Hall Effect in Semiconductor

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Physics 111B: Advanced Experimentation Laboratory, Spring 2020

Signatures

SHE - Hall Effect in Semiconductor

Signature Sheet

Student's Name Jiani Chen Partner's Name Alec Bohnett, Clay Halbert

Pre-Lab Discussion Questions

It is your responsibility to discuss this lab with an instructor before your first day of your scheduled lab period. This signed sheet must be included as the first page of your report. Without it you will lose grade points. You should be prepared to discuss at least the following before you come to lab:

1. Why are there energy bands in materials? What is a valence band? A conduction band? A band gap?
2. How do conductors, insulators, and semiconductors differ in their energy-band structures?
3. How do we explain the fact that there are free electrons in a metallic conductor? What is an extrinsic semiconductor?
4. What is the Hall Effect?
5. Explain the Van Der Pauw Technique.
6. What measurements are needed for studying the Hall Effect?

Staff Signature ________ Date 3-4-20

Completed before the first day of lab? (Circle one) Yes / No

Mid-Lab Discussion Questions

1. By day 4, measure the Hall coefficient R_H of the sample at room temperature.

Staff Signature ________ Date 3-6-20

Completed by day 4 of lab? (Circle one) Yes / No

Checkpoint Signatures

1. Hall Coefficient and Van der Pauw Method

Staff Signature ________

2. Apparatus and Procedures

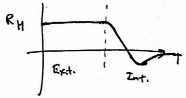
Staff Signature ________

3. Extrapolating Data

Staff Signature ________

4. *Electron or Hole Concentrations*

Staff Signature WLH



*Sum $n(T) = \text{const.}$ → band gap energy$_2$.

σ

$p = \frac{1}{eR_H}$

Introduction

- Semiconductors are deeply integrated in many electronics such as diodes, transistors, and integrated circuits.
- We can study the Hall Effect in semiconductors to better understand its material properties.
- Using the Hall Effect, we can find the type of doping in the semiconductor (p-type or n-type), the carrier mobilities, and the conductivity/resistivity of the material at various temperatures.
- In our experiment, we will be working with p-type Germanium.

Theory

1. Properties of solids
2. Charge carriers (electrons or holes).
3. Properties of semiconductors.
4. What is the Hall Effect?
5. Explain the Van Der Pauw Technique.
6. P-type semiconductors

Properties of solids

- Energy spectrum consists of bands of allowed energies due to delocalized electron quantum levels caused by strong neighboring atomic forces
- Three energy band continuums
  - Valence band: Highest energy continuum with occupied states
  - Conduction band: Lowest energy continuum with not fully occupied states
  - Band gap: Not allowed energy gap between valence and conduction band
- Three types of solids: Conductor, Insulator, Semiconductor

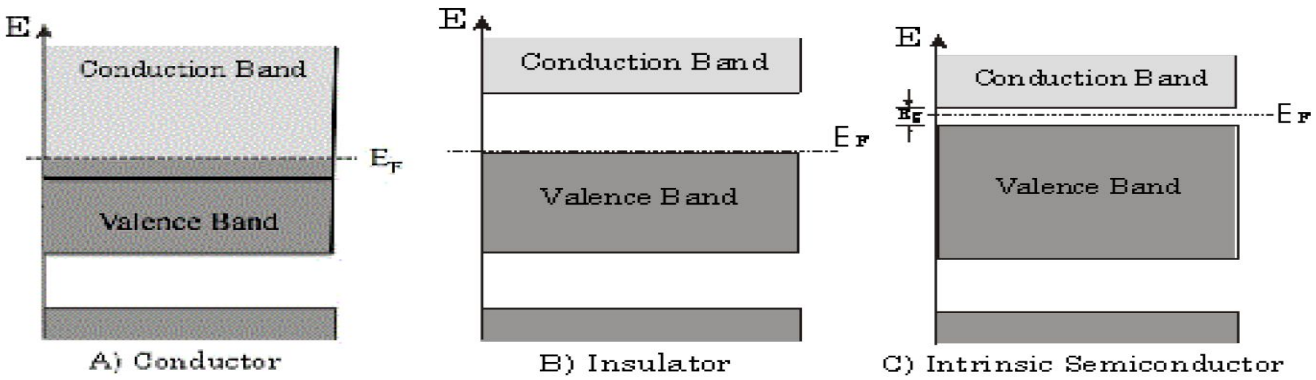


Figure: Energy band structure of
(a) Conductor
(b) Insulator
(c) Intrinsic Semiconductor.

Charge Carriers (electrons or holes)

- If an electron is excited to a higher energy state, it can break free from the nuclear bonds, leaving behind an empty state.
- This absence of an electron (or empty state) in the valence band is called the hole. Holes can be treated like quasi particles with charge opposite of the electron charge (+e).
- Because we cannot distinguish which hole came from which electron, this delocalized position means the hole spans an area in the crystal lattice.

For conductors, these electrons can be easily liberated from their shells.

Properties of Semiconductors

- A semiconductor is a crystalline solid where the energy gap between the valence band and the conduction band is small (on the order of $k_b T$).
- Has empty states (holes) in the valence band and filled states (electrons) in the conduction band
- Small, strongly temperature dependent, conductivity
- Two types of semiconductors materials
  - Extrinsic: Impure, “doped” to improve conductivity. Unequal free electrons and holes
  - Intrinsic: Pure, not been doped. Equal free electrons and holes.

