Investigating Hall Effect in Semiconductors

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Phys 382 Creative Project

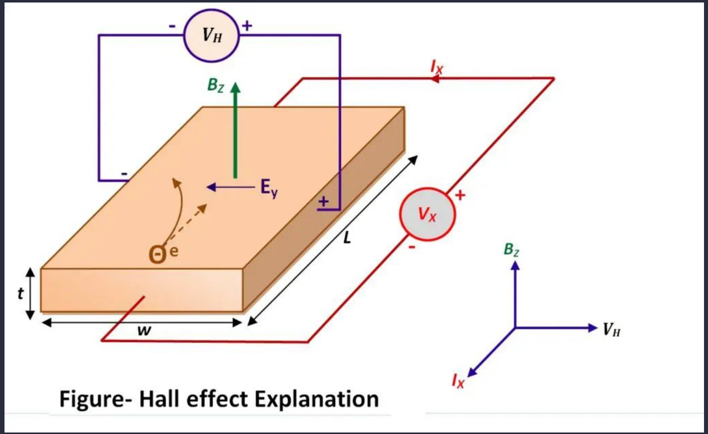
Hall Effect Definition

Emergence of a potential difference due to perpendicular magnetic field.

Voltage is transverse to the electric current. Discovered by Edwin Hall in 1879.

Magnetic field is perpendicular to the voltage and current.

More Hall Effects – Anomalous Hall Effect, Quantum Hall Effect etc.

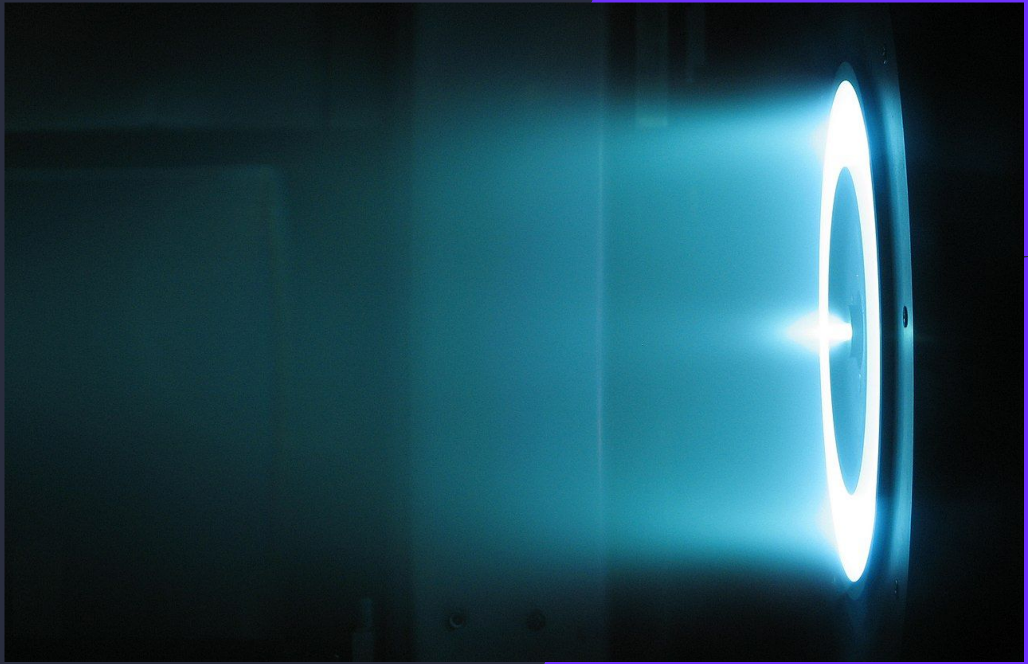


Credit: Physics Stack Exchange

Motivation and Significance

- Wheel speed sensors for anti-lock braking systems (ABS) and cruise control.
- Smartphone cover and screen-guards.
- Spin Quantum Hall Effect used in research areas such as spintronics etc.
- Also useful in star formation - gravitational collapse of gas to form protostars.
- Hall Effect thrusters - hall effect is used to control charged particles.

Goal of this Project - Investigate the Hall Effect and verify we detected it by comparing Hall coefficients.



