Lab #3: Hall Effect

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Abstract

The following experiment utilized two samples of doped silicon to observe the Hall effect through these samples. Using the data acquired in the lab, we were able to determine that the first sample is a p-type semiconductor, and that the second sample is an n-type semiconductor. We then calculated values of carrier density and carrier mobility from our measured data and created plots with best fit lines. We found that carrier density increased for both samples with temperature, and that carrier mobility increased with temperature for sample one, but decreased with temperature for sample two.

1 Introduction

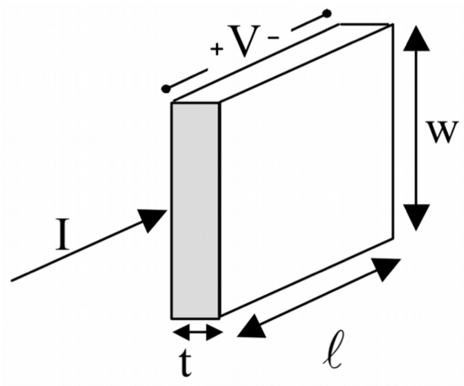
The Hall Effect observed in this experiment was first discovered by Edwin Hall in 1879 [3]. In his studies, he found that a force outside of the electromotive force can act on currents, and that is the magnetic force [2]. It has since been used in developing the Quantum Hall effect, and it is used in many sensory applications [4]. It occurs when an electric current flows through a conductor in a magnetic field, causing the magnetic field to exert a transverse force on the charge carriers and push them to one side of the conductor. This effect produces a measurable voltage, called the Hall Voltage between the sides of the conductor. In this experiment, our focus will be on the Hall Effect in semiconductors. Some common semiconductors are Si, Ge, GaAs, and InAs, and they contain a concentration of electrons or holes that lies between conductors and insulators. Semiconductors are used in plenty of modern day technological instruments such as radios, phones, and computers and are often the subject of study in laboratories. We can use measurements of semiconductor resistivity to measure carrier mobility, carrier concentration and scattering rate for materials. We use measurements of Hall voltages and resistivities in order to determine such properties.

For this experiment, we will be utilizing two samples of doped silicon. Our goal is to measure the DC 2-probe resistances of the various configurations of the Silicon samples, as well as the DC 4-probe resistances. Additionally, we will measure the DC Hall voltage as we vary the magnetic field, the 4-probe resistances of the sample with varying magnetic field, and the DC Hall voltage with high magnetic field strength and lowering temperature. This will allow us to better understand the properties of semiconductors, and allow us to differentiate between n and p-type doped silicon. This experiment is important in that it will allow us to calculate the number of charge carriers per unit volume of a material, and it was later found that through studying this effect n and p type doped samples could form junctions or diodes, which convert alternating current to direct current and are used in many technological devices.

2 Theory

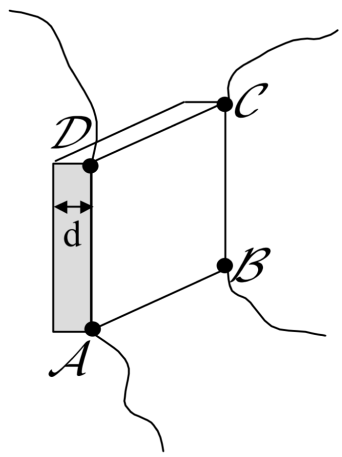
The Hall Effect is the result of an applied electric field through a material with a magnetic field perpendicular to that electric field. This produces a transverse voltage through the material and this is called the Hall effect. To start with describing the Hall effect, we must first describe the way an electric current density travels through a material, and the effects it has. A current density $\vec{j}$ travelling through a material produces an electric field that is proportional to the resistivity ρ of the material such that $\vec{E} = \rho\vec{j}$. In order to achieve an expression which represents the potential difference across the material, we multiply both sides of the equation by the length of the material, and then replace the current density with the current over the area of the material. Thus we arrive at $V = \rho\frac{l}{A}I$. This expression is equivalent to Ohm's law $V = IR$, where $R = \rho\frac{l}{A}$. A material of thickness t, length l and width w with the dimensions shown in the figure below has a current I flowing through it, which produces a voltage across its length. We find that the resistance of this sample is given by $R = \rho\frac{l}{wt}$. In order to measure the resistivity of the sample that we are

Figure 1: Longitudinal configuration for measuring resistivity [Taken from 1]



observing, we must use what is called the van der Pauw method. This method can be used if the conditions are met that the contacts used to measure the materials resistivity are on the outer edges of the sample, that the contacts are small, that the sample is homogeneous, and that the surface is singly connected. In this lab we use the following configuration in which four contacts are attached at each edge of the sample This four probe method is superior to the two probe

Figure 2: van der Pauw measurement configuration [Taken from 1]

