Hall Effect & Hysteresis Curve

PHYS 3606

Lab Report

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ABSTRACT

This Lab report focuses on hall effect on a semiconductor (Indium Arsenide - InAs in this case) and the Hysteresis curve due to a ferromagnetic material (Iron - Fe in this case). InAs is setup as a Hall probe and the current, potential and hall potential across it is measured while it is placed in various external magnetic fields strengths. Using the measured quantities the hall constant ((7.12 +/- 0.14) $*10^{-4}$ m^3/C), Hall mobility ((0.39 +/- 0.11) *(1/T).) and resistivity ((18.4 +/- 2.4) $*10^{-4}$ Ω/m) of Indium arsenide were calculated. For the hysteresis curve the current and potential across the ferromagnetic material is measured while reversing the polarity of flow of current. The measured data is then analyzed to form a hysteresis curve for magnetic field strength and magnetic flux density. From this plot the coercivity (60A/m) and remanent flux density (1.42E-08 Tesla) of iron are measured.

THEORY

Hall Effect

While a current carrying conductor (For this experiment InAs, it could be any conductor though) is placed in a magnetic field the charge carriers are exposed to a force in a direction perpendicular to their direction of motion. This force tends to move the carriers towards one end of the conductor, thus resulting in a buildup of potential across the width of the conductor such that it balances out the influence of the magnetic field. This buildup of potential across the width of the conductor is called Hall effect [1]. At the state of equilibrium with hall effect can be defined by equation 1. In equation 1, q is the charge of the current carrier, v_x is the velocity of the carrier, B_z is the external magnetic field and E_y is the potential developed across the conductor due to Hall effect [2].

$$qv_xB_z = qE_y \tag{1}$$

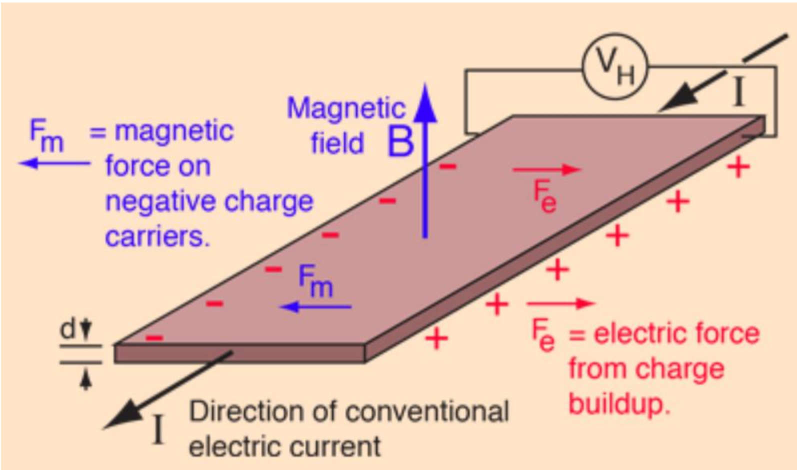


Figure 1: Hall Effect on a thin conductor [1]

The Hall effect electric field developed across the conductor is directly proportional to the current density (J_x) and the external magnetic field (B_z) and Hall coefficient of the material (R_H) and can be defined using equation2 [2].

$$E_y = R_H J_x B_z = v_x B_z \tag{2}$$

Drude Theory

When charge carriers are moving in the direction of applied potential, they lose energy due to interactions with the lattice and other charge carriers. This results in the constant velocity of the carrier being drift velocity v_x. Drift velocity can be defined using equation 3. In equation 3, q is the charge of the carrier, E_x is the applied potential, τ is the relaxation time, i.e., the average time between each collision and m is the mass of the charge carrier [3].

$$v_x = \frac{qE_x\tau}{m} \tag{3}$$

Hall Constant

Hall constant (R_H) is the inverse product of the number of charge carriers and the charge on the carriers hence the total charge hence it is the inverse if the total charge being carried. It can also be calculated using physical parameters, such as in equation 4. In equation 4, V_H is the hall effect voltage, c is the width of the conductor and I_x is the current through the conductor [4].

$$R_H = \frac{V_H c}{I_x B_z} \tag{4}$$

Hall Mobility

Mobility can be defined as drift velocity per unit electric field, thus equation 5 depicts the mobility (μ) of the charge carries, it further uses equation 2 to analyze it's dependance on the electric field strength in x and y direction, i.e, the direction of hall current and the direction of actual current [5].

$$\mu = \frac{v_x}{E_x} = \frac{E_y}{B_z E_x} \tag{5}$$

Further in equation 5, the electric field strength can be replaced by electric potential in each direction thus by using each 6a, 6b, in which a and b are the dimensions of the conductor in x and y dimension respectively. This resulting in equation 7 [2].

$$E_x = \frac{V_x}{a};\ E_y = \frac{V_y}{b} \tag{6a, 6b}$$

$$\mu = \frac{v_x}{E_x} = \frac{aV_y}{bB_z V_x} \tag{7}$$

Resistivity

To measure the resistivity of the hall probe Ohms law is applied on the potential and current to measure the resistance and then the resistance is analyzed based on the dimension of the hall probe to extract resistivity. Equation 8 depicts the dependance of resistivity on resistance and the dimensions of the hall probe.

$$Resistivity\ (\rho) = \frac{V_x * b * c}{I_x * a} = \frac{R * b * c}{a} \tag{8}$$

Hysteresis Curve
Hysteresis is characterized as lack of magnetic flux density (B) proportional to magnetic field strength (H). The phenomenon of hysteresis is exhibited by all ferromagnetic substances. When a ferromagnetic substance is placed inside a current carrying coil it gets magnetized due to the presence of magnetic field. When the direction of current is reversed the substance gets demagnetize, thus the variation in the magnetic field strength is depicted in the hysteresis. Figure 2 represents a standard ferromagnetic hysteresis curve.

