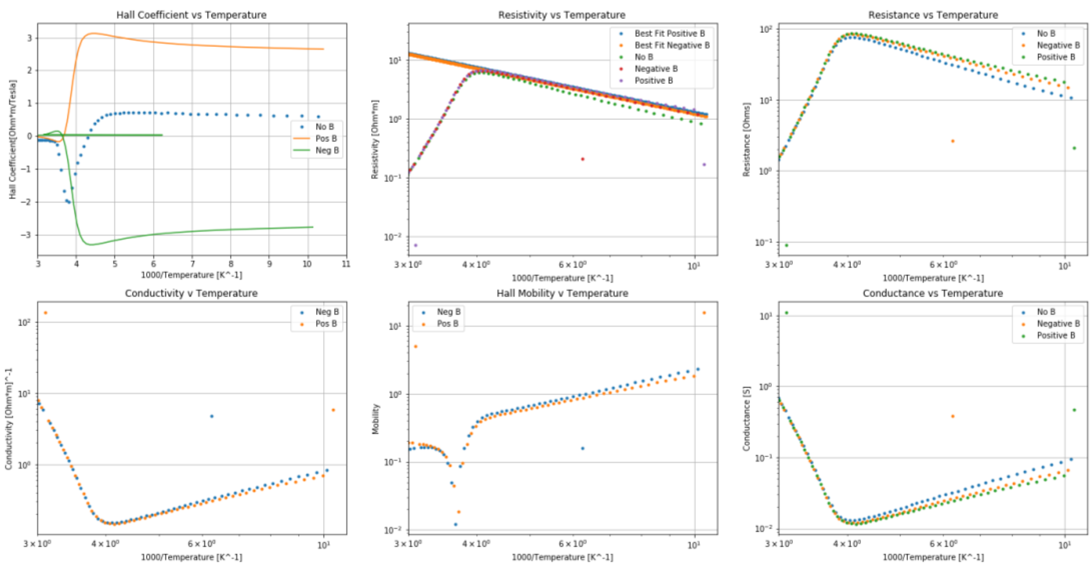

Figure 6 225uA sample current. This is for the data using positive voltage and current

450uA

Overall the 450uA sample current was our best run *Figure 7*, I calculated the hall coefficient at room temperature to be about .003 [Ohm-m/T] with a standard deviation of .115 [Ohm-m/T]. The hall coefficient continues to increase the 225uA sample returned -.023 [Ohm-m/T]. I believe this is due to the increase in sample current since we use it to calculate the Hall coefficient. The resistivity at room temperature remained relatively the same as the 225uA sample current which returned a resistivity of 1.01 [Ohm-m]. The resistivity at room temperature for the 450uA sample is 1.008 [Ohm-m]. Again I measured the inversion point to be at 222.97K with a standard deviation of 1.41K which is the same as the previous sample currents. The average Hall mobility in low temperatures is 1.11[m_2/V*s] with a standard deviation of .062[m_2/V*s].

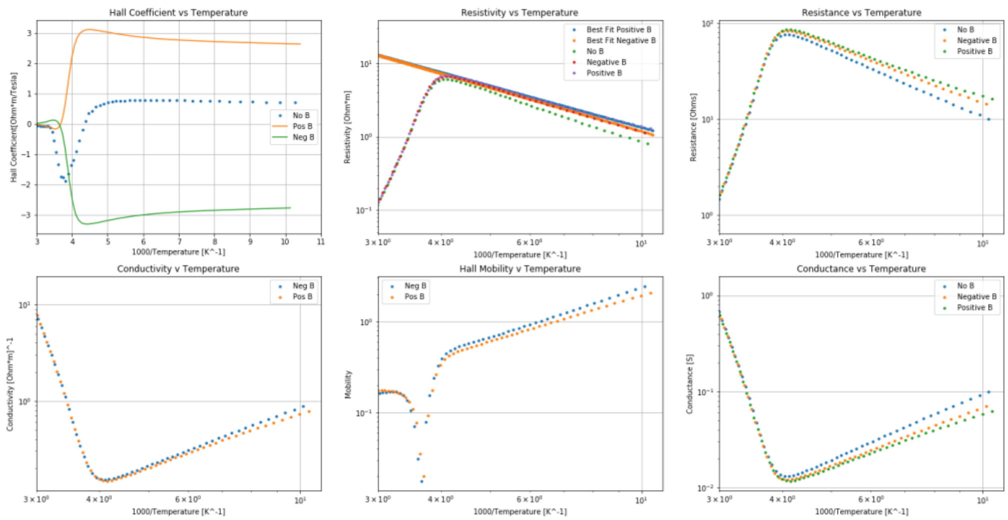

Figure 7 450uA sample current. This is for the data using positive voltage and current