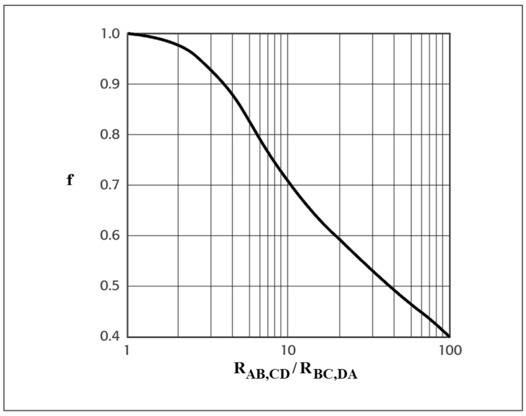


method in that we can use it to ignore resistances in the contacts and wires as the voltage is only measured across the body. We can thus use the following equation to measure the resistivity using the van der Pauw method

$$\rho = \frac{\pi t}{ln2}\frac{R_{AB,CD}+R_{BC,DA}}{2}f(\frac{R_{AB,CD}}{R_{BC,DA}})$$

where $R_{AB,CD}$ and $R_{BC,DA}$ are the resistance values obtained from the two configurations used. The function f is a function that slowly varies and is detailed in the plot below, with sample values given in the lab manual So far we

Figure 3: Plot of the function f [Taken from 1]



have discussed the properties of the materials with an electric current density applied through them, however when a magnetic field B is applied perpendicular to the surface, we can measure the hall voltage, V_{Hall} in the y direction of the sample. These Hall voltage values allow us to determine several properties of the material such as the sign of charge carriers, as well as the carrier density and mobility. Using the same method of converting the electric field equation into an Ohm's law equation, we can do the same for the Hall voltage to arrive at an equation for Hall voltage of $V_{Hall} = R_{xy}I$, where R_{xy} is the Hall resistance, that is written as $R_{xy} = \frac{R_H}{t}B$, where B is the magnetic field, t is the thickness of the material, and R_H is the Hall constant of the material, which is related to the carrier density and charge of the charge carriers by $R_H = \frac{1}{nq}$. For the purpose of this experiment, since we will be using a magnetic field to measure Hall voltage, we can rearrange these equations to find that R_H, the Hall constant can be written as

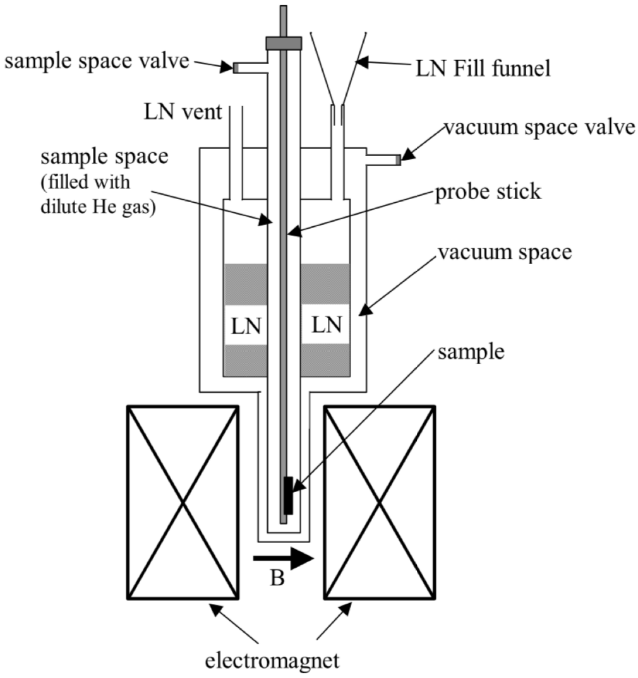
$$R_H = \frac{V_{Hall}}{B}\frac{t}{I}$$

From this Hall constant we can calculate values of carrier mobility, and carrier density using the equation $\mu = \frac{1}{\rho n q} = \frac{R_H}{\rho}$

3 Experimental Set-Up

The set up for this experiment requires a cryostat, a sample probe, one n type and one p type doped silicon sample, a vacuum pump, an external switch box, a temperature controller, two multimeters, a Keithley 227 current source, and an electromagnet powered by a Lambda Genesys power supply.
The cryostat is the chamber within which the temperature dependent experiments will be controlled, and the sample is placed. The cryostat has three separate chambers: the vacuum space, the sample space, and a chamber for the liquid nitrogen used.

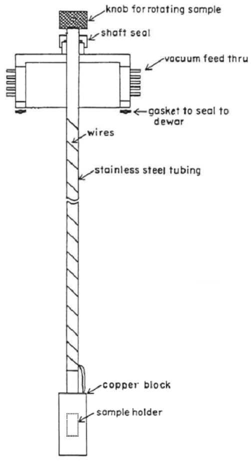
Figure 4: The cryostat used for low temperature measurements [Taken from 1]



The three chambers are shown in the above figure. In order to use the cryostat, the sample space has the air pumped out of it first for about 2-3 minutes. This is done so that the liquid nitrogen placed in its chamber does not freeze the air and thus cause damage to the sample. After this space has been evacuated, helium gas can be injected into the sample space to serve as the heat exchange gas. This valve is then closed and the outer vacuum space can be evacuated. The fill funnel is used to facilitate the pouring of liquid nitrogen, which is never to be poured until the cryostat is properly evacuated. The rate of temperature change throughout this experiment should be kept relatively slow, at about 10 K/min to maintain thermal equilibrium within the sample space.
The next device used in the experiment is the sample probe. The sample probe is used to lower and position the sample in the cryostat. This probe consists of 5 parts: a suspension tube, which varies the height of the sample, a copper vessel and heater coils which reduce thermal fluctuations, a DT741 diode which measures the sample temperature, heater coils which help control the rate of

temperature change of the sample, and a sample holder on which the sample can be mounted. The entire apparatus is pictured below. For this lab, two different kinds of samples are used, n-type doped silicon and p-type doped silicon. They are about 400 μm thick and have around $10^1 5$ dopant atoms/cm^3. Attached to the corners of the sample are thin copper wires. There are 14 pins on the sample that are numbered 1-14, however for this experiment the pins labelled 2, 3, 12 and 13 are the ones wired for use.