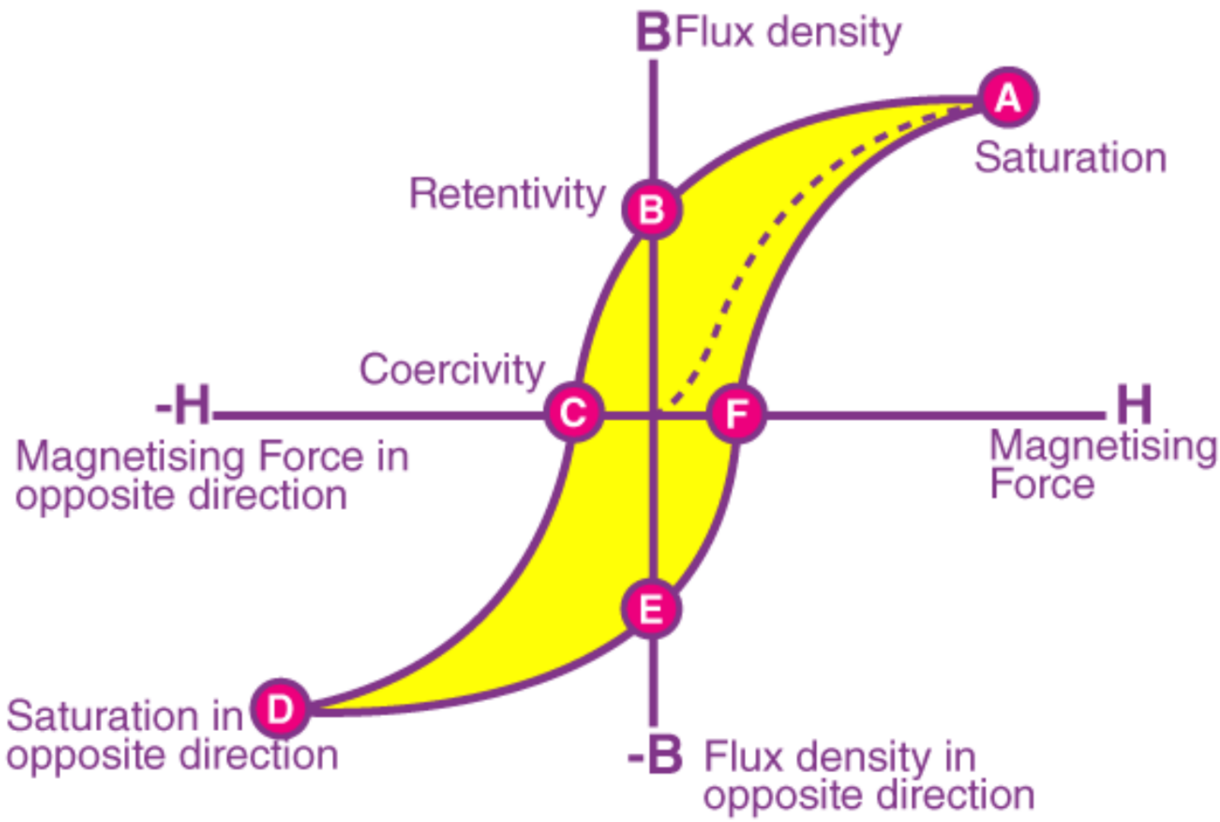


Figure 2: Hysteresis Curve for a Ferromagnetic Substance [6]

The current and hall potential can be converted to the magnetic field strength and magnetic flux density based on their dependencies as depicted in equation 9 and 10. In equation the ration of N/L refers to the ration of number of loops per unit length of the solenoid [2].

$$B_Z = \frac{V_H c}{I_x R_H} \tag{9}$$

$$H = \frac{\mu N I}{L} \tag{10}$$

Coercivity

Coercivity can be defined as the amount of magnetic field required to completely demagnetize the substance in question. Point ‘C’ in figure 2 represents the coercivity of a substance [6].

Remanent Flux Density

Remanent Flux density or Retentivity as depicted as point ‘B’ is the amount of magnetization left when as external magnetic field is removed is known as remanent flux density [6].

APPARATUS

This section lists the apparatus used for collecting the data for the Hall Effect experiment.

List of apparatus

- Hall Probe
- Double Pole Double Throw (DPDT) switch
- Solenoid coils
- Instrumental Amplifier
- Current sensor
- High current sensor
- Voltage sensor
- Power supply
- B&K power supply
- Lab quest mini

PROCEDURE

This section discusses the procedure followed to collect the data for both the parts of the experiment.

Part 1: Hall Effect

The apparatus was connected as per the depiction in figure 3. The B&K power supply was setup to a 3000 Gauss magnetic field strength. 3k Gauss magnetic field strength corresponds to 0.899 Amps (As depicted in figure 4) in terms of I_c Current. The current through the power supply (I_x) was slowly increased by 20-25mA, without exceeding the 350mA limit for the power supply. For each increment a measurement was taken for the current (I_x) through the power supply, voltage (V_x) across the power supply and potential (V_H) across the hall probe. This procedure was repeated for 4k Gauss and 5k Gauss.

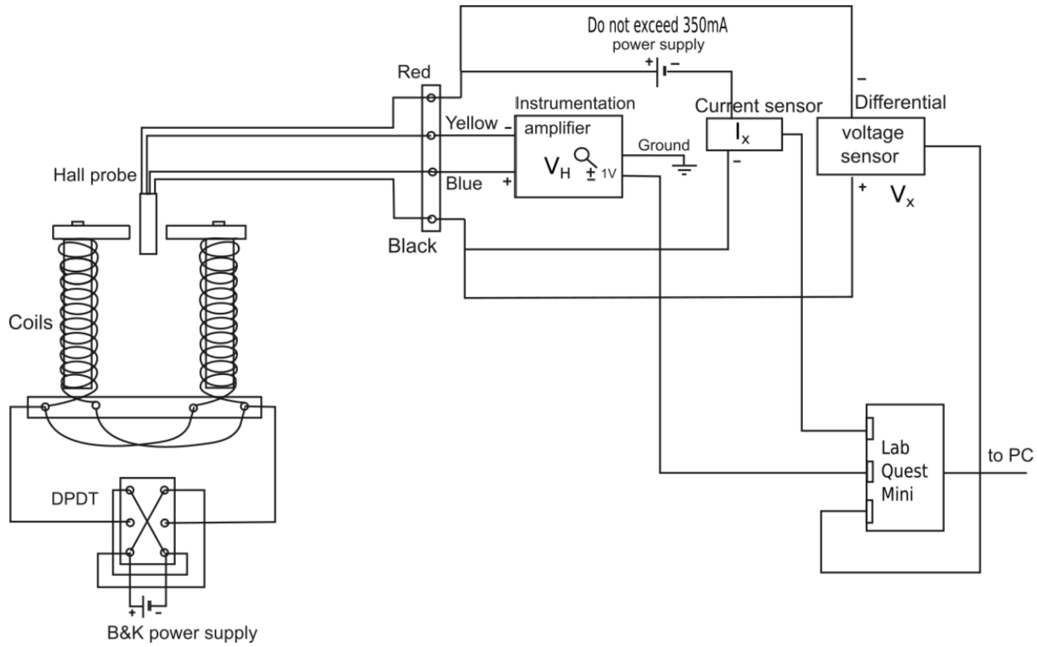
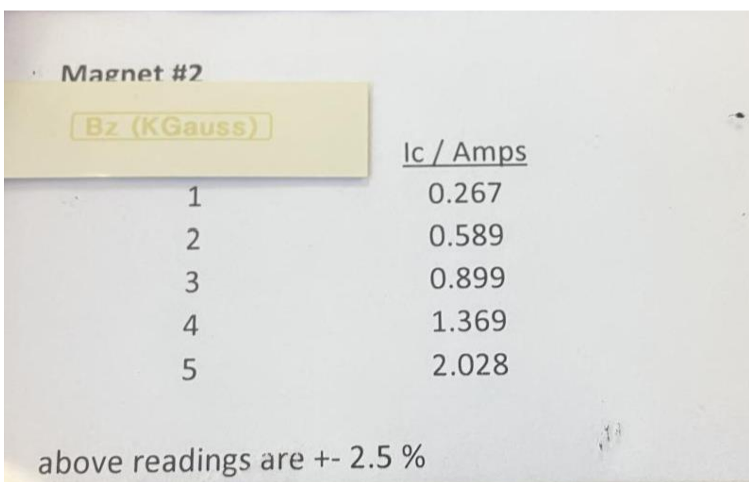


Figure 3: Apparatus Setup for Hall Effect Experiment



Magnet #2

Bz (KGauss)	Ic / Amps
1	0.267
2	0.589
3	0.899
4	1.369
5	2.028

above readings are +- 2.5 %

Figure 4: Ic Current corresponding to Gauss Magnetic field applied

Part 2: Hysteresis Curve

The apparatus was connected as per the depiction in figure 5. The main current supply (Ic) was setup to 350mA. Loggers' pro was setup at automated data collection at 100samples/s. The Ic current was slowly varied starting from the maxima, that is 350mA, once the current was zeroed the direction of the current was changed using the DPDT switch and then it was taken to the maxima followed by another minima. The DPDT switch was used again to changed to direction of the applied current and thus finally taking it back to maxima again.