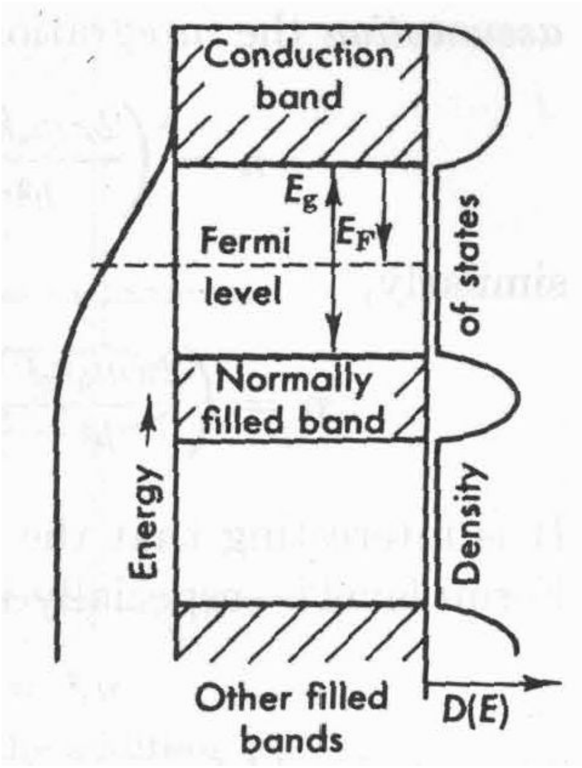


Figure: Energy band structure of a pure semiconductor.

Hall Effect

When a magnetic field is placed perpendicular to the current running through a semiconductor or conductor, the charge carriers experience a force $\vec{F} = q(\vec{v} \times \vec{B})$ that deflects any charge carriers. The deflected carriers generate induces an electric field E_H called the Hall field perpendicular to both the current and magnetic field.

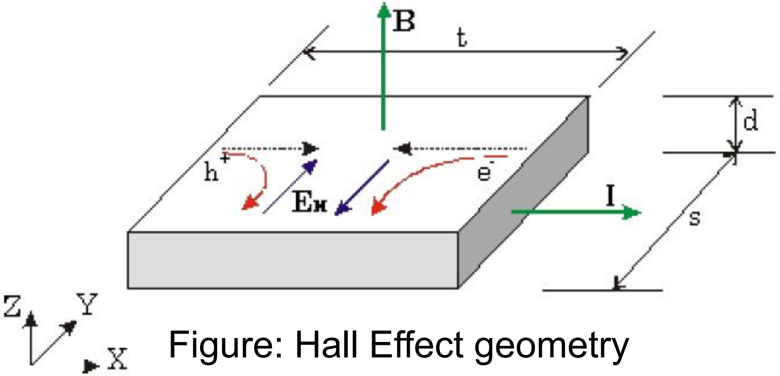


Figure: Hall Effect geometry

When we set Lorentz Force to zero, we get

$$E_H = v_x B_z = R_H J_x B, \text{ where } J_x = e v_x p \text{ is the current density}$$

$$R_H = \frac{E_H}{J_x B_z} = \frac{1}{en} \text{ or } R_H = -\frac{1}{ep}$$

$$V_H = -\frac{I_x B_z}{end} \text{ or } V_H = \frac{I_x B_z}{epd}$$

*Hall potential has dependence on temperature

Van Der Pauw Technique

Technique used to determine Hall voltage and resistivity.

Current	Voltage	Trans-resistance
I_{BA}	V_{DC}	$R_{BA,DC} = V_{DC}/I_{BA}$
I_{DA}	V_{BC}	$R_{DA,BC} = V_{BC}/I_{DA}$
I_{CA}	V_{DB}	$R_{CA,DB} = V_{DB}/I_{CA}$
I_{DB}	V_{AC}	$R_{DB,AC} = V_{AC}/I_{DB}$

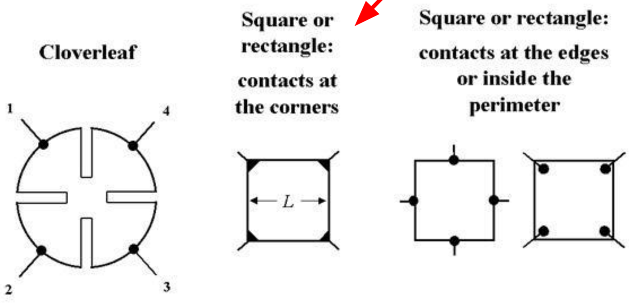
Adjacent points,
Measures resistivity

Non-adjacent points
Measures Hall Voltage

Used in experiment

As long as our sample is planar, no holes, and with electrodes place at perimeter, we can use it for a sample of any shape.

Use four-point ohmic contacts placed around the perimeter of the sample. (Symmetric shapes reduces error.)



(a) Preferred

(b) Acceptable

(c) Not Recommended

From Van der Pauw Equation,

$$\exp\left(\frac{-\pi d}{\rho}R_{AB,CD}\right) + \exp\left(\frac{-\pi d}{\rho}R_{AD,CB}\right) = 1$$

We can obtain the resistivity using first two trans-resistances

$$\rho = \frac{\pi d}{\ln(2)} \cdot \frac{(R_{AB,CD} + R_{AD,CB})}{2} \cdot f\left(\frac{R_{AB,CD}}{R_{AD,CB}}\right) \quad \text{where } f(x) = \frac{1}{cosh(lnx/2.403)}$$

Using the resistivity, we can obtain the mobilities of the charge carriers, where carrier densities come from the Hall voltage measurements

$$1/\rho = e \cdot (n \cdot \mu_n + p \cdot \mu_p) \qquad \mu_h \text{ hole mobility, } \mu_e \text{ electron mobility}$$

Using the Hall coefficient, we can obtain carrier densities, mobilities, and impurity concentrations.