Credit: Wikipedia

Theory

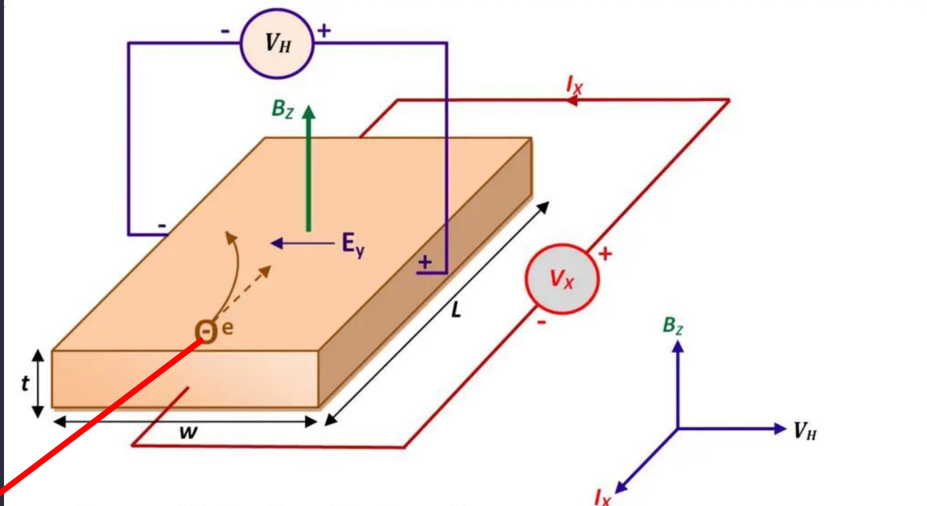


Figure- Hall effect Explanation

Lorentz Force

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

In equilibrium:

- F = 0

$$E_y = V_H/t$$

$$E_y = v_x B_z$$

$$V_H = v_x B_z t$$

$$V_H = \frac{IB}{nqt}$$

Classical Hall Effect

$$V_H = \frac{IB}{nqt}$$

Magnetic Field
(z-direction)

Thickness of
Sample

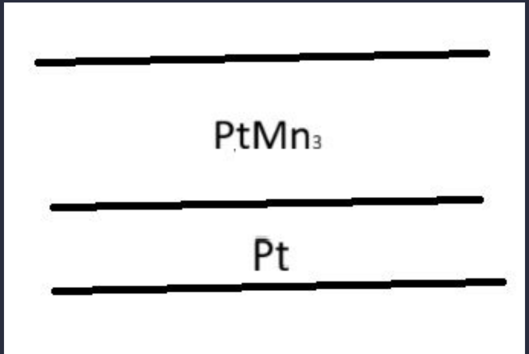
Hall Voltage
(x-direction)

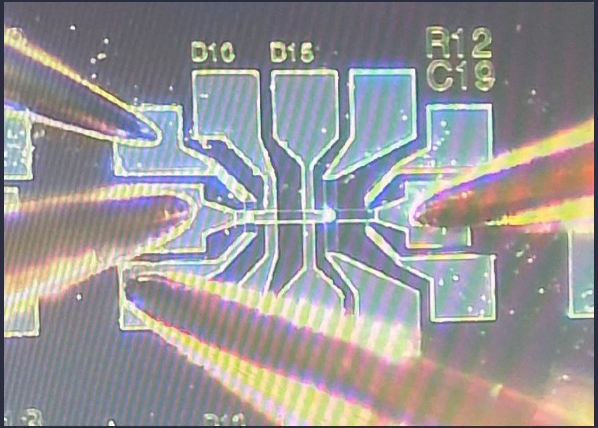
Current
(x-direction)

Charge magnitude

Carrier Charge
Density

Sample Used





- Used 2 semiconductor samples: Pt-PtMn layers
  - A850M
  - A850Mb
- Sample has multiple rows and columns with grids containing the semiconductor structure.
- Platinum layer - Current Carrying Layer - 5 nm thick
- Width - 20 μm, Length - 60 μm
- $PtMn_3$ layer - Resistive Layer - No current - 13 nm thick
- Platinum - Paramagnetic
  - Anomalous Hall Effect seen
  - Spin Hall Effect (tiny contribution)

Modifying the Working Equation

Classical

$$V_H = \frac{IB}{nqt}$$

Does not work for our sample due to complex structure

Classical + Anomalous

$$\rho_H = R_H B + R_s M$$

Magnetization

Anomalous Hall Coefficient

Hall Resistivity

Magnetic Field

Hall Coefficient

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

Goal: Convert this into observable quantities we can take measurements.

Modifying the Working Equation

$$\rho_H = R_H B + R_s M$$

$$M = \frac{\chi B}{\mu_0}$$

Magnetic Susceptibility

Approximation for paramagnetic materials.