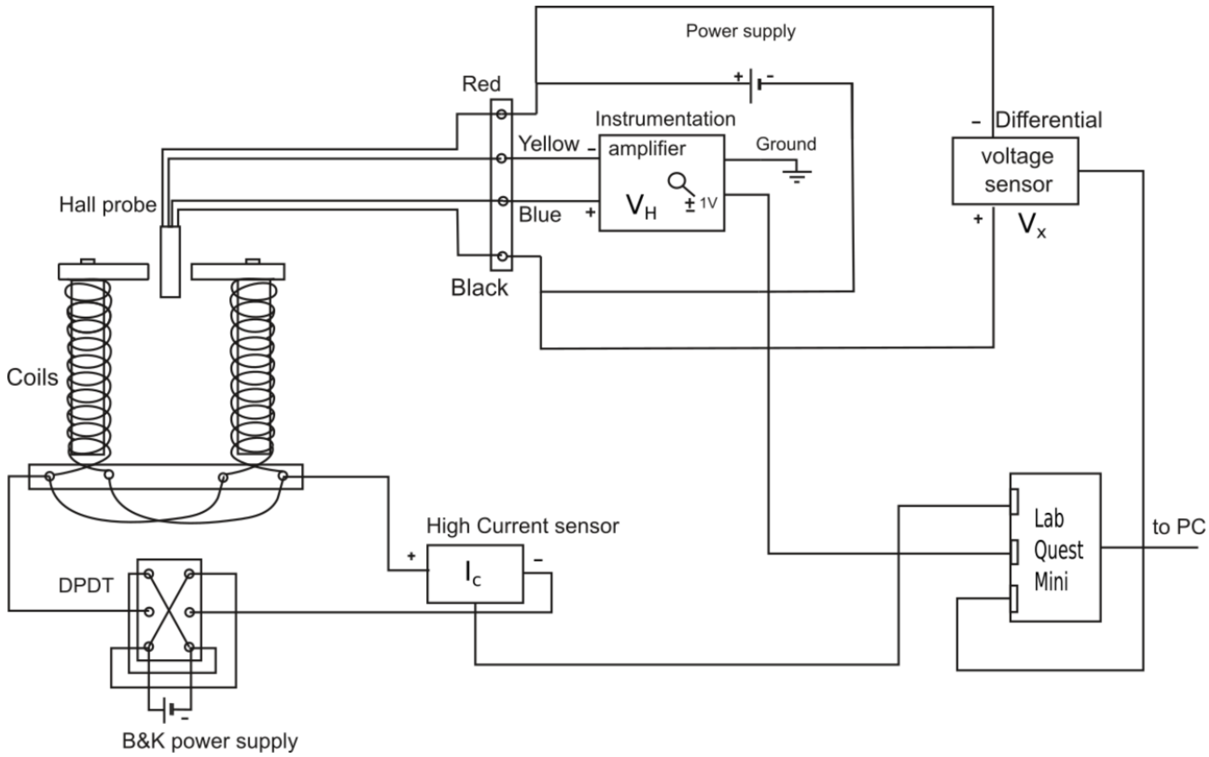


Figure 5: Apparatus Setup for Hysteresis Curve Experiment

RESULTS

This section discusses the results obtained in both the parts of the experiment along with the errors and uncertainties and their causes.

Hall effect

This section focuses on the results obtain by the analyzing the data for part 1 of the experiment. The focus for this section would be to calculate the hall coefficient, resistivity, and hall mobility for the hall probe. The material used for the hall probe is indium arsenide. It was planned to compare the results with the standard values found on the internet, but no specific standard values were found. MATLAB was used to analyze the data. The code used in MATLAB can be found in the appendix.

Hall Constant

The hall constant was calculated by plotting the hall potential against the applied current. Using the graphs obtained by the three different applied magnetic field across the hall probe. The graphs for all the various magnetic field are used to measure the slopes for all the fits. Equation 4 is then used to measure the hall constant. The resulting graph for these measurements can be found in figure 6.

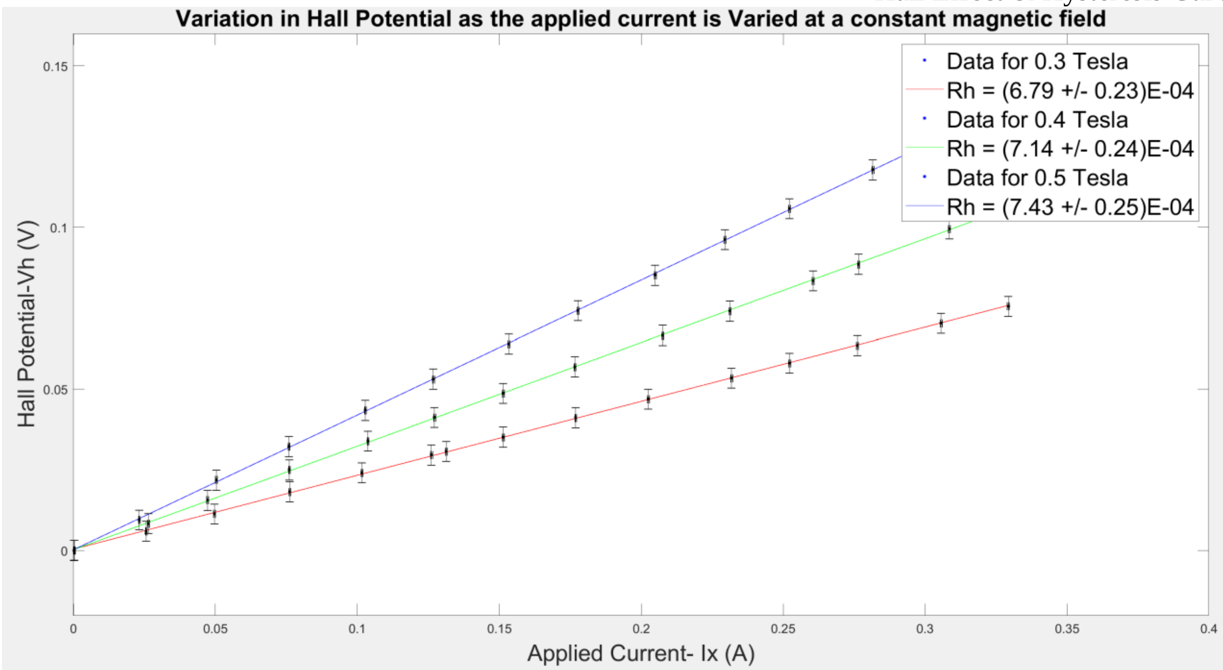


Figure 6: Variation in Hall Potential as a function of applied current under particular applied magnetic field

Sample Calculation

$$Slope\ (m) = \frac{V_H}{I_X}$$

Applying equation 4

$$R_H = \frac{V_H c}{I_x B_z} = \frac{m * c}{B_z}$$

Error Propagation

Error on slope is calculated using Jacobian method in MATLAB. For hall constant the error propagation using weighted error is applied. Below are the equations that are used to calculate the error on the hall constant for each applied magnetic field.