Figure 5: The sample probe [Taken from 1]

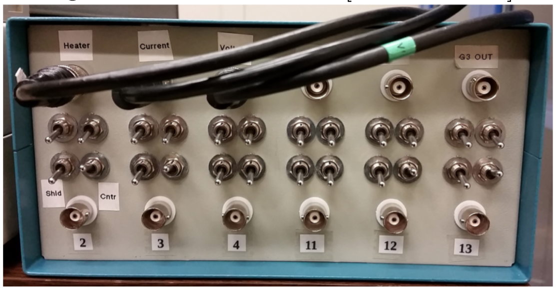


The next piece of equipment used in this lab is the vacuum pumping system. The vacuum pump we are using is a two stage rotary vane pump which we use to pump air out of the inner sample space and the outer sample space. When a space is being pumped, the pump should be connected to the desired valve, after which the valve should be opened and the pump should be turned on. When the space is finished being pumped, the valve should first be closed and then the pump can be turned off. Once it is turned off, the hose is to be removed from the valve so that pump oil is not drawn out from the device. The vacuum pump used is pictured below.

Figure 6: The vacuum pump [Taken from 1]

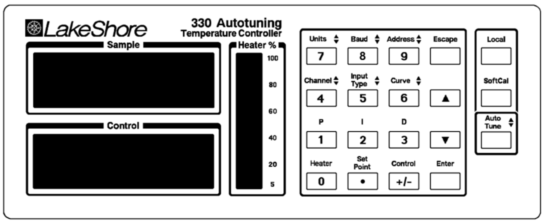
Another piece of equipment required for this experiment is the external switch box that is connected to the sample. For this experiment, the ports labelled 2, 3, 12, and 13 are connected to the wires which are connected to the sample. Above each port there are two switches. The switch on the right is for the center connection, and is to be enabled, and the one on the left is for enabling the outside shield connections. The switches above those for heater coil current, temperature sensitive diode current and voltage are wired internally. The switch box is shown below.

Figure 7: The switch box [Taken from 1]



The Lakeshore 330 autotuning temperature controller is what is used to regulate the temperature in this experiment. It is shown in the following image

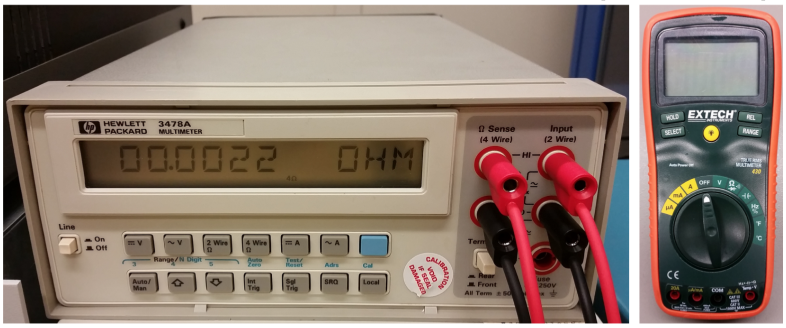
Figure 8: The Lakeshore 330 temperature controller [Taken from 1]



The controller uses a Proportional-Integral-Derivative, or PID feedback loop to set the temperature values. The heater can be set between off, low, medium, and high settings using the Heater button. For this experiment, we will solely use the High setting. In order to change the temperature, the set point button is used, and the set rate can be changed by holding down the set point button. The set rate for this experiment should primarily be set to 10 K/min.

For this experiment we also use two multimeters, an HP 3478A and an Extech 430. These are used to measure the resistivity and voltage for this experiment. The HP 3478A is used to measure the 2 probe and 4 probe measurements by hitting the 2 wire Ω button and the 4 probe Ω buttons respectively. For the 2 probe method, only the 2 wire inputs are used, however for the 4 probe method all 4 ports are used. This multimeter injects a probe current from the 2 Wire ports and in the 4 probe mode, it measures voltage from the Ω sense ports and it displays the measured resistance on the screen. The Extech 430 is handheld, and can measure voltage, current or resistance by using a rotary switch. It can be used to measure AC or DC values. The two multimeters are shown below.

Figure 9: HP 3478A and Extech 430 multimeters [Taken from 1]



Next, the Kiethley 227 is the DC current source used for the experiment, and in this experiment produces a 2.0 mA current. The rightmost knob is set to the mA with 50 MAX COMP VOLT. The units knob, third from the left sets current and it should be set to 2, and the others to zero. The Keithley 227 is shown below.