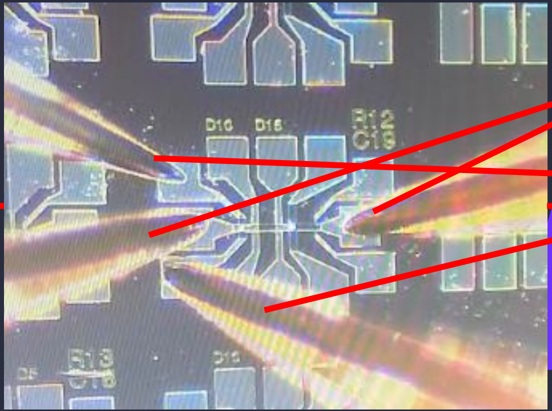
Permeability of Vacuum

$$\rho_H = (R_H + \frac{R_s \chi}{\mu_0})B$$

This is the working equation we will use.

Procedure and Materials Used

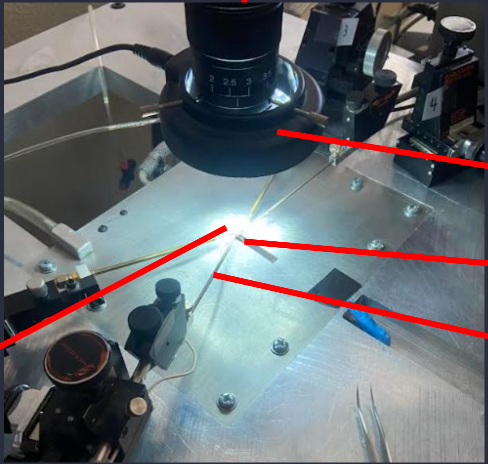
Keithley 2400 Multimeter (Magnetic Field and Measurements)



Current Probes

Hall Voltage Probes

Custom LabView Software



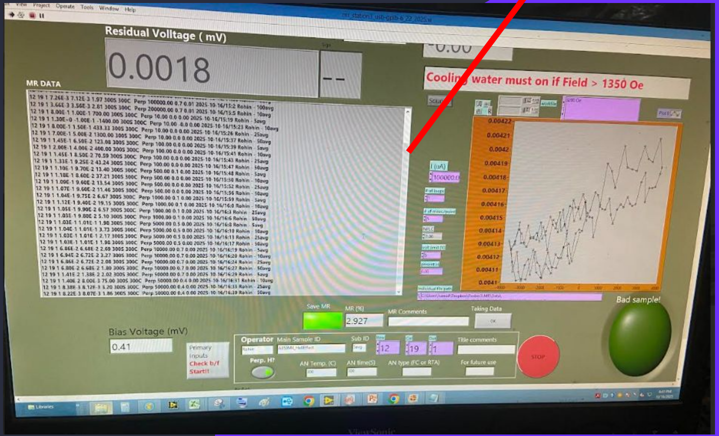
High Resolution Camera

Sample

Probes

Keithley 220 Current Source

Magnetic Coil under the table



Procedure

01.

Connect all the circuit elements to each other. Current source to current probes and multimeter to voltage probes.

02.

Place the probes on the cells of samples using camera and knobs. Switch on the the currents and magnetic fields.

03.

Set up file instructions, such as the average points and begin measurements using the LabView Software. Take magnetic field current sweeps.

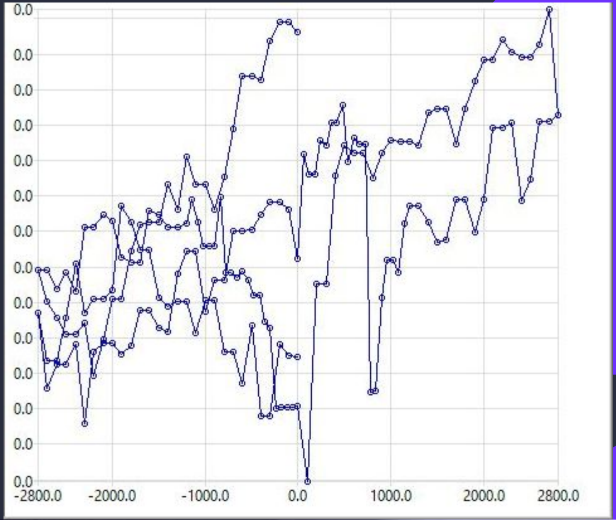
04.