$$\sigma_{Rh} = \sqrt{\left(\left(\frac{dR_H}{dm}\right)^2 * \sigma_m^2\right) + \left(\left(\frac{dR_H}{dc}\right)^2 * \sigma_c^2\right) + \left(\left(\frac{dR_H}{dB_Z}\right)^2 * \sigma_{Bz}^2\right)}$$

$$\sigma_{Rh} = \sqrt{\left(\left(\frac{c}{B_Z}\right)^2 * \sigma_m^2\right) + \left(\left(\frac{m}{B_Z}\right)^2 * \sigma_c^2\right) + \left(\left(\frac{m * c}{B_Z^2}\right)^2 * \sigma_{Bz}^2\right)}$$

Averaging the Results

For averaging the Rh values, a basic mean formula is used as shown below.

$$R_H = \frac{R_H(0.3\,Tesla) + R_H(0.4\,Tesla) + R_H(0.5Tesla)}{3}$$

To Calculate the error on the average R_H error propagation is applied on the average formulae above.

$$\sigma_{Rh} = \sqrt{\left(\left(\frac{dR_{H0.3}}{dR_{H0.3}}\right)^2 * \sigma_{Rh0.3}^2\right) + \left(\left(\frac{dR_{H0.4}}{dR_{H0.4}}\right)^2 * \sigma_{Rh0.4}^2\right) + \left(\left(\frac{dR_{H0.5}}{dR_{H0.5}}\right)^2 * \sigma_{Rh0.5}^2\right)}$$

$$\sigma_{Rh} = \sqrt{\frac{\sigma_{Rh0.3}^2 + \sigma_{Rh0.4}^2 + \sigma_{Rh0.5}^2}{9}}$$

Table 1 depicts the results for the calculation of the Hall Constant.

Applied Magnetic Field	Slope (m) (V/A)	Hall Constant (m^3/C)*10^{-4}	Error on Hall Constant (m^3/C) *10^{-4}
0.3 Tesla	0.2290	6.79	0.23
0.4 Tesla	0.3208	7.14	0.24
0.5 Tesla	0.4174	7.43	0.25
Average		7.12	0.14

Thus, the value of hall constant calculated is (7.12 +/- 0.14) *10^{-4} m^3/C.

Resistivity

The Resistivity was calculated by plotting the applied potential against the applied current. Using the graphs obtained by the three different applied magnetic field across the hall probe. The graphs for all the various magnetic field are used to measure the slopes for all the fits. Equation 8 is then used to calculate the resistivity. The resulting graph for these measurements can be found in figure 7.

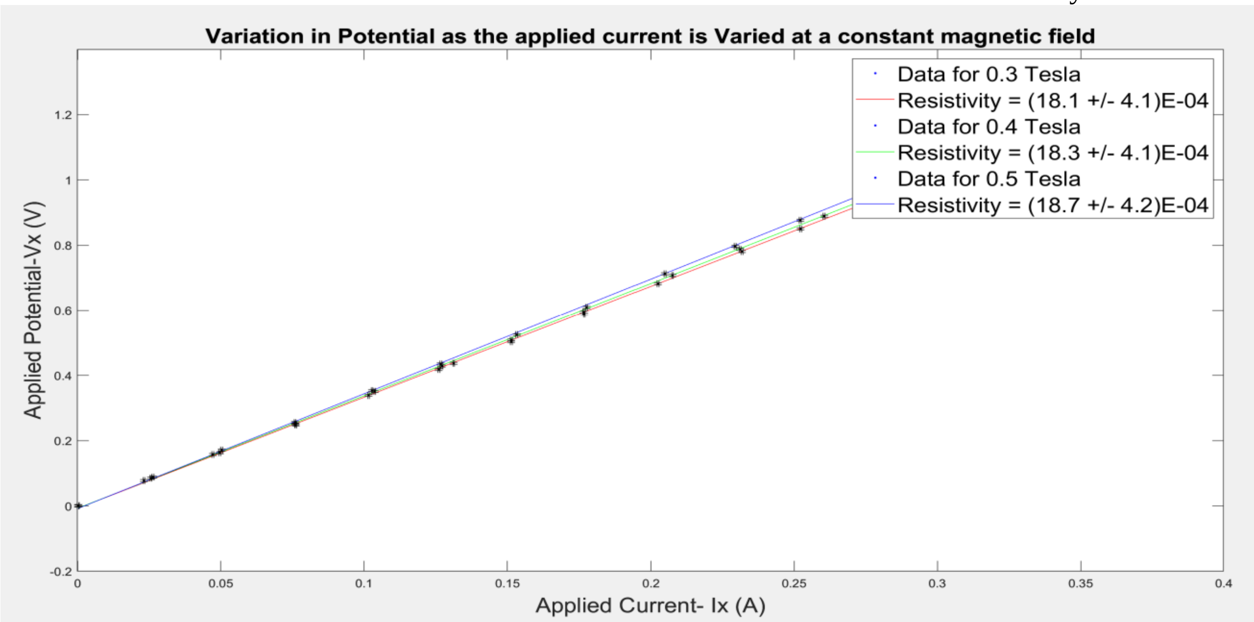


Figure 7: Variation in Applied Potential as a function of applied current under particular applied magnetic field

Sample Calculation

$$Resistance\ (R) = Slope\ (R) = \frac{V_X}{I_X}$$

Applying equation 8

$$Resistivity\ (\rho) = \frac{V_x * b * c}{I_x * a} = \frac{R * b * c}{a}$$

Error Propagation

Error on slope is calculated using Jacobian method in MATLAB. For resistivity the error propagation using weighted error is applied. Below are the equations that are used to calculate the error on the hall constant for each applied magnetic field.

$$\sigma_\rho = \sqrt{\left(\left(\frac{d\rho}{dR}\right)^2 * \sigma_R^2\right) + \left(\left(\frac{d\rho}{db}\right)^2 * \sigma_b^2\right) + \left(\left(\frac{d\rho}{dc}\right)^2 * \sigma_c^2\right) + \left(\left(\frac{d\rho}{da}\right)^2 * \sigma_a^2\right)}$$

$$\sigma_\rho = \sqrt{\left(\left(\frac{b * c}{a}\right)^2 * \sigma_R^2\right) + \left(\left(\frac{R * c}{a}\right)^2 * \sigma_b^2\right) + \left(\left(\frac{R * b}{a}\right)^2 * \sigma_c^2\right) + \left(\left(\frac{R * b * c}{a * a}\right)^2 * \sigma_a^2\right)}$$

Averaging the Results

For averaging the Resistivity values, a basic mean formula is used as shown below.

$$\rho = \frac{\rho(0.3\ Tesla) + \ \rho(0.4\ Tesla) + \rho(0.5 Tesla)}{3}$$

To Calculate the error on the average resistivity error propagation is applied on the average formulae above.

$$\sigma_\rho = \sqrt{\left(\left(\frac{d\rho}{d\rho_{0.3}}\right)^2 * \sigma_{\rho 0.3}^2\right) + \left(\left(\frac{d\rho}{d\rho_{0.4}}\right)^2 * \sigma_{\rho 0.4}^2\right) + \left(\left(\frac{d\rho}{d\rho_{0.5}}\right)^2 * \sigma_{\rho 0.5}^2\right)}$$

$$\sigma_\rho = \sqrt{\frac{\sigma_{\rho 0.3}^2 + \sigma_{\rho 0.4}^2 + \sigma_{\rho 0.5}^2}{9}}$$

Table 2 depicts the results for the calculation of the Resistivity.

Applied Magnetic Field	**Slope (m) (V/A)**	**Resistivity (Ω/m) $*10^{-4}$**	**Error on Resistivity (Ω/m) $*10^{-4}$**
0.3 Tesla	3.4059	18.1	4.1
0.4 Tesla	3.4484	18.3	4.1
0.5 Tesla	3.5214	18.7	4.2
Average		18.4	2.4

Thus, the value of resistivity calculated for indium arsenide is (18.4 +/- 2.4) $*10^{-4}$ Ω/m.