Figure 10: Keithley 227 [Taken from 1]

The electromagnet and power supply used are a large water cooled electromagnet and a Lambda Genesys power supply. The static magnetic field is produced through an electric current in a wire that is wound into many coils. Instead of attempting to calculate values of the magnetic field, it is more convenient to measure magnetic field strength for specific current values with a magnetometer, which is the method used in this experiment. In order to avoid overheating the magnet, it is important to ensure water is running at all times. Additionally, the current through the magnet cannot exceed 35 A. These steps are crucial to avoid damaging the magnet. Atop the magnet is a bar which reverses the magnet polarity. The current through the magnet should be set to 0 before changing the magnet direction. The Lambda Genesys power supply is first turned on by flipping the switch on the left side to the on position, and then the output is enabled through hitting the out button and current can be set to specific values using the current knob. This knob is to be turned slowly to avoid disrupting the temperature equilibrium of the sample. The magnet and power supply are shown below.

Figure 11: The electromagnet [Taken from 1]

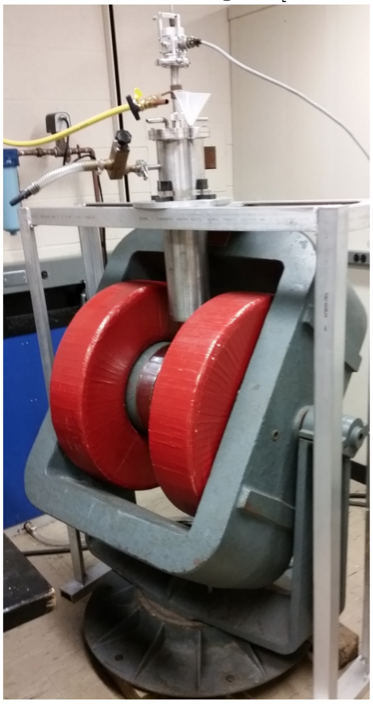
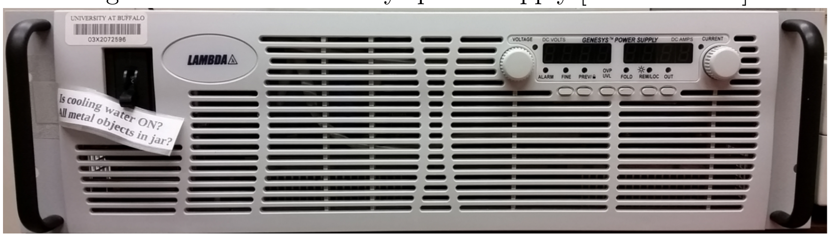


Figure 12: Lambda Genesys power supply [Taken from 1]



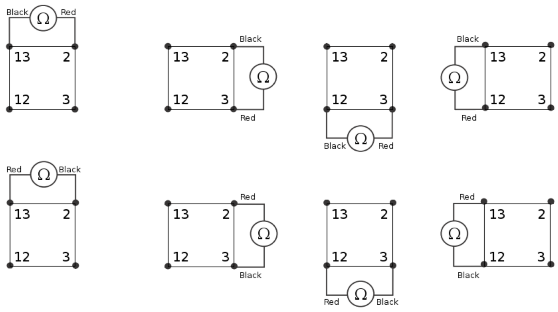
4 Procedure

The following experimental methods are performed for two different samples in this lab, of n-type doped silicon and p-type doped silicon. The following steps should be repeated for each sample.

4.1 DC 2-probe resistance

For the first step of the experiment we are using the HP multimeter to measure the DC 2 probe resistances of the sample in various different configurations. These configurations are shown below.

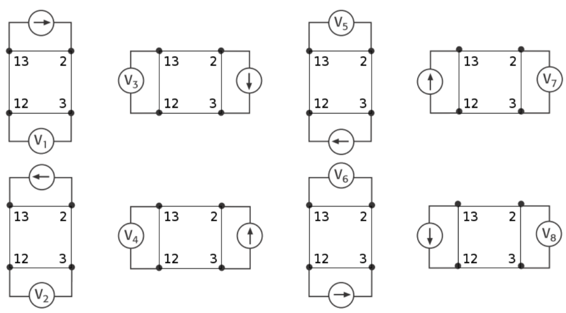
Figure 13: Longitudinal configurations for 2-probe resistance measurements [Taken from 1]



4.2 DC 4-probe resistance

The next part of the experiment uses the HP multimeter to measure the DC 4-probe resistances for 8 possible longitudinal configurations shown by the following figure

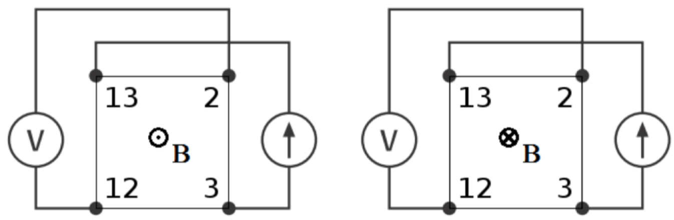
Figure 14: Longitudinal configurations for 4-probe resistance measurements [Taken from 1]



These measurements are then compared to the 2 probe resistance measurements from the first part, and the resistivity ρ is calculated using the van der Pauw method.