(1) For two types of carriers $$R_H = \frac{E_y}{J_x H} = \frac{\mu_h^2 p - \mu_e^2 n}{e(\mu_h p + \mu_e n)^2}$$

(2) For p-type only $$R_H = \frac{1}{pe}\text{, where } p \text{ is hole concentration}$$

(3) For n-type only $$R_H = \frac{1}{ne}\text{, where } n \text{ is electron concentration}$$

P-type semiconductors

In our experiment, we will be working with p-type Germanium. P-type semiconductors, "Hall coefficient inversion" may happen when the electron mobilities are faster than hole mobilities, such that p>n. At a particular inversion temperature $T = T_0$, the hall coefficient is zero. We can define an intrinsic regime when n-type dominates and an extrinsic regime when p-type dominates.

$$\text{Intrinsic Regime, } T < T_0\text{: } p = N_a + N \text{ and } n = N$$

$$\text{Extrinsic Regime, } T > T_0\text{: } p = N_a \text{ and } n = 0$$

At the inversion point, the conductivity $\sigma = 1/\rho$ can be zero. And we can solve for the ratio of mobilities b

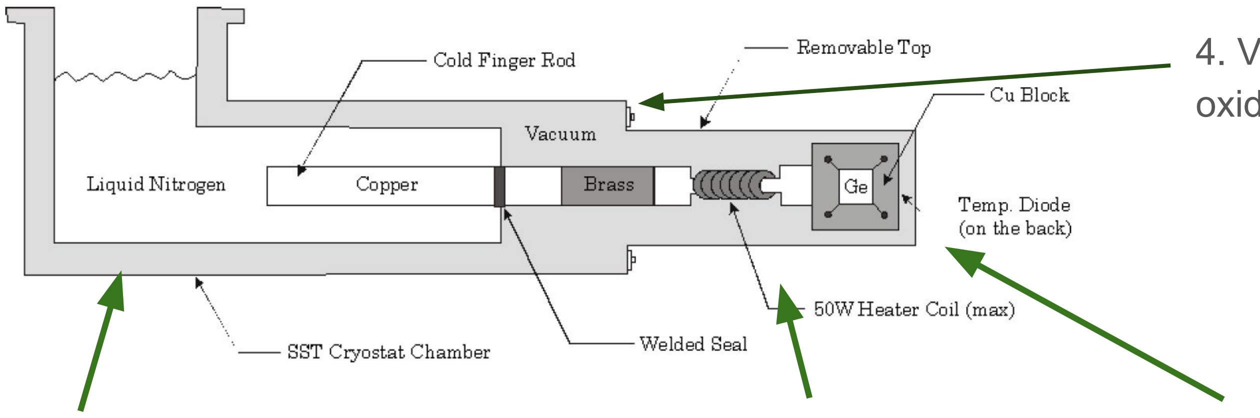
$$b = \mu_e/\mu_h = \sqrt{p/n} \text{ when } R_H = 0$$

Because in the extrinsic region, all carriers are p-type, then we can solve for p in the extrinsic region and the drift mobilities of each carrier in the extrinsic region.

$$p = \frac{1}{eR_H} \qquad \mu_h = \frac{\sigma}{pe} \qquad \mu_n = b\mu_h$$

*Extrapolation techniques for b will be talked about in the analysis section.

Apparatus: Operating Position of the Cryostat



4. Vacuum prevents sample from oxidizing in room temperature.

1. Liquid Nitrogen is poured into the Cryostat Chamber. This cool down the semiconductor into the desired initial temperature.

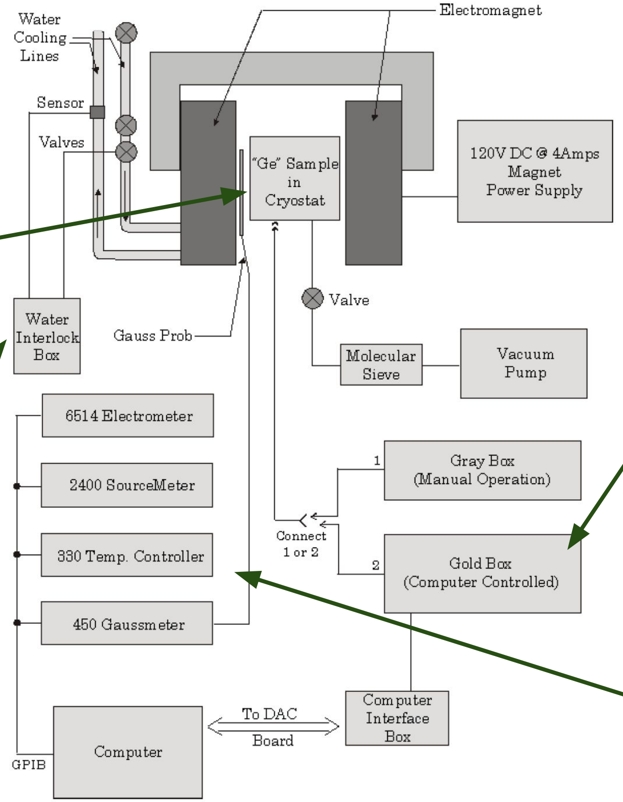
2. The heater will reheat the sample up to the final temperature. Brass coil is thermal resistance to limit the rate of heat transfer. (Temperature increases at 5K per minute.)

3. The semiconductor is placed here. There is a diode on back of the semiconductor to measure its temperature.

Block Diagram for the Hall Effect in Semiconductors

1. Cryostat is kept in between the poles of the magnet and serves to hold the magnetic field measurement probe in place perpendicular to the magnetic field.

2. Water lines keeps the magnet cool. The grey box monitors the water circulation.



3. The Gold box is controlled by the Labview program to automatically control the magnetic field. This also monitors the status of the experiment.

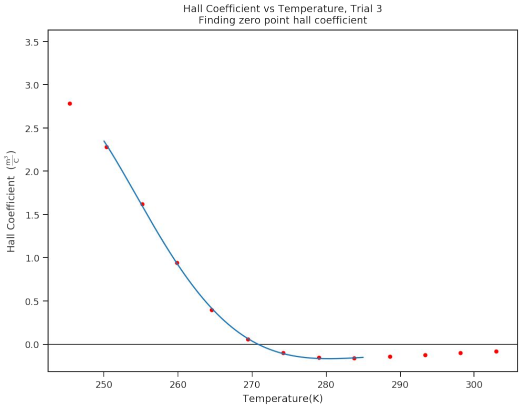
4. Electrometer, SourceMeter, Temp. Controller, and Gaussmeter are used to monitor and record measurements.