Hall Mobility

The hall mobility was calculated by plotting the hall potential against the applied potential. Using the graphs obtained by the three different applied magnetic field across the hall probe. The graphs for all the various magnetic field are used to measure the slopes for all the fits. Equation 7 is then used to measure the hall mobility. The resulting graph for these measurements can be found in figure 8.

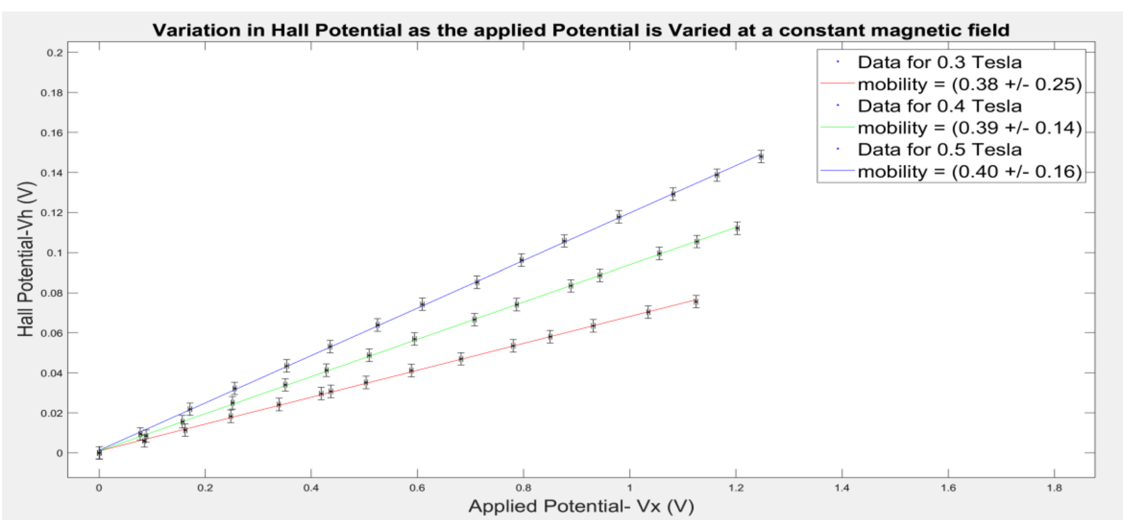


Figure 8: Variation in Hall Potential as a function of applied potential under particular applied magnetic field

Sample Calculation

$$Slope\ (m) = \frac{V_h}{V_X}$$

Applying equation 7

$$Mobility\ (\mu) = \frac{v_x}{E_x} = \frac{aV_h}{bB_ZV_x} = \frac{a*m}{b*B_Z}$$

Error Propagation

Error on slope is calculated using Jacobian method in MATLAB. For mobility the error propagation using weighted error is applied. Below are the equations that are used to calculate the error on the hall constant for each applied magnetic field.

$$\sigma_\mu = \sqrt{\left(\left(\frac{d\mu}{da}\right)^2 * \sigma_a^2\right) + \left(\left(\frac{d\mu}{dm}\right)^2 * \sigma_m^2\right) + \left(\left(\frac{d\mu}{db}\right)^2 * \sigma_b^2\right) + \left(\left(\frac{d\mu}{dB_Z}\right)^2 * \sigma_{Bz}^2\right)}$$

$$\sigma_\mu = \sqrt{\left(\left(\frac{m}{b*B_Z}\right)^2 * \sigma_a^2\right) + \left(\left(\frac{a}{b*B_Z}\right)^2 * \sigma_m^2\right) + \left(\left(\frac{a*m}{b*b*B_Z}\right)^2 * \sigma_b^2\right) + \left(\left(\frac{a*m}{b*B_Z*B_Z}\right)^2 * \sigma_{Bz}^2\right)}$$

Averaging the Results

For averaging the mobility values, a basic mean formula is used as shown below.

$$\mu = \frac{\mu(0.3\ Tesla) + \mu(0.4\ Tesla) + \mu(0.5 Tesla)}{3}$$

To Calculate the error on the average resistivity error propagation is applied on the average formulae above.

$$\sigma_\mu = \sqrt{(\left(\frac{d\mu}{d\mu_{0.3}}\right)^2 * \sigma_{\mu 0.3}^2) + (\left(\frac{d\mu}{d\mu_{0.4}}\right)^2 * \sigma_{\mu 0.4}^2) + (\left(\frac{d\mu}{d\mu_{0.5}}\right)^2 * \sigma_{\mu 0.5}^2)}$$

$$\sigma_\mu = \sqrt{\frac{\sigma_{\mu 0.3}^2 + \sigma_{\mu 0.4}^2 + \sigma_{\mu 0.5}^2}{9}}$$

Table 2 depicts the results for the calculation of the mobility.

Applied Magnetic Field	Slope (m)	Resistivity (1/T)	Error on Resistivity (1/T)
0.3 Tesla	0.0672	0.38	0.25
0.4 Tesla	0.0930	0.39	0.14
0.5 Tesla	0.1185	0.40	0.16
Average		0.39	0.11

Thus, the value of resistivity calculated for indium arsenide is (0.39 +/- 0.11) *(1/T).

Hysteresis Curve

This section focuses on the results obtain by the analyzing the data for part 2 of the experiment. The focus for this section would be to calculate the coersive force and remanent flux density. The material used for the solenoid core is iron, thus giving a ferromagnetic core. The results are compared to the standard values obtained for iron from the internet. MATLAB was used to analyze the data. The code used in MATLAB can be found in the appendix.

By plotting the magnetic flux density and the Magnetic Field Strength the Coersive Force (60A/m) and the remnant flux density ($1.42*10^{-8}$ Tesla) is found from the plot in figure 9.