4.3 DC Hall effect measurement - determining sample type

Figure 15: Diagonal configurations for the DC Hall effect measurement in the forward and reverse directions [Taken from 1]

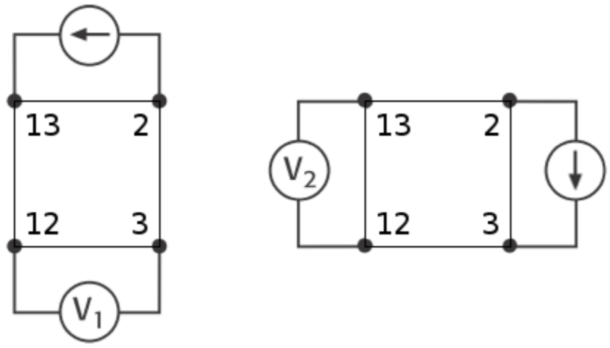


The diagonal 4-probe connections pictured above are set up and the Kiethley 227 is turned on with a 2.0 mA current. After we have secured all magnetic materials far from the magnet, we turn on the magnet with the Lambda Genesys power supply and measure the DC Hall voltage with the voltmeter for magnetic currents of 0-35 A in 5 A increments. We make sure to vary the magnetic current slowly in order to keep the sample at thermal equilibrium. When the data is recorded of the magnet in the forward direction, we flip the bar on the magnet around to record it in the reverse direction. After this data is recorded, a plot of Hall voltage vs magnetic field strength is constructed from the data in order to determine whether the sample is n or p type doped silicon.

4.4 Resistivity versus Temperature

For the next part of the experiment, we will for the first time evacuate the cryostat by using the method in the experimental set up. Using the temperature controller, we first set the temperature to 300 K, with the heater on High. We then pour in 5 liters of liquid nitrogen and begin acquiring data. After the temperature has stabilized, we can measure the 4-probe resistances with the HP 3478A for the following configurations.

Figure 16: Longitudinal configurations for resistivity versus temperature measurements [Taken from 1]



In steps of 20 K, we take measurements of the resistances down to 160 K, in order to construct a plot of resistivity ρ for each temperature using the van der Pauw method.

4.5 DC Hall voltage versus Temperature

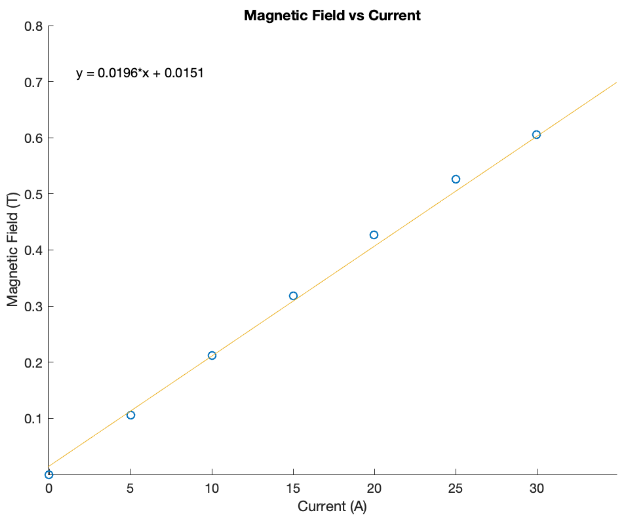
For the final section of the lab, we again evacuate the cryostat as in step four, turn on the heater to 300 K, and fill the cryostat with 5 liters of liquid nitrogen. We then set up the diagonal configurations as in 4.3, and apply a 2.0 mA current using the Kiethley 227, and use the HP 3478A as the voltmeter. Upon again stowing away all magnetic materials, and applying the cooling water to the magnet, we turn the magnet on and measure the Hall voltage for magnetic fields in both directions for currents in 5 A steps from 0-35 A. We then repeat all of these measurements for temperatures down to 160 K in 20 K increments. After this data has been acquired, we produce a plot of Hall voltage versus magnetic field strength, creating separate linear fits for the data at each temperature. Using equations 23 and 26 from the lab manual, we can finally produce plots of carrier density versus temperature and carrier mobility versus temperature.

5 Results

5.1 Magnetic Field Strength vs. Current

First, we find that for this experiment it is more convenient to take measurements in terms of current, so in order to produce plots that yield accurate results we must convert our current measurements to magnetic field values using the table provided. This produces a linear plot shown below.

Figure 17: Plot of magnetic field strength as a function of current



5.2 DC Hall Voltage vs. Magnetic Field Strength at Room Temperature

Next, we produce plots of the DC Hall Voltage at room temperature using the voltages we acquired. These yield a plot with a positive slope for the first sample, and a negative slope for the second sample.