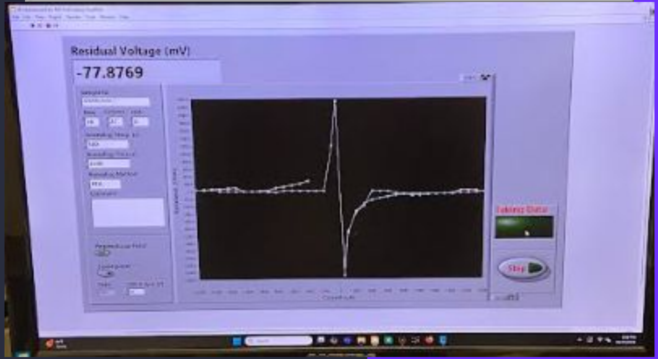
Transfer files over to local machine and begin analysis.

Data Obtained

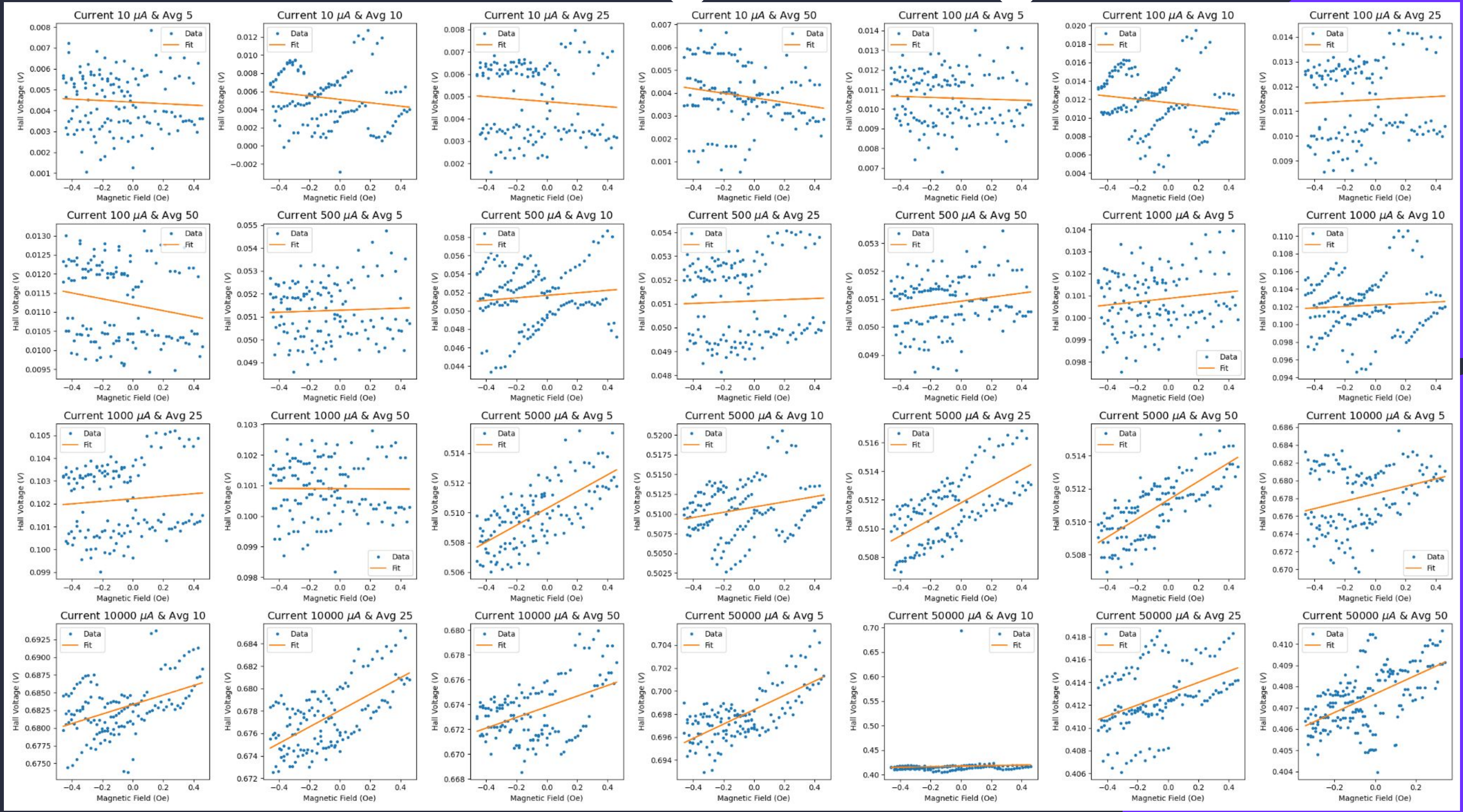
A850M and A850Mb Sample

- Resistance (mΩ) (in hall voltage direction) vs Magnetic Field (Oe):
  - For currents in [10, 100, 500, 1000, 5000, 10000, 50000, 100000] μA.
  - For average data points in [5,10,25,50] average.
  - Multiply by current to get hall voltage.
- Resistance (Ω) (in hall voltage direction) vs Current (μA):
  - For magnetic fields from -800 Oe to 800 Oe in intervals of 50 Oe till -400 Oe and after 400 Oe and intervals of 25 Oe between -400 Oe and 400 Oe.
  - Multiply each current data point to get hall voltage.