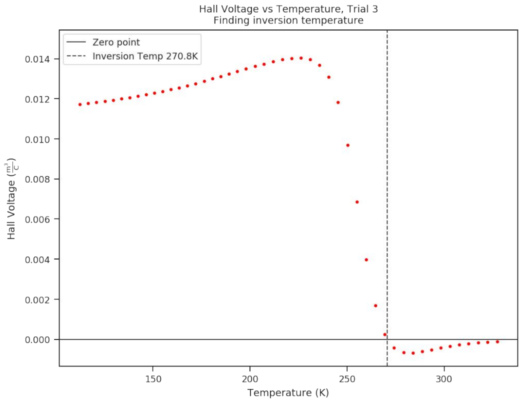
Procedure

1. Turn the water valves on. First turn the one labeled “out” then the one labeled “in”. Now push the button on the grey interlock box for 5 seconds.
2. Turn the vacuum on if it isn’t already on. (This is the one machinery you can leave on).
3. Turn on the red power strip switch attached under the upper shelf. This controls the power for the Electrometer, Current Source, Gauss Meter, the Lakeshore Temperature Controller, and the GOLD Box. Turn on all of these five components.
4. Additionally, make sure the two power switches controlling the magnetic field is on. This switch is located underneath the table.
5. On the gold box, press the “run” button.
6. Turn on the computer and open the ”Control Program v9 multifield” labview program. It will prompt you to save the data into a file. Choose your filename and save directory.
7. Set the temperature range to between 95K to 350K. In our experiment, we used 110K to 330K.
8. On the program, set the desired input current and magnetic field. Do not exceed over 5000 Gauss.
9. First we must cool down to the initial temperature. Put on gloves, glasses, and face shield, and fill Dewar with liquid nitrogen. Next fill the Cryostat.
10. The data collection will automatically begin once it reaches the initial temperature. Once it warms back up to the final temperature, it will stop taking data. Once it completes, do not close it immediately. Let it run for a few more minutes as it needs time to record the data.

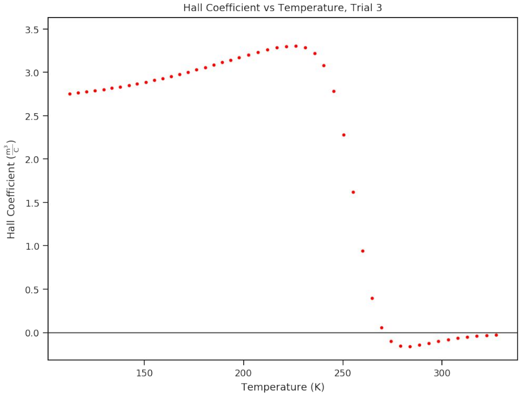
Analysis

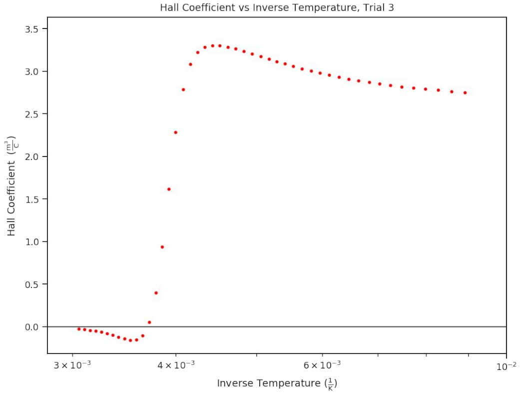
Experimental values were calculated through averaging all possible combination of transresistance and each magnetic field. To obtain the inversion temperature, we performed a polynomial fit to find when the hall coefficient is zero.





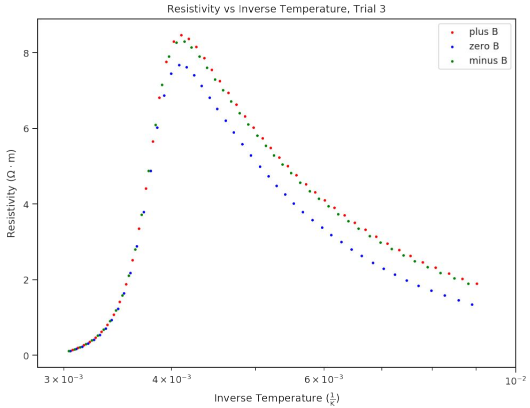
Sample plots for curve fitting (left) and visualization of inversion temperature in hall potential versus temperature (right).

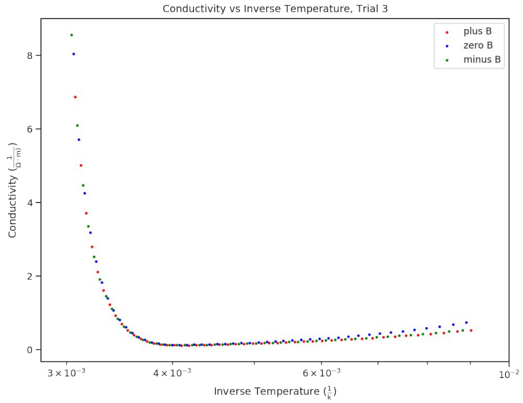




Sample plots for the hall coefficient versus temperature (left) and hall coefficient versus inverse temperature (right).

*Plots for all trials can be found in the appendix.