Figure 18: Plot of DC Hall Voltage vs magnetic field for sample 1

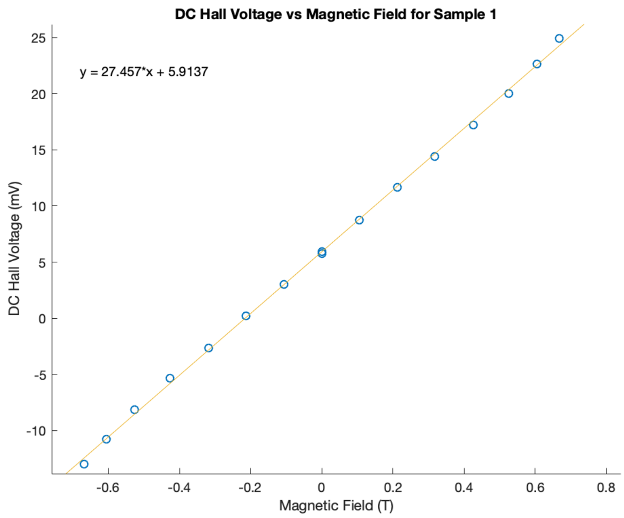
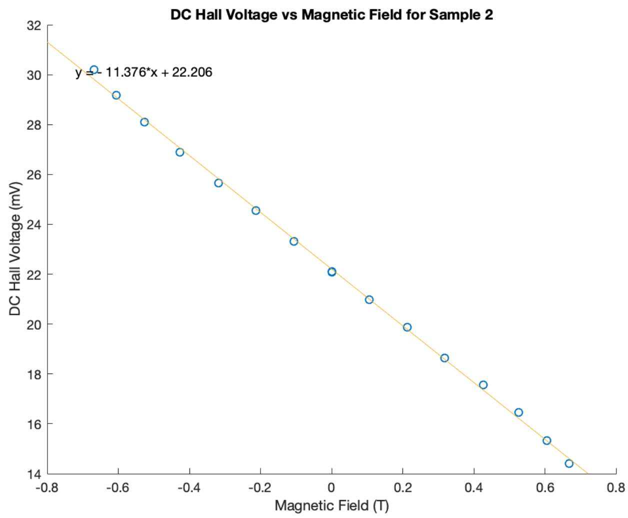


Figure 19: Plot of DC Hall Voltage vs magnetic field for sample 2



5.3 Resistivity vs. Temperature

We then plotted the resistivity of the samples as a function of the temperature in the cryostat. In order to attain values for the resistivity, we use the equation from the lab manual

$$\rho = \frac{\pi t}{ln2} \frac{R_{AB,CD} + R_{BC,DA}}{2} f(\frac{R_{AB,CD}}{R_{BC,DA}})$$

, and the table of values for the function f in the appendix of the lab report. For the first sample at 300 K, we can calculate the resistivity using the measured resistance values of 10Ω for $R_{BC,DA}$ and 12.5Ω for $R_{AB,CD}$. Using the table of values for the function f, we find that $f = 0.99$, and we can use the remaining values of the thickness $t = 400\mu$m, and the current $I = 2$mA, to evaluate the resistivty which is 0.02Ωm. We then use the same method to evaluate the remaining values and construct the following plots

Figure 20: Plot of resistivity vs temperature for the first sample

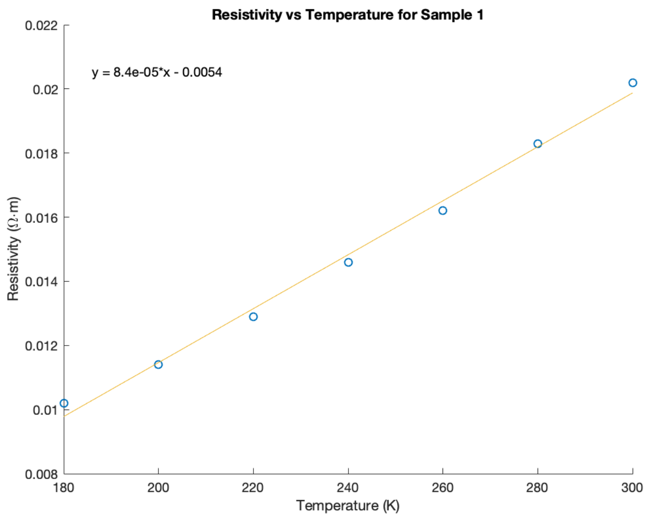
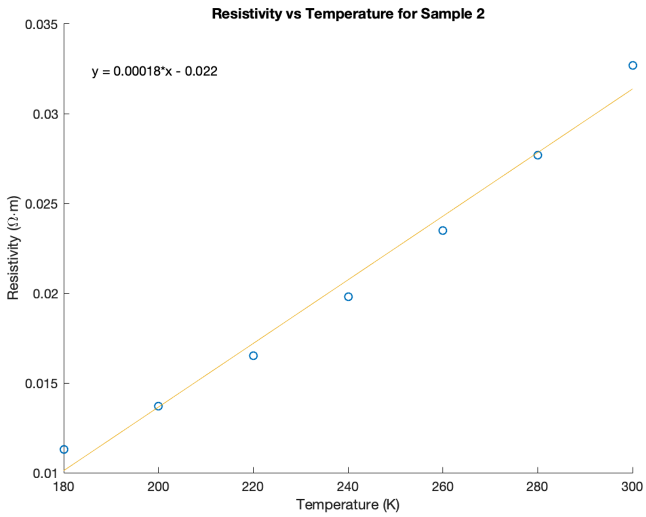


Figure 21: Plot of resistivity vs temperature for the second sample



5.4 DC Hall Voltage vs. Magnetic Field Strength at Various Temperatures

Next, we have plotted the following two plots of the DC Hall Voltage vs magnetic field for each sample and examine the trends as temperature is decreased in the cryostat. The values recorded yield the following plots

Figure 22: Plot of DC Hall Voltage vs magnetic field for sample 1 at various temperatures