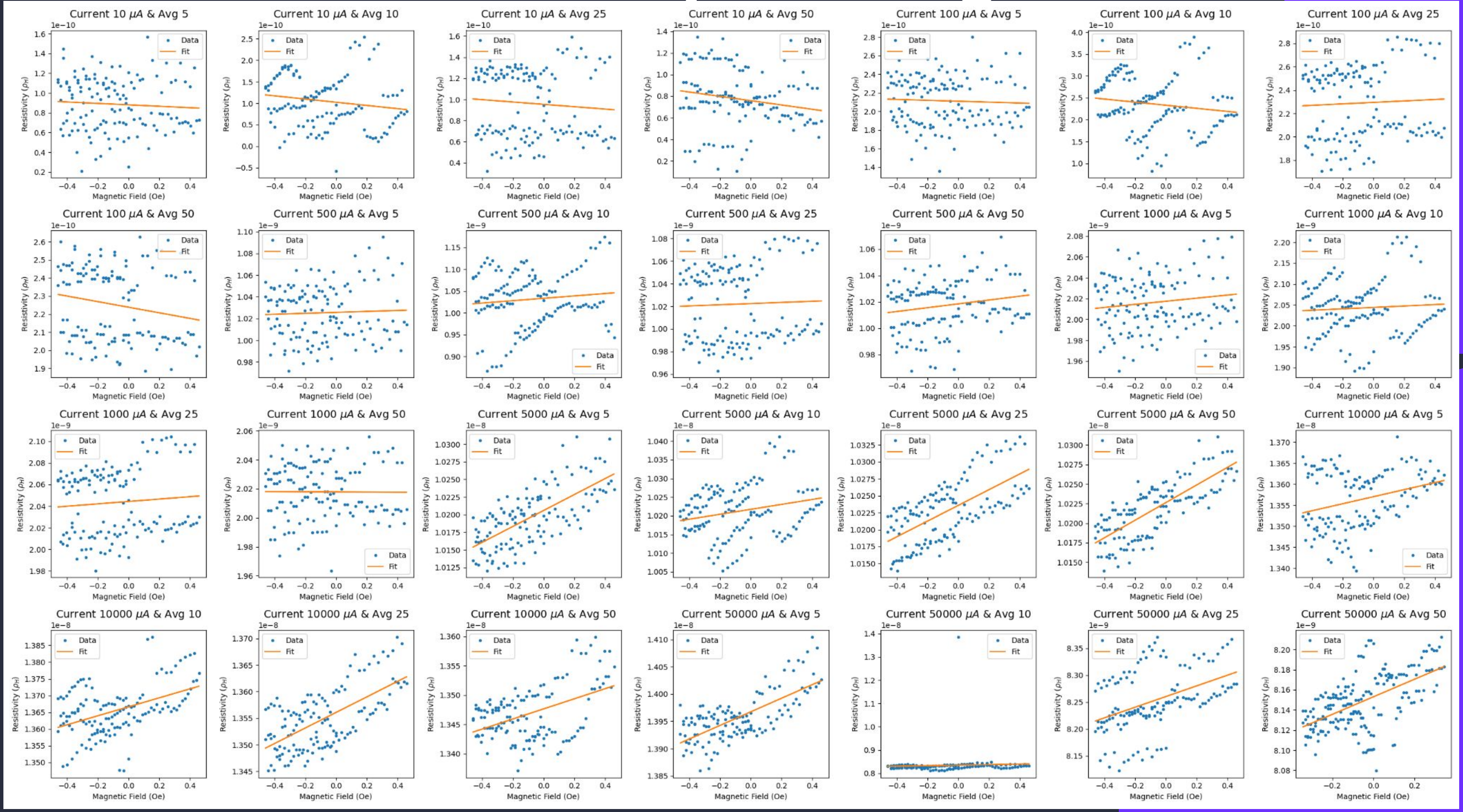




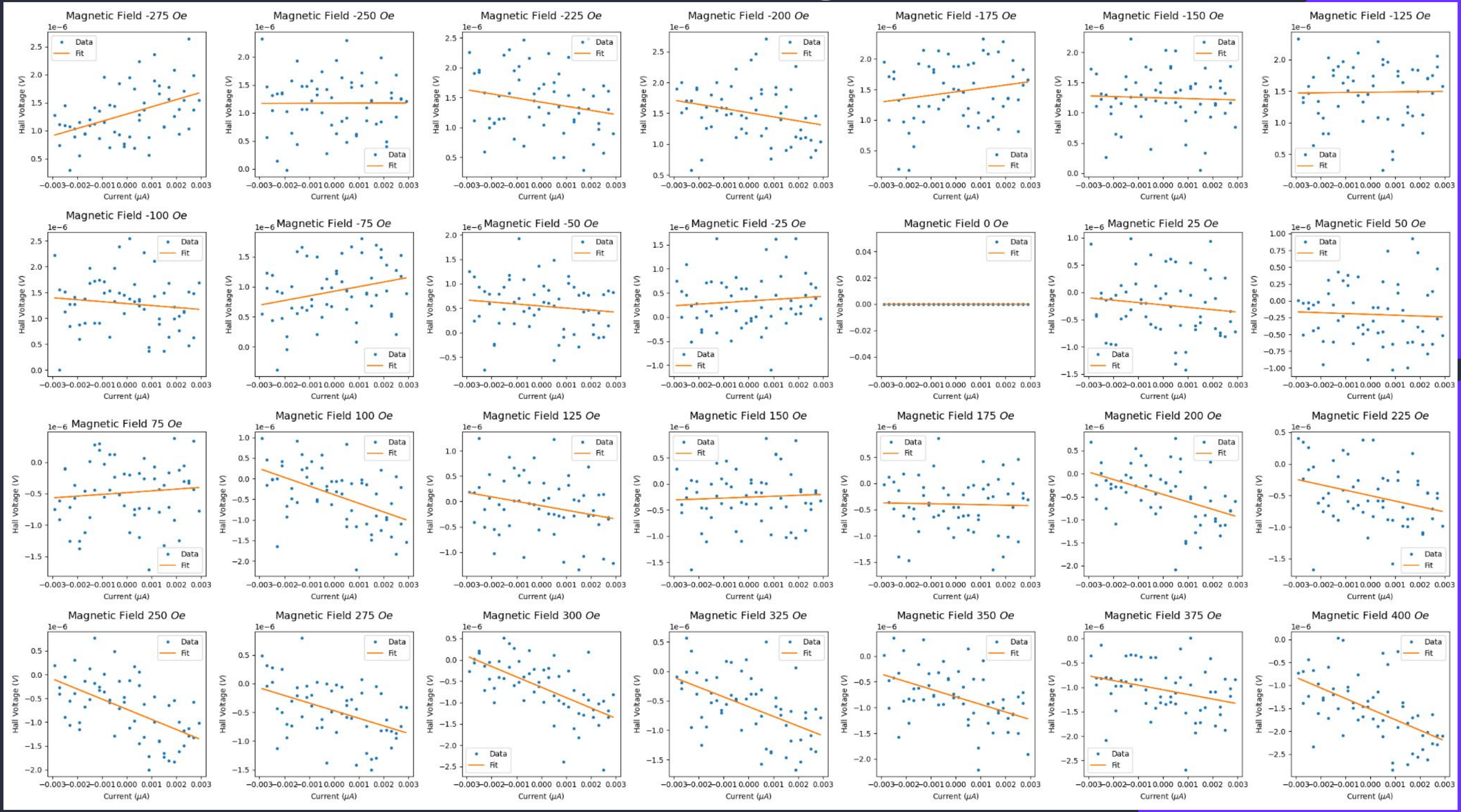
A850M Hall Voltage vs Magnetic Field



A850M Resistivity vs Magnetic Field



A850M Hall Voltage vs Current



Data Analysis

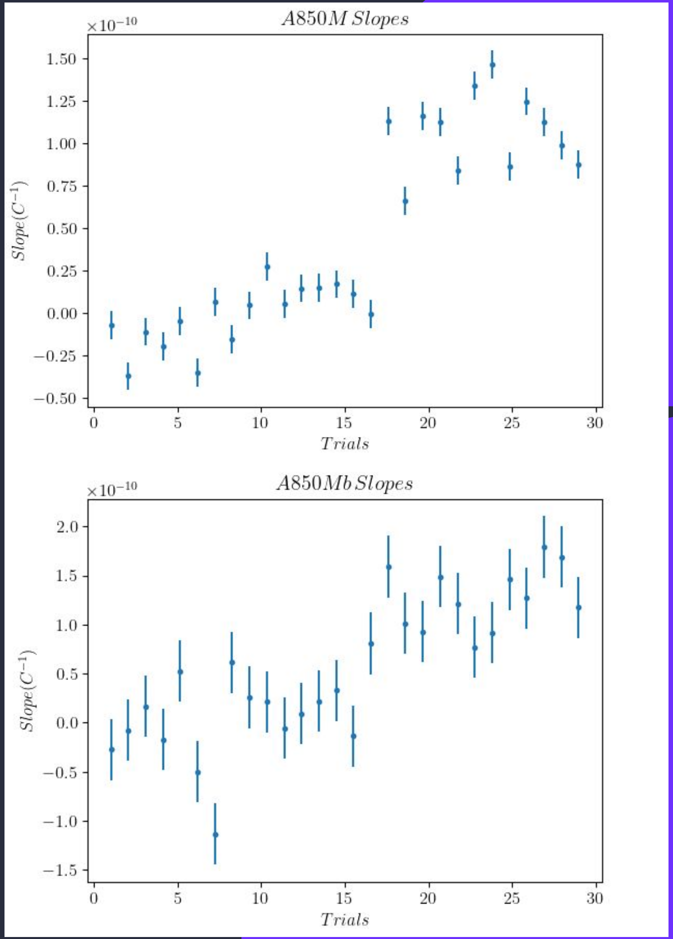
- Transferred files locally
- Analysed the data and used a linear model to fit the data.