675uA

Unlike the previous runs the Hall coefficient at room temperature decreased to -.001[Ohm-m/T] with a standard deviation of .116[Ohm-m/T], *Figure 8.* However, the resistivity at room temperature remained relatively the same as the previous runs, I found it to be 1.01[Ohm-m] with a standard deviation of .003. I found that the hall coefficient and Hall mobility also does not change much from before, I calculated a hall mobility of 1.12[Ohm-m] with a standard deviation of 0.072.

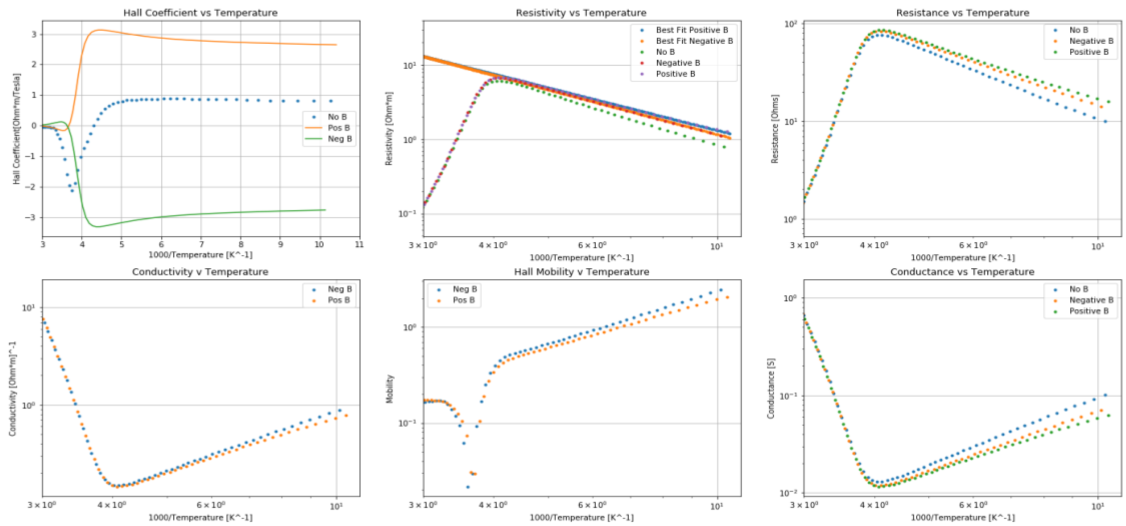

Figure 8 675uA sample current. This is for the data using positive voltage and current

900uA

I was expecting to have the worst results for the 900uA plots due to the high standard deviation in the applied magnetic field, however the data seemed to stay relatively consistent (*Figure 9*). The hall coefficient measured at room temperature is .001 [Ohm-m/T] with a standard deviation of .116 [Ohm-m/T] which was consistent with the 450uA sample but still varied with the other sample current measurements. The resistivity at room temperature was calculated to be .955 [Ohm-m] with a standard deviation of .004[Ohm-m]. The hall coefficient is zero at 221.72K (Standard deviation of 1.39K) which is similar to what we previously calculated. Therefore, the inversion point for our Germanium P-doped sample is at about 222K. The Hall/hole mobility is then .936[m^2/V*s] with a SD of .044[m^2/V*s].