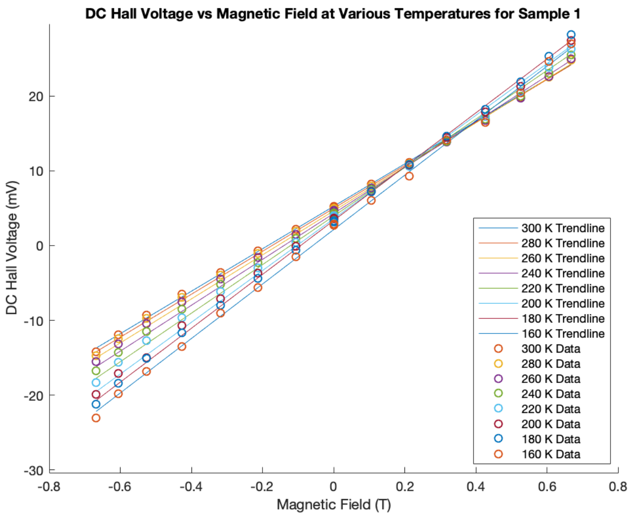
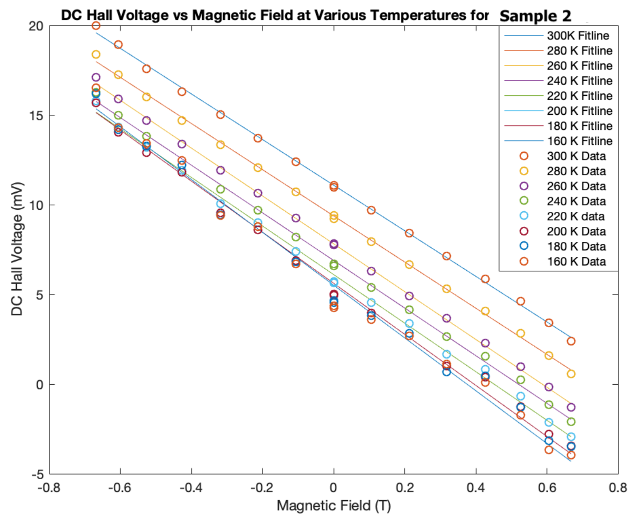


Figure 23: Plot of DC Hall Voltage vs magnetic field for sample 2 at various temperatures



5.5 Carrier Density vs. Temperature

For the next part of the experiment, we will produce a graph of carrier density vs temperature from our data. To do this we must first calculate a value for the Hall constant, given by the equation

$$R_H = \frac{V_{Hall}}{B}\frac{t}{I}$$

Where V_{Hall} is the Hall voltage, B is the magnetic field, t is the thickness of the sample (in this case 400μm, and I is the current, which is 2.0 mA. For the Hall voltage and magnetic field values we will instead use the values of the slopes from our DC Hall voltage vs magnetic field strength at various temperatures plots. We find that the slope is equal to V_{Hall}/B, and so using the known values of current and thickness, we can calculate a value of the Hall coefficient for the second sample at 300 K for example to be $R_H = s\frac{t}{I} = -12.7090\frac{400\times10^{-6}}{2\times10^{-3}} = -2.54m^3/A \cdot sec$. Using the same method we can calculate the remaining Hall constant values for each sample at each temperature, and then use the equation $\frac{1}{nq} = R_H$ to find the carrier density. Rearranging this equation, it becomes $n = \frac{1}{qR_H}$ and thus we can solve for each carrier density value. Using the example found above, where the Hall Coefficient is -2.54, and the electron charge is -1.602×10^{-19} C, we find a value of n of 2.46×10^{18} m^{-3}. We then repeat this for the remaining values and construct the following plots

Figure 24: Plot of carrier density vs temperature for the first sample

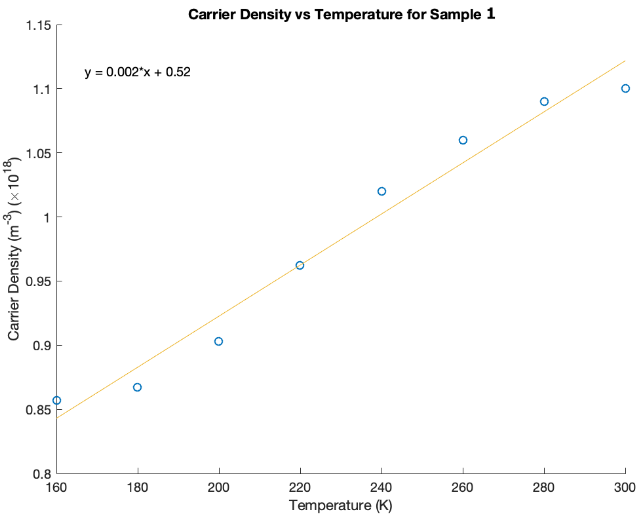
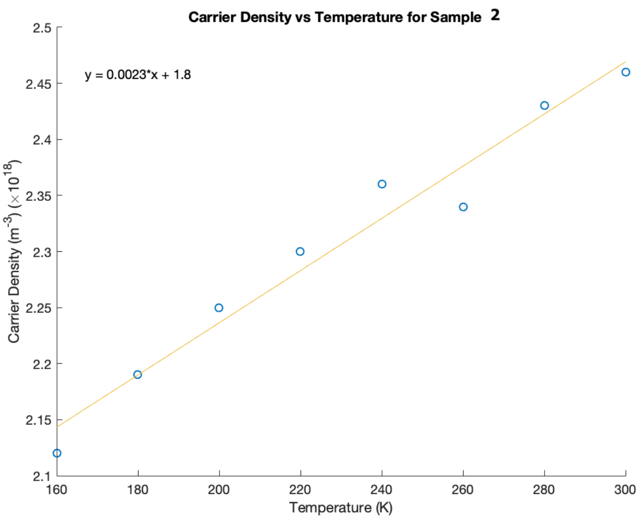