$$L = ax + b$$

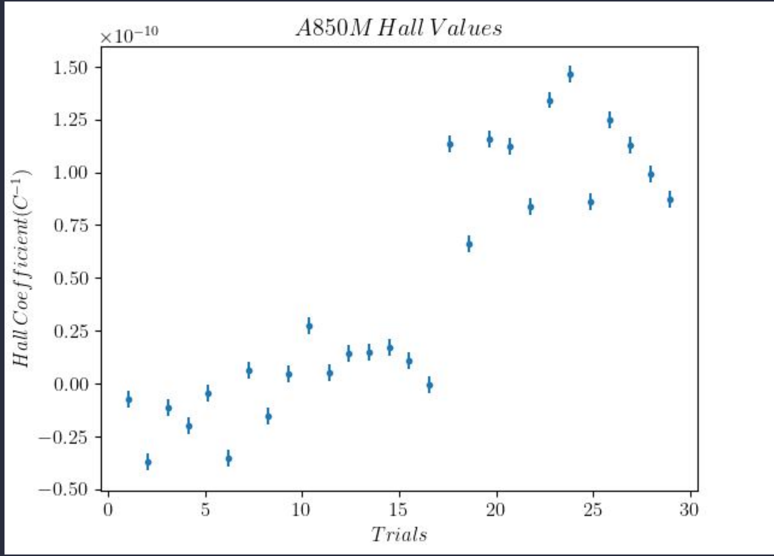
- Conducted χ^2 fitting using Python.
- Found the slope and intercept of the data.
- Slope is found from the working equation.

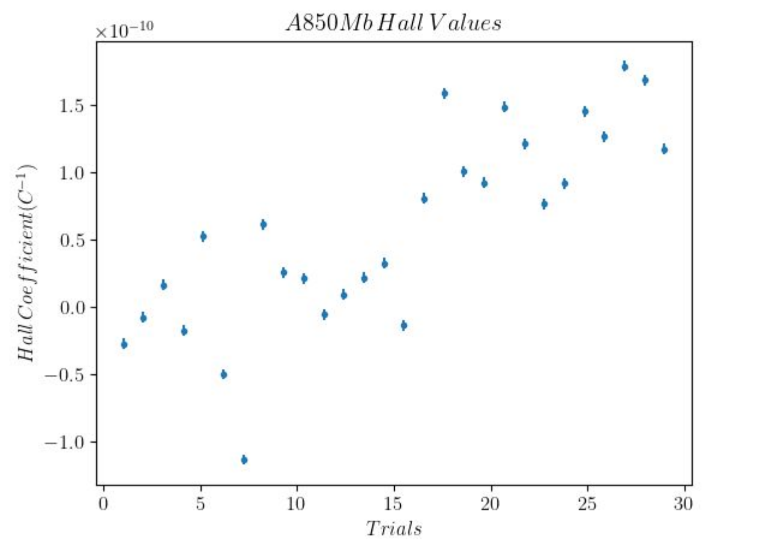
$$\left(R_H + \frac{R_s \chi}{\mu_0}\right)$$

- Conducted for both the samples.
- Subtracted 0 magnetic field data from R vs I measurements.
- We took Anomalous Hall Coefficient to be 10^{-10}, a typical literature value in paramagnetic samples.
- Direction change in R vs I graphs due to electron transport, current is spin-polarized, also different setups.
- Error-bars scaled for better visualization.