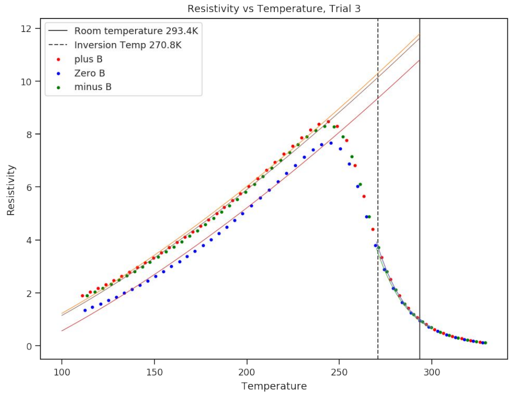


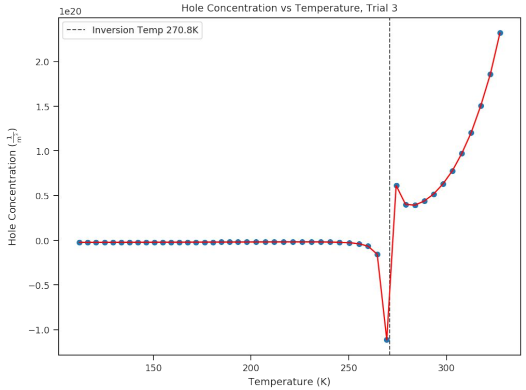


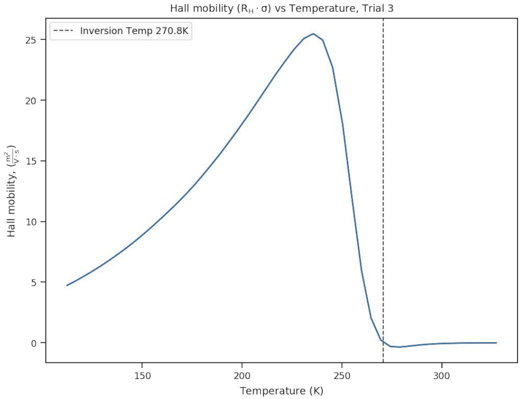
- Sample plots for resistivity versus inverse temperature (left) and conductivity versus inverse temperature (right).
- Peak of resistivity ~244K
- Zero field (blue) has less resistance compared to positive B field(red) in the extrinsic region.

To find the carrier concentration and mobilities, we must solve for b. Where it is given by

$$b = \frac{R_e(T = T_0)}{R_e(T = T_0) - R_0} \qquad \begin{array}{l} R_e\ , \text{Resistane extrpolated} \\ R_0\ , \text{Measured resistance at inversion} \end{array}$$







Sample plot of polynomial fit and extrapolation (left), hole concentration (center), and hall mobility (right).

Data/Measurements (All Trials)

Trial Number	Input Current (A)	Input Magnetic Field (Gauss)	Inversion Temperature (K)	Room Temperature (K)
1	5.0E-06	1000	275.0	293.5
2	1.00E-05	2000	269.1	293.9
3	1.50E-05	3000	270.8	293.4
4	2.00E-05	4000	269.5	293.4
5	1.25E-05	2500	271.8	294.5

Values evaluated at room temperature. (Extrinsic region)

Trial Number	Hall Coefficient (m^3/C)	Resistivity (Ωm)	Hole concentration (1/m^3)	Hole mobility (m^2/ Vs)	Electron Mobility (m^2/ Vs)	Ratio of mobilities, b
1	-0.0920 ± 0.004	0.7738	6.783E+19	0.1189	0.1578	1.33
2	-0.104 ± 0.002	0.8776	5.988E+19	0.1189	0.1939	1.63
3	-0.121 ± 0.002	0.9395	5.165E+19	0.1189	0.1754	1.47
4	-0.131 ± 0.002	0.9487	4.747E+19	0.1189	0.1821	1.53
5	-0.109 ± 0.002	0.8694	5.716E+19	0.1189	0.1703	1.43

	Inversion Temperature (K)	Room Temperature (K)	Hall Coefficient (m^3/C)	Resistivity (Ωm)	Hole concentration (1/m^3)	Hole mobility (m^2/ Vs)	Electron Mobility (m^2/ Vs)	Ratio of mobilities, b
Averaged Values	271.2	293.725	-0.1114	0.8818	5.680E+19	0.1189	0.1759	1.48

Sources of error

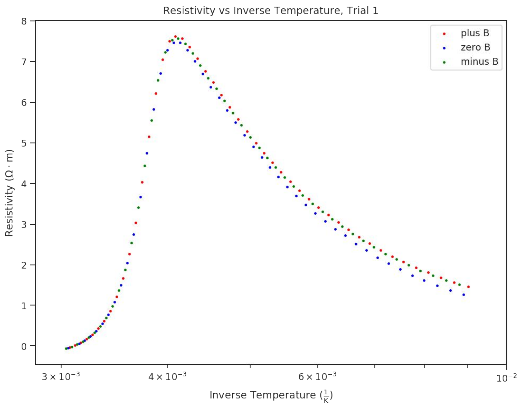
- Hall coefficient has slight dependence on magnetic field → Hysteresis from magnetoresistance measurements.
- Magnetoresistance causes decrease of mean free path → increase in resistivity
  - reach saturation at very strong fields
  - for lower fields, quadratic dependence on field strength
- Collisions between carriers. Lattice vibrations and imperfections causes collisions in the carrier that is not accounted for when calculating the drift velocity. The actual path followed by the carrier is a curved trajectory in the crossed electric and magnetic field → Higher mobility.
- Van der Pauw method is not perfect → Dependent on geometry of sample. To reduce errors, we want highly symmetric sample with no isolated holes in the sample. We also want ohmic contacts to be small.
- Systematic errors come from reading of the measurement. Not all measurements between fields were recorded at the same temperature.