Figure 25: Plot of carrier density vs temperature for the second sample



5.6 Carrier Mobility vs. Temperature

Using the data attained in the second part of the procedure, of measuring the 4-probe resistances, we can calculate the resistivity of each sample using the van der Pauw method. Using these values of the resistivity, and the equation $\mu = \frac{R_H}{\rho}$ with the calculated values of the Hall coefficient from the previous step, we can calculate μ, the carrier mobility for each sample at the temperatures used, in order to construct the following plots

Figure 26: Plot of carrier mobility vs temperature for the first sample

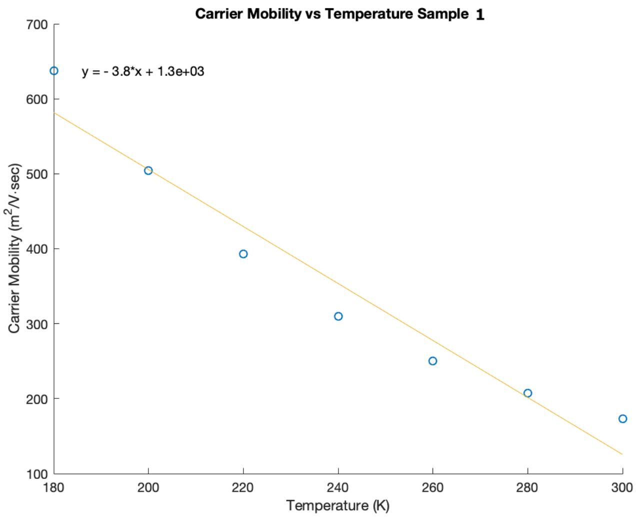
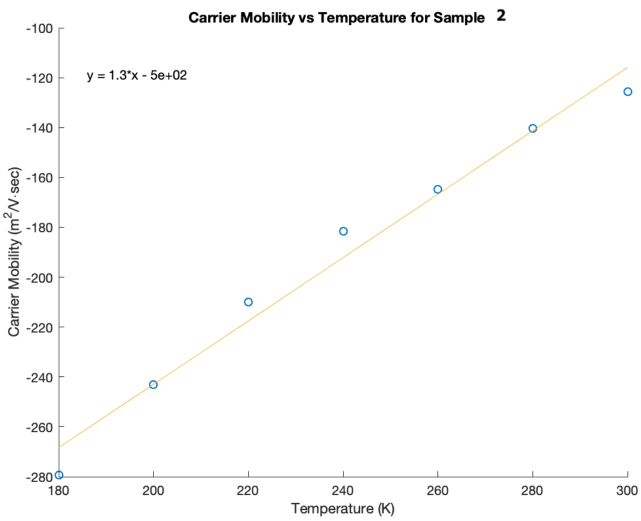


Figure 27: Plot of carrier mobility vs temperature for the second sample



6 Summary and Conclusions

Through the data gathered in this lab we were able to construct plots of first the DC Hall voltage as a function of the magnetic field applied for both of the samples. In doing so, we found that for the first sample, the voltage increased with increasing magnetic field, and for the second sample it decreased. Next, with the data we acquired of resistances of the samples at various temperatures, and in the AB,CD and BC,DA configurations, we were able to calculate resistivity values for each of these. This allowed us to plot resistivity as a function of temperature, which we found increased for each sample. We then plotted the DC Hall voltage as a function of magnetic field at various temperatures for the samples. We found a general trend that as temperature decreased the Hall voltages measured decreased, however for the first sample there was still a trend of increasing voltage with increasing magnetic field regardless of temperature, and for the second sample it decreased regardless of temperature. Finally, we determined carrier density and mobility through calculation and plotted those as functions of temperature. For both samples, we found that carrier density increased with with increasing temperature, and carrier mobility decreased for the first sample, yet increased for the second. Through studying these various properties of the two samples, we are able to conclude that the first sample is a p-type sample, due to its positive Hall constant values which are a result of its positively sloped Hall voltages with increasing magnetic field. Similarly, we find that the second sample is n-type. The data gathered in this experiment was useful in studying the properties of these semiconductors, however perhaps this experiment could be improved by using samples with less impurities, which could have been the source of various errors in our experiment, for example, our first plot of DC Hall voltage as a function of magnetic field at various temperatures does not increase steadily with increasing temperature as magnetic field strength increases. Other sources of error for the experiment could have arisen from failure to fully evacuate the vacuum chambers in the experiment, and taking measurements when the temperature was not fully at equilibrium due to minor fluctuations.

References

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