Results





Taking Weighted Mean and Mean Error

Sample	**Hall Coefficient R_H (m^3C^{-1})**	**Error**
A850M	4.465×10^{-11}	7.519×10^{-11}
A850Mb	5.778×10^{-11}	7.522×10^{-11}

Error Propagation

- Using our working equation and using error propagation, we obtain:

$$\Delta R_H = \sqrt{\Delta S^2 + \left(\frac{R_s}{\mu_0}\Delta\chi\right)^2}$$

Error in Hall Coefficient   Error in Slope   Error in Magnetic Susceptibility

Uncertainties	**Values**	**Source**
Resistance	0.000002 Ω	Least Count of Multimeter
Current	0.000002 A	Least Count of Current Source

Discussion and Error Sources

Sample	Hall Coefficient R_H (m^3C^{-1})	Error
A850M	4.465×10^{-11}	7.519×10^{-11}
A850Mb	5.778×10^{-11}	7.522×10^{-11}

- Actual value for platinum is 2.300×10^{-11} m^3/C. Obtained in the same order of magnitude.
- Largely imprecise value as high error value.
- Hall Effect is very sensitive to noise.

Sources of Error:

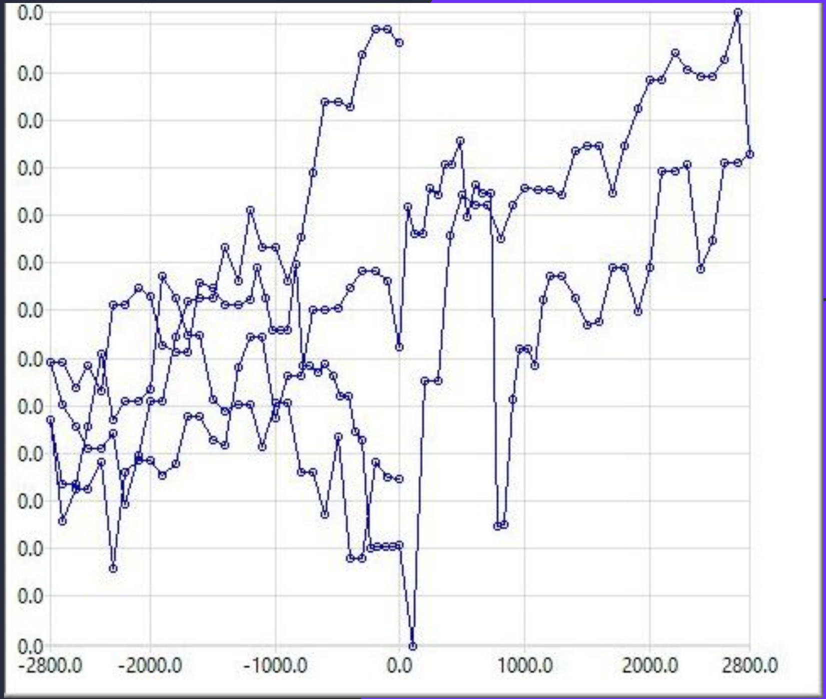
- One Dataset had to be removed due to displacement of probe (Systematic Error).
- Background noise, electronic noise and disturbances from phones, laptop etc. (Random Error)
- Small in plane component, affects reading of magnetic field values outside -400 to 400 Oe range. (Random Error).
- Intrinsic voltage at 0 magnetic field (Random Error).
- Resistance in probes and wires (probes are extremely sensitive to motion) (Random Error).
- Presence of Quantum and Spin Hall Effect (Random Error).
- Different setups used in magnetic fields and current measurements (Systematic Error).

Conclusion and Improvements

- We investigated the Hall effect in a platinum semiconductor sample.
- We used two samples and research grade setups to measure the effect.
- We found linear trends in our data, suggesting signature for the effect.
- Our obtained values were 4.465×10^{-11} m^3C^{-1} and 5.778×10^{-11} m^3C^{-1}.
- The dominant source of uncertainty was the background noise and disturbances

Improvements:

- More control over temperature, vacuum environment.
- Confined Experiment
- More cleaner sample, materials and less complex structures.



Thank you!

I also thank Brecken Larsen and Ali Habiboglu for their immense support in this project.