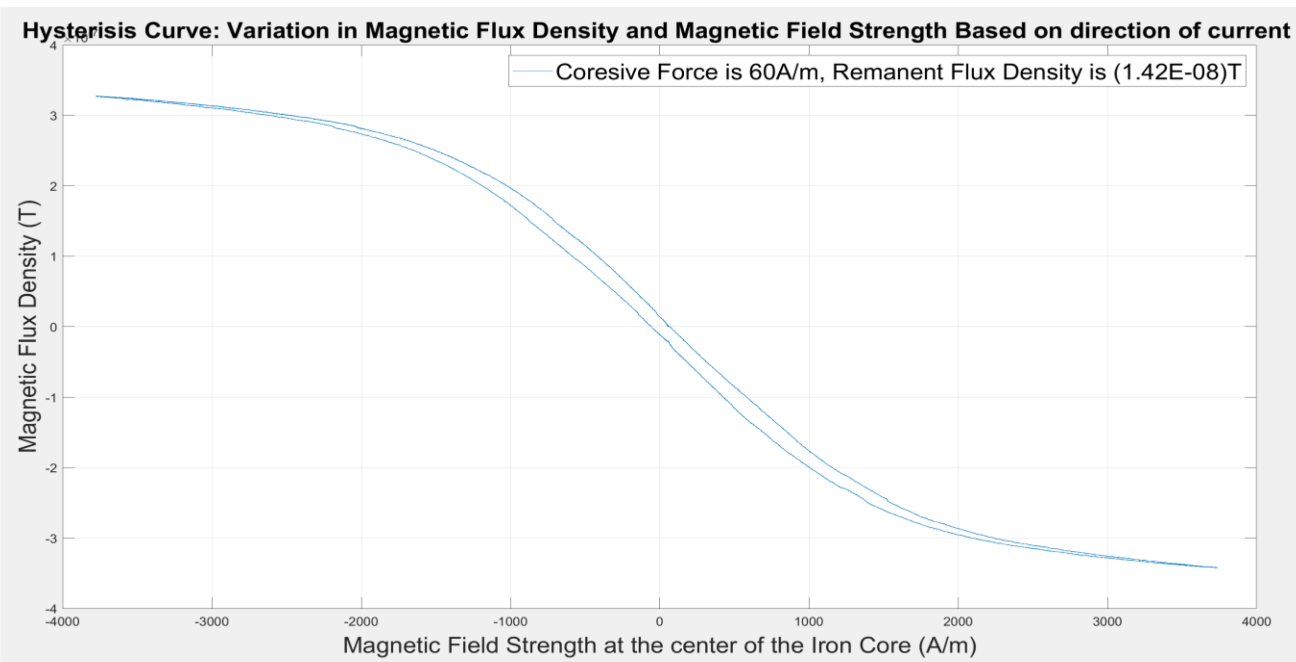


Figure 9: Hysteresis Curve for Ferromagnetic behavior of iron

DISCUSSION

This experiment studied the hall effect on an Indium Arsenide (n-type semiconductor) and measured its hall constant, hall mobility and resistivity. For the experiment the semiconductor used had the dimensions of (0.0159, 0.0095, 0.00089) m with an uncertainty of 0.0002m on each. The specimen was analyzed under there different magnetic field strengths (0.3, 0.4, 0.5) Tesla with an uncertainty of 0.2 Tesla that corresponded to three different applied currents (0.899, 1369, 2.028) Amps with an uncertainty of 0.002 Amp through the solenoid. All the uncertainties above are based on reading errors.

The current, potential and hall potential across the specimen were measured and the uncertainty on these measurements were based on the uncertainty of the measuring instruments. The uncertainty on the voltmeter was ($3.1*10^{-3}$) Volts, that on the current sensor is (0.31mA) and that for the high current sensor is (5.5 mA). Other than the instrumental uncertainties the system was highly sensitive to any uncertainty caused due to the purity of the iron core of the solenoid and the doping levels of the indium arsenide probe. Even though purity of the iron core was known even the slightest amount of uncertainty in that cause huge variation in the permeability value thus the part 2 of the experiment that is the hysteresis curve part cannot be very accurate.

The second part of the experiment analyzed the current, potential and hall potential measured such that the polarity of the current following was altered mid experiment to form the hysteresis curve for the applied potential and the current flowing through the solenoid. The data from the I-V Hysteresis curve was extracted and manipulated to extract a hysteresis curve of magnetic field strength and magnetic flux density and further from that plot the values of coercive force (60 A/m) and remanent flux density (1.42E-08 Tesla) were extracted. No uncertainty has been added to these values here as these values were extracted from the hysteresis curve and the uncertainty on the is a result of the uncertainty on the hysteresis curve. The hysteresis curve plot with the error bars is present in the appendix. The error bars on the hysteresis curve are huge which is a result of the huge uncertainty in the permeability of the iron core as with the slightest variation in purity of iron causes a huge change in the permeability of the core.

A semiconductor is used instead of metal for the hall probe as the density of the charge carriers is inversely proportional to the hall constant and to obtain a substantial hall constant a semiconductor is used for the hall probe. Some common application of hall probes are in magnetic sensors. Such sensors are applied in automotive systems, washing machine components, transformers, computers, keyboard switches, speed detection, anti-lock braking system and many more [7] [8].

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APPENDIX I: Data Collected

Part I: Hall Effect

The tables below consist of the measured data for the hall effect part of the experiment.

I3(A)	Vx3 (V)	Vh3 (mV)	Drift Veocity 3 (m/s)
-2.86E-04	-0.00076	0.035984	0.012626
-0.0256	-0.08526	5.973325	2.095904
-0.04961	-0.16251	11.33492	3.977167
-0.07614	-0.24815	18.27981	6.41397
-0.10159	-0.33894	24.14519	8.471996
-0.12611	-0.41866	29.65072	10.40376
-0.1313	-0.43678	30.73024	10.78254
-0.15139	-0.50297	35.19224	12.34816
-0.17685	-0.58823	41.20155	14.45668
-0.20248	-0.68207	46.95897	16.47683
-0.23178	-0.7803	53.47206	18.76213
-0.25221	-0.85011	58.04201	20.36562
-0.27607	-0.93117	63.47558	22.27213
-0.3056	-1.03493	70.3485	24.68368
-0.3293	-1.12476	75.56616	26.51444

I4 (A)	Vx4 (V)	Vh4 (mV)	Drift Veocity 4 (m/s)
-1.91E-04	-0.00038	0.035984	0.012626
-0.02638	-0.08869	8.348262	2.929215
-0.04721	-0.15736	15.58102	5.467026
-0.07605	-0.25158	25.04479	8.787644
-0.10374	-0.35095	33.96879	11.91887
-0.12716	-0.42858	41.3095	14.49456
-0.15139	-0.50888	48.75817	17.10813
-0.17658	-0.59433	56.92651	19.97421
-0.20754	-0.70744	66.60618	23.37059
-0.23117	-0.78697	74.09082	25.99678
-0.26047	-0.88902	83.48262	29.29215
-0.27649	-0.94357	88.59233	31.08503
-0.30844	-1.05572	99.53143	34.92331
-0.32694	-1.12648	105.4328	36.99396
-0.34857	-1.20277	112.1258	39.34238

I5 (A)	Vx5(V)	Vh5(mV)	Drift Veocity 5 (m/s)
-1.72E-04	-0.00019	0	0
-0.02317	-0.07801	9.463762	3.320618
-0.0503	-0.17147	21.84222	7.663937

-0.07587	-0.25558	32.24156	11.31283
-0.10279	-0.35362	43.46854	15.25212
-0.12678	-0.43526	53.1482	18.64849
-0.15331	-0.5249	63.94337	22.43627
-0.17767	-0.60902	74.27074	26.05991
-0.20487	-0.7122	85.20985	29.89819
-0.22938	-0.79613	96.22092	33.76172
-0.25213	-0.87643	105.7926	37.12022
-0.28152	-0.97942	117.8112	41.33728
-0.30848	-1.08166	129.1102	45.30182
-0.33136	-1.16405	138.6459	48.64769
-0.35456	-1.2476	147.9298	51.90518

Part II: Hysteresis Curve

The Data could not be added here as there were 6000+ Rows of data and MS Word kept crashing on that.