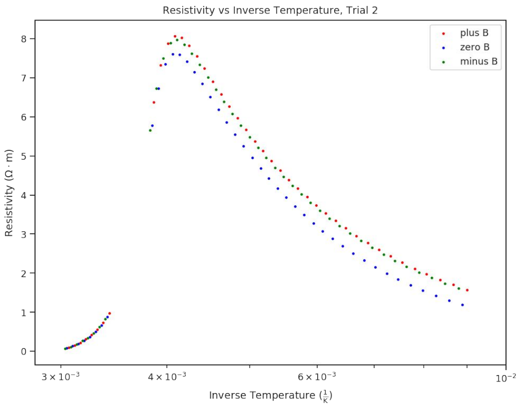
Conclusion

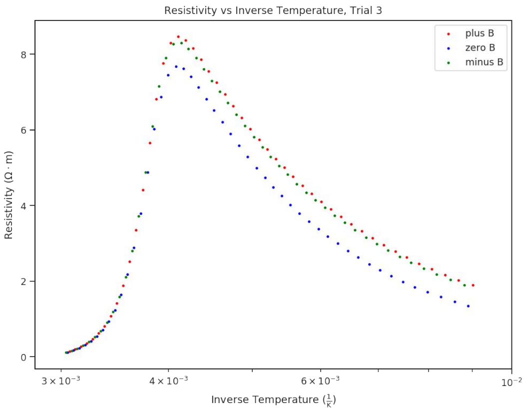
By studying the Hall Effect in the semiconductor sample, we were able to quantify properties of the p-type germanium sample. We found the hall coefficient, resistance, carrier concentration, and carrier mobilities in the extrinsic region (or room temperature).