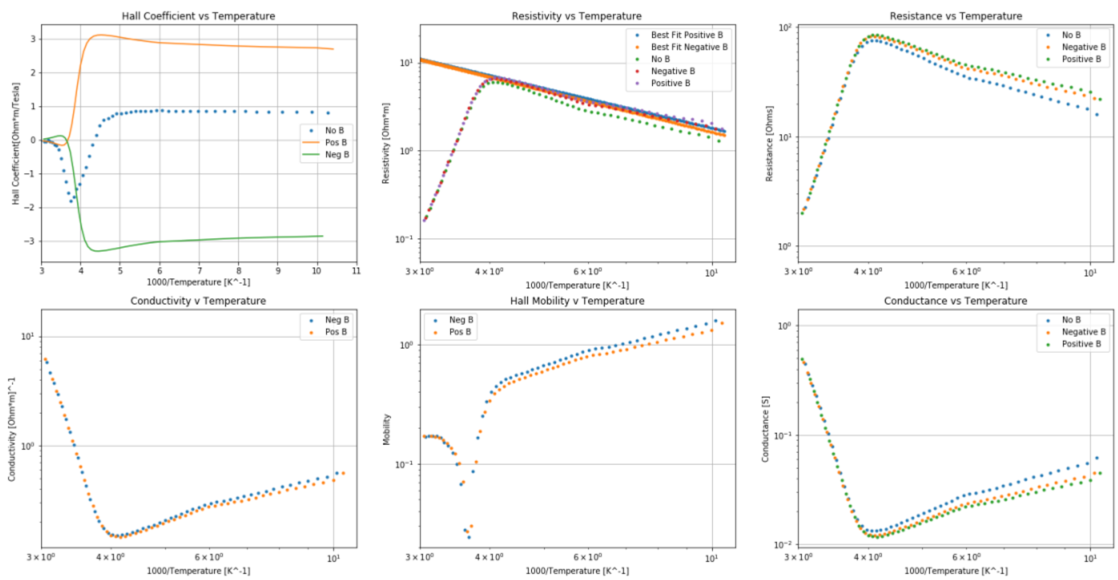

Figure 9 900uA sample current. This is for the data using positive voltage and current

	1uA	225 uA	450 uA	675 uA	900 uA
Hall Coefficient Room Temp	-0.766	-0.0230	0.0028	-0.0010	0.000500
Hall Coefficient Room Temp STD	0.119	0.0870	0.1148	0.1160	0.116400
Resistivity Room Temp	-8.030	1.0100	1.0080	1.0136	0.955800
Resistivity Room Temp STD	0.167	0.0070	0.0041	0.0031	0.004000
Hall Coefficient is Zero at Temp	223.740	222.9890	222.9710	222.7100	221.727875
Zero Hall Coefficient STD	1.410	1.4010	1.4110	1.4800	1.393700
Hall Mobility	2.404	1.3100	1.1175	1.1160	0.936000
Hall Mobility STD	2.404	0.1975	0.6240	0.0720	0.044000

Figure 10 Calculated Results all in Si units

Conclusion

Furthermore, given more time we would have conducted more measurements, unfortunately give n the time restraints this lab did not leave a lot of room for error. Each run lasted about two hours which meant we were at most only able to collect about 2 sample runs per day if we did not make a mistake which was difficult to avoid the first two days. I believe if we were to run the experime nt again we would see a lot better data as we would be able to have more runs.

I also had a hard time looking through all the references for the required information to analyze t he data properly however it was really helpful to have my partner Andre to work through analyzi ng the data properly. He was also very helpful and patient with me as I was really busy this mont h due to exams along with applying to different programs for after graduation. I definitely would not have been able to complete this lab without him.

Note: For some reason my word is formatting my document incorrectly and the margins are cutti ng (like this) off the words at the end of a line. I have tried for hours to fix it and have not been a ble to fix it. I apologize for the ugly formatting and hope it will not impact my grade.

1. *SHE - Hall Effect in Semiconductor Physics 111B: Advanced Experimentation Laboratory*. University of California, Berkeley, http://experimentationlab.berkeley.edu/sites/default/files/writeups/SHE.pdf.
2. Neamen, Donald A. *Semiconductor Physics and Devices: Basic Principles*. Irwin, 1992. *Library of Congress ISBN*, http://physics111.lib.berkeley.edu/Physics111/Reprints/SHE/09-Semiconductors.pdf.
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