APPENDIX II: MATLAB Code

Part I: Hall Effect

```
                   % Import Values
I3 = Data1(:,1);
I3 = table2array(I3);
I3 = abs(I3);
I4 = Data1(:,5);
I4 = table2array(I4);
I4 = abs(I4);
I5 = Data1(:,9);
I5 = table2array(I5);
I5 = abs(I5);

Vx3 = Data1(:,2);
Vx3 = table2array(Vx3);
Vx3 = abs(Vx3);
Vx4 = Data1(:,6);
Vx4 = table2array(Vx4);
Vx4 = abs(Vx4);
Vx5 = Data1(:,10);
Vx5 = table2array(Vx5);
Vx5 = abs(Vx5);

Vh3 = Data1(:,3);
Vh3 = table2array(Vh3);
Vh3 = 0.001*Vh3;
Vh3 = abs(Vh3);
Vh4 = Data1(:,7);
Vh4 = table2array(Vh4);
Vh4 = 0.001*Vh4;
Vh4 = abs(Vh4);
```

```
Vh5 = Data1(:,11);
Vh5 = table2array(Vh5);
Vh5 = 0.001*Vh5;
Vh5 = abs(Vh5);

a = 0.0159;
err_ab = 0.0002;
b = 0.0095;
c = 0.00089;
err_c = 0.00002;
q = 1.6E-19;
err_T = 0.2;

err_B3 = 2.5*0.01*0.3;
err_B4 = 2.5*0.01*0.4;
err_B5 = 2.5*0.01*0.5;

 %Error
 I_high_err = (5.5E-03)*ones(size(I3));
 I_err = (0.31E-03)*ones(size(I3));
 V_err = (3.1E-03)*ones(size(I3));

 %Curve Fit

 %I Vs VH
 figure(1);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%I3 Vs VH3
[I_Vh3,goF_I_Vh3,Fit_output_I_Vh3] = fit(I3,Vh3,'(m*x)+b','Weight',V_err.^(-2));

    % Extract weighted jacobian
    J_I_Vh3 = Fit_output_I_Vh3.Jacobian;

    %Get the covariance and curvature matrix and extract the errors on F
    %parameters from there.
    curvature_matrix_I_Vh3 = J_I_Vh3'*J_I_Vh3;
    covariance_matrix_I_Vh3 = inv(curvature_matrix_I_Vh3);

    % Calculate CHI_squared
    min_chi2_I_Vh3 = goF_I_Vh3.sse;
    dof_I_Vh3 = goF_I_Vh3.dfe;

    reduced_chi2_I_Vh3 = min_chi2_I_Vh3/dof_I_Vh3;

    err_I_Vh3_m = covariance_matrix_I_Vh3(1,1);

Rh_I_Vh3_m = (I_Vh3.m)*c/0.3;
err_Rh_I_Vh3_m = sqrt((((c*err_I_Vh3_m)/0.3)^2) +(((I_Vh3.m*err_c)/0.3)^2) +
(((I_Vh3.m*c*err_B3)/0.09)^2));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%I4 Vs VH4
[I_Vh4,goF_I_Vh4,Fit_output_I_Vh4] = fit(I4,Vh4,'(m*x)+b','Weight',V_err.^(-2));

    % Extract weighted jacobian
```

```
    J_I_Vh4 = Fit_output_I_Vh4.Jacobian;

    %Get the covariance and curvature matrix and extract the errors on F
    %parameters from there.
    curvature_matrix_I_Vh4 = J_I_Vh4'*J_I_Vh4;
    covariance_matrix_I_Vh4 = inv(curvature_matrix_I_Vh4);

    % Calculate CHI_squared
    min_chi2_I_Vh4 = goF_I_Vh4.sse;
    dof_I_Vh4 = goF_I_Vh4.dfe;

    reduced_chi2_I_Vh4 = min_chi2_I_Vh4/dof_I_Vh4;

    err_I_Vh4_m = covariance_matrix_I_Vh4(1,1);

Rh_I_Vh4_m = (I_Vh4.m)*c/0.4;
err_Rh_I_Vh4_m = sqrt((((c*err_I_Vh4_m)/0.4)^2) +(((I_Vh4.m*err_c)/0.4)^2) +
(((I_Vh4.m*c*err_B4)/0.16)^2));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% I5 Vs Vh5
[I_Vh5,goF_I_Vh5,Fit_output_I_Vh5] = fit(I5,Vh5,'(m*x)+b','Weight',V_err.^(-2));

    % Extract weighted jacobian
    J_I_Vh5 = Fit_output_I_Vh5.Jacobian;

    %Get the covariance and curvature matrix and extract the errors on F
    %parameters from there.
    curvature_matrix_I_Vh5 = J_I_Vh5'*J_I_Vh5;
    covariance_matrix_I_Vh5 = inv(curvature_matrix_I_Vh5);

    % Calculate CHI_squared
    min_chi2_I_Vh5 = goF_I_Vh5.sse;
    dof_I_Vh5 = goF_I_Vh5.dfe;

    reduced_chi2_I_Vh5 = min_chi2_I_Vh5/dof_I_Vh5;

    err_I_Vh5_m = covariance_matrix_I_Vh5(1,1);

Rh_I_Vh5_m = (I_Vh5.m)*c/0.5;
err_Rh_I_Vh5_m = sqrt((((c*err_I_Vh5_m)/0.5)^2) +(((I_Vh5.m*err_c)/0.5)^2) +
(((I_Vh5.m*c*err_B5)/0.25)^2));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Calculate value of Hall Constant and mean error on it
Rh = (Rh_I_Vh3_m + Rh_I_Vh4_m + Rh_I_Vh5_m)/3;
err_Rh =
(sqrt((err_Rh_I_Vh3_m*err_Rh_I_Vh3_m)+(err_Rh_I_Vh4_m*err_Rh_I_Vh4_m)+(err_Rh_I_Vh5_m
*err_Rh_I_Vh5_m)))/3;

n = 1/(q*Rh);
err_n = err_Rh/(q*Rh*Rh);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% PLotting Figure 1
 F1_3 = plot(I_Vh3,'r',I3,Vh3);hold on;
```

```
 F1_4 = plot(I_Vh4,'g',I4,Vh4);
 F1_5 = plot(I_Vh5,'b',I5,Vh5);

 F1 =[F1_3;F1_4;F1_5];
 xlabel('Applied Current- Ix (A)','FontSize',18);
 ylabel('Hall Potential-Vh (V)','FontSize',18);
 title ('Variation in Hall Potential as the applied current is Varied at a constant
magnetic field','FontSize',18)

 legend('Data for 0.3 Tesla', 'Rh = (6.79 +/- 0.23)E-04','Data for 0.4 Tesla','Rh =
(7.14 +/- 0.24)E-04','Data for 0.5 Tesla','Rh = (7.43 +/- 0.25)E-04','FontSize',18)
 errorbar(I3 ,Vh3, I_err,'horizontal',"k.",'HandleVisibility','off');
 errorbar(I3 ,Vh3, V_err,"k.",'HandleVisibility','off');
 errorbar(I4 ,Vh4, I_err,'horizontal',"k.",'HandleVisibility','off');
 errorbar(I4 ,Vh4, V_err,"k.",'HandleVisibility','off');
 errorbar(I5 ,Vh5, I_err,'horizontal',"k.",'HandleVisibility','off');
 errorbar(I5 ,Vh5, V_err,"k.",'HandleVisibility','off');
 hold off
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Vx Vs Vh
figure(2);
%Vx3 Vs Vh3
[Vx_Vh3,goF_Vx_Vh3,Fit_output_Vx_Vh3] = fit(Vx3,Vh3,'(m*x)+b','Weight',V_err.^(-2));

mobility3 = ((Vx_Vh3.m)*a)/(0.3*b);
    % Extract weighted jacobian
    J_Vx_Vh3 = Fit_output_Vx_Vh3.Jacobian;

    %Get the covariance and curvature matrix and extract the errors on F
    %parameters from there.