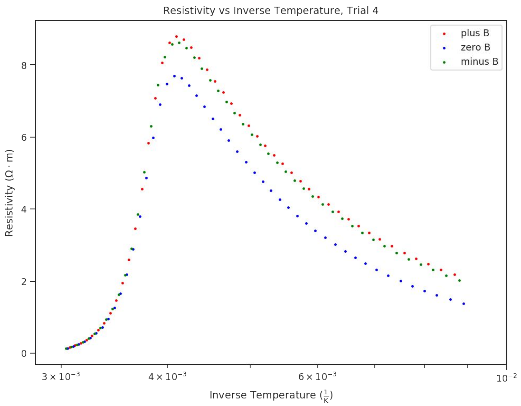
Appendix: Plots for all trials

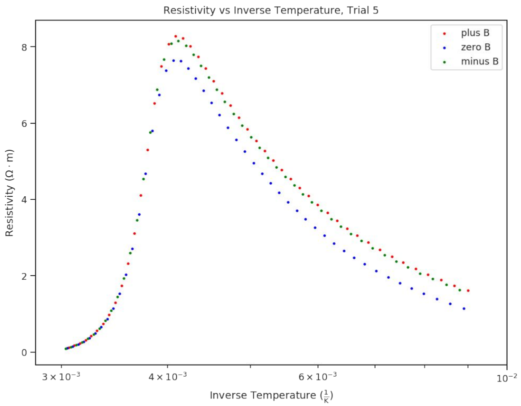
Resistivity vs. Inverse Temperature



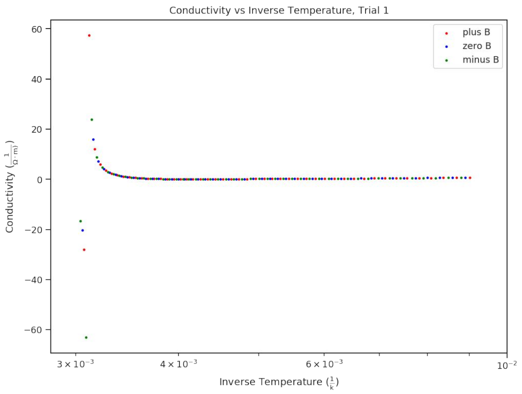


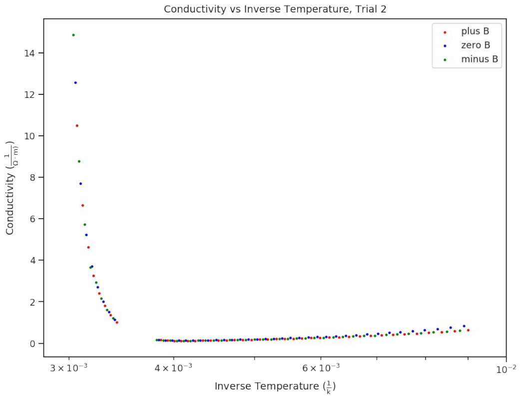


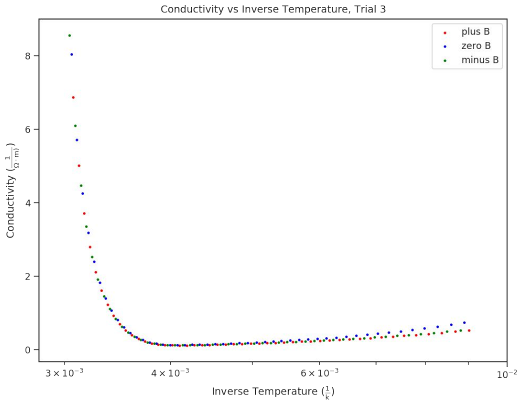


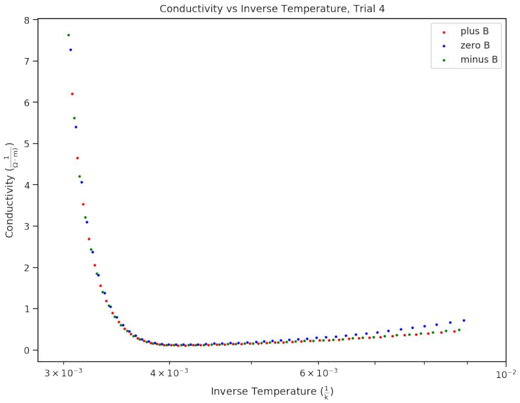


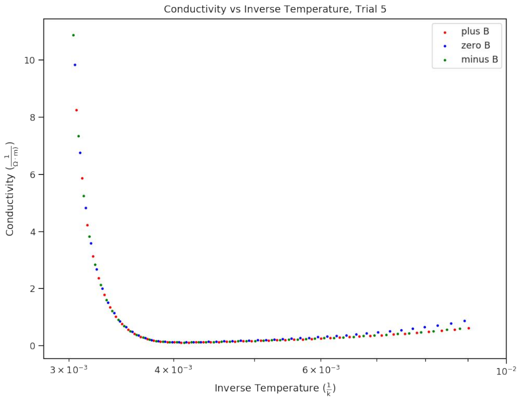
Conductivity vs. Inverse Temperature



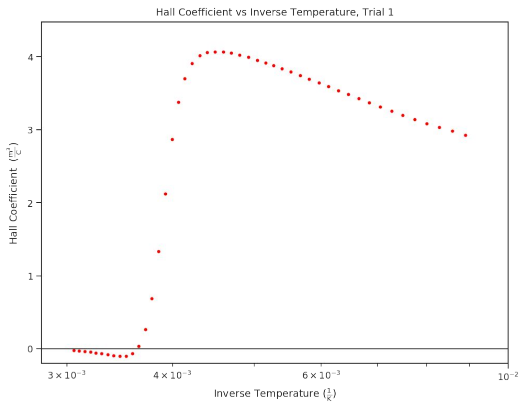


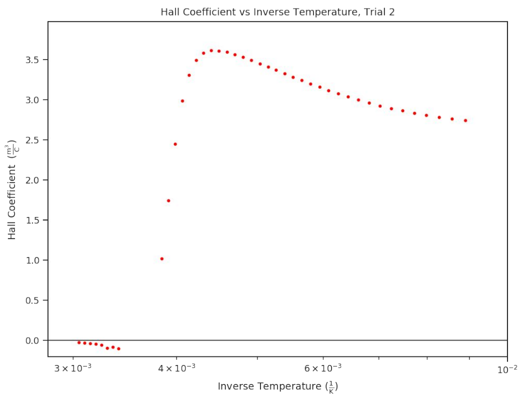


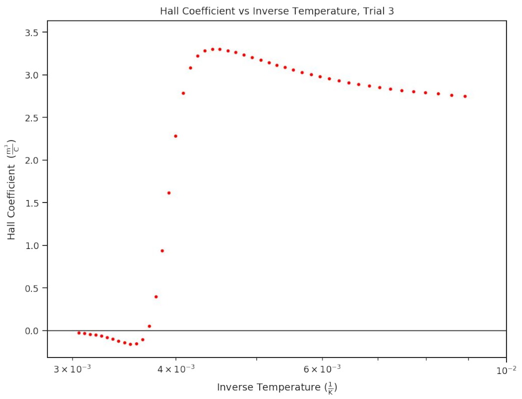


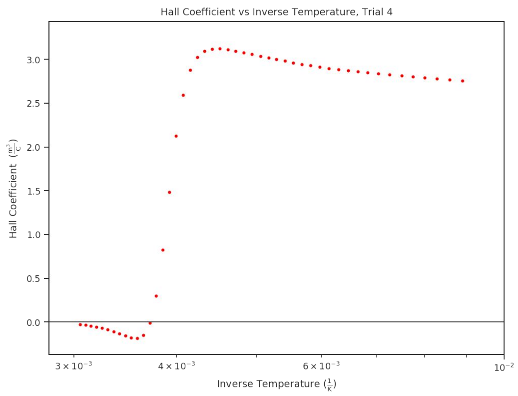


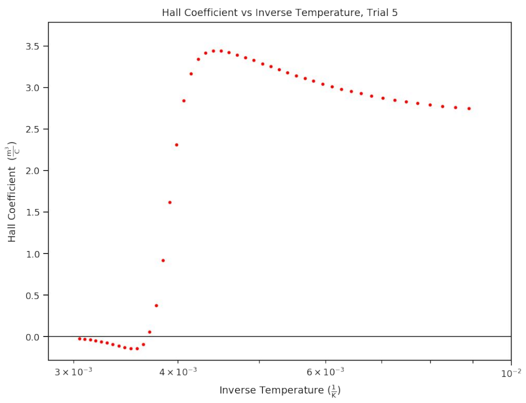
Hall Coefficient vs. Inverse Temperature





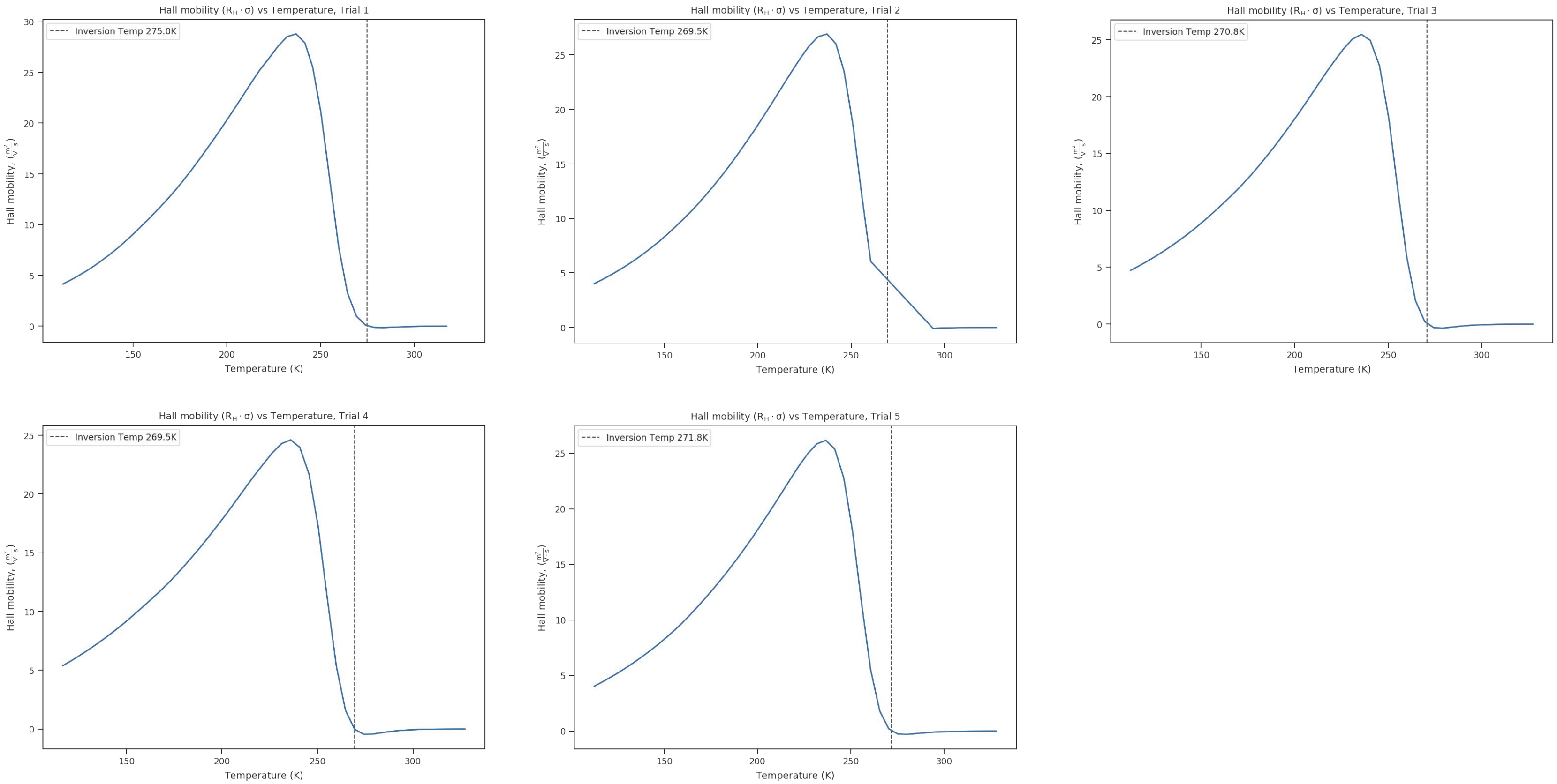




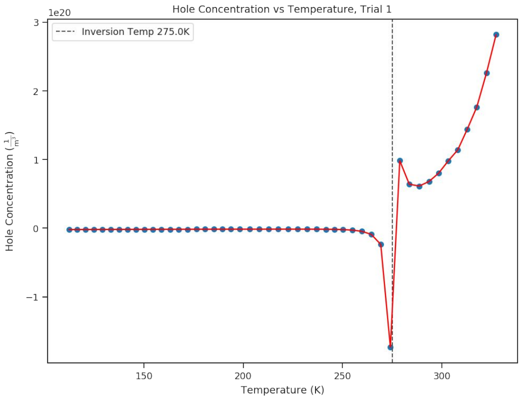


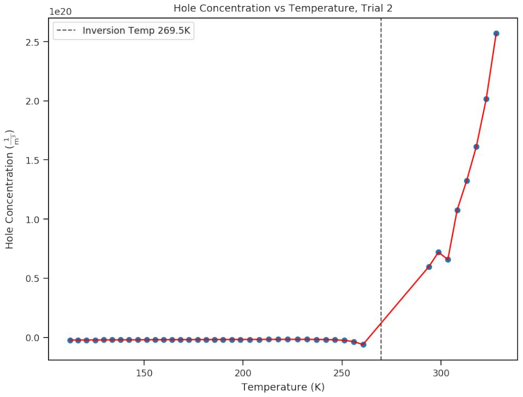
Hall Mobility (Hall coefficient x Conductivity) vs. Temperature

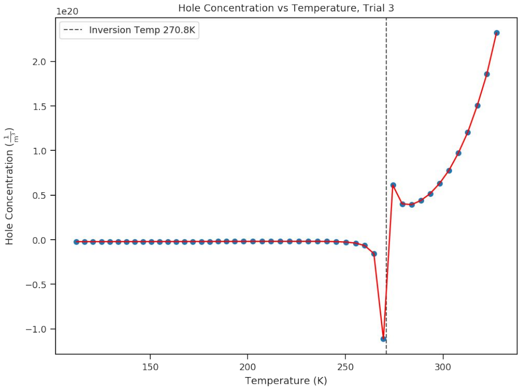
Where does the Hall coefficient becomes zero?

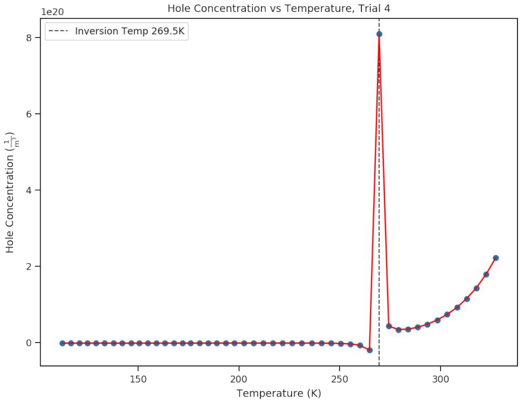


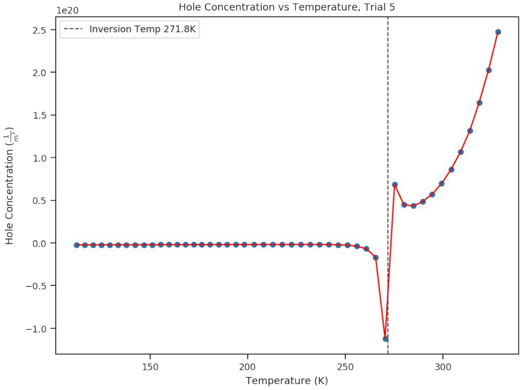
Hole Concentration vs. Temperature











Hall Coefficient vs. Temperature