    curvature_matrix_Vx_Vh3 = J_Vx_Vh3'*J_Vx_Vh3;
    covariance_matrix_Vx_Vh3 = inv(curvature_matrix_Vx_Vh3);

    % Calculate CHI_squared
    min_chi2_Vx_Vh3 = goF_Vx_Vh3.sse;
    dof_Vx_Vh3 = goF_Vx_Vh3.dfe;

    reduced_chi2_Vx_Vh3 = min_chi2_Vx_Vh3/dof_Vx_Vh3;

err_Vx_Vh3_m = covariance_matrix_Vx_Vh3(1,1);
err_mobility_Vx_Vh3 = sqrt((err_Vx_Vh3_m*(a/(0.3*b)))^2 +
(((Vx_Vh3.m)*err_ab)/(0.3*b))^2 + (((Vx_Vh3.m)*a*err_ab)/(0.3*b*b))^2 +
(((Vx_Vh3.m)*a*err_T)/(0.09*b))^2);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Vx4 Vs Vh4
[Vx_Vh4,goF_Vx_Vh4,Fit_output_Vx_Vh4] = fit(Vx4,Vh4,'(m*x)+b','Weight',V_err.^(-2));

mobility4 = ((Vx_Vh4.m)*a)/(0.4*b);
    % Extract weighted jacobian
    J_Vx_Vh4 = Fit_output_Vx_Vh4.Jacobian;
```

```
    %Get the covariance and curvature matrix and extract the errors on F
    %parameters from there.
    curvature_matrix_Vx_Vh4 = J_Vx_Vh4'*J_Vx_Vh4;
    covariance_matrix_Vx_Vh4 = inv(curvature_matrix_Vx_Vh4);

    % Calculate CHI_squared
    min_chi2_Vx_Vh4 = goF_Vx_Vh4.sse;
    dof_Vx_Vh4 = goF_Vx_Vh4.dfe;

    reduced_chi2_Vx_Vh4 = min_chi2_Vx_Vh4/dof_Vx_Vh4;

err_Vx_Vh4_m = covariance_matrix_Vx_Vh4(1,1);
err_mobility_Vx_Vh4 = sqrt((err_Vx_Vh4_m*(a/(0.4*b)))^2 +
(((Vx_Vh4.m)*err_ab)/(0.4*b))^2 + (((Vx_Vh4.m)*a*err_ab)/(0.4*b*b))^2 +
(((Vx_Vh3.m)*a*err_T)/(0.16*b))^2);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Vx5 Vs Vh5
[Vx_Vh5,goF_Vx_Vh5,Fit_output_Vx_Vh5] = fit(Vx5,Vh5,'(m*x)+b','Weight',V_err.^(-2));

mobility5 = ((Vx_Vh5.m)*a)/(0.5*b);
    % Extract weighted jacobian
    J_Vx_Vh5 = Fit_output_Vx_Vh5.Jacobian;

    %Get the covariance and curvature matrix and extract the errors on F
    %parameters from there.
    curvature_matrix_Vx_Vh5 = J_Vx_Vh5'*J_Vx_Vh5;
    covariance_matrix_Vx_Vh5 = inv(curvature_matrix_Vx_Vh5);

    % Calculate CHI_squared
    min_chi2_Vx_Vh5 = goF_Vx_Vh5.sse;
    dof_Vx_Vh5 = goF_Vx_Vh5.dfe;

    reduced_chi2_Vx_Vh5 = min_chi2_Vx_Vh5/dof_Vx_Vh5;

err_Vx_Vh5_m = covariance_matrix_Vx_Vh5(1,1);
err_mobility_Vx_Vh5 = sqrt((err_Vx_Vh5_m*(a/(0.5*b)))^2 +
(((Vx_Vh5.m)*err_ab)/(0.5*b))^2 + (((Vx_Vh5.m)*a*err_ab)/(0.5*b*b))^2 +
(((Vx_Vh5.m)*a*err_T)/(0.25*b))^2);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Calculate mean mobility and error on it

mobility = (mobility3 + mobility4 + mobility5)/3;
err_mobility =
(sqrt((err_mobility_Vx_Vh3*err_mobility_Vx_Vh3)+(err_mobility_Vx_Vh4*err_mobility_Vx_
Vh4)+(err_mobility_Vx_Vh5*err_mobility_Vx_Vh5)))/3;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Potting figure 2
 VV3 = plot(Vx_Vh3,'r',Vx3,Vh3);hold on;
 VV4 =  plot(Vx_Vh4,'g',Vx4,Vh4);
 VV5 = plot(Vx_Vh5,'b',Vx5,Vh5);
```

```
 VV =[VV3;VV4;VV5];

 xlabel('Applied Potential- Vx (V)','FontSize',18);
 ylabel('Hall Potential-Vh (V)','FontSize',18);
 title ('Variation in Hall Potential as the applied Potential is Varied at a constant
magnetic field','FontSize',18)
 legend('Data for 0.3 Tesla', 'mobility = (0.38 +/- 0.25)','Data for 0.4
Tesla','mobility = (0.39 +/- 0.14)','Data for 0.5 Tesla','mobility = (0.40 +/-
0.16)','FontSize',18)

 errorbar(Vx5, Vh5, V_err,"k.",'HandleVisibility','off');
 errorbar(Vx4, Vh4, V_err,"k.",'HandleVisibility','off');
 errorbar(Vx3, Vh3, V_err,"k.",'HandleVisibility','off');
  errorbar(Vx5, Vh5, V_err,'horizontal',"k.",'HandleVisibility','off');
 errorbar(Vx4, Vh4, V_err,'horizontal',"k.",'HandleVisibility','off');
 errorbar(Vx3, Vh3, V_err,'horizontal',"k.",'HandleVisibility','off');
 hold off

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

 %I Vs Vx
 figure(3);
% Making Fit
 [I_Vx3,goF_I_Vx3,Fit_output_I_Vx3] = fit(I3,Vx3,'(m*x)+b','Weight',V_err.^(-2));
 [I_Vx4,goF_I_Vx4,Fit_output_I_Vx4] = fit(I4,Vx4,'(m*x)+b','Weight',V_err.^(-2));
 [I_Vx5,goF_I_Vx5,Fit_output_I_Vx5] = fit(I5,Vx5,'(m*x)+b','Weight',V_err.^(-2));
 % Calculating Resistance
 R3 = I_Vx3.m;
 R4 = I_Vx4.m;
 R5 = I_Vx5.m;
% Calculating Resistivity
 resistivity3 = (R3*b*c)/a;
 resistivity4 = (R4*b*c)/a;
 resistivity5 = (R5*b*c)/a;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 % error propogation
    %0.3Tesla Error Prpogation
     % Extract weighted jacobian
    J_I_Vx3 = Fit_output_I_Vx3.Jacobian;

    %Get the covariance and curvature matrix and extract the errors on F
    %parameters from there.
    curvature_matrix_I_Vx3 = J_I_Vx3'*J_I_Vx3;
    covariance_matrix_I_Vx3 = inv(curvature_matrix_I_Vx3);

    % Calculate CHI_squared
    min_chi2_I_Vx3 = goF_I_Vx3.sse;
    dof_I_Vx3 = goF_I_Vx3.dfe;

    reduced_chi2_I_Vx3 = min_chi2_I_Vx3/dof_I_Vx3;

    err_R3 = covariance_matrix_I_Vx3(1,1);
```

```
    err_resistivity3 = sqrt((((err_R3*b*c)/a)^2) + (((R3*c*err_ab)/a)^2) +
(((R3*b*err_ab)/a)^2) + (((R3*b*c*err_ab)/(a*a))^2));


    %0.4Tesla Error Prpogation
     % Extract weighted jacobian
    J_I_Vx4 = Fit_output_I_Vx4.Jacobian;

    %Get the covariance and curvature matrix and extract the errors on F
    %parameters from there.
    curvature_matrix_I_Vx4 = J_I_Vx4'*J_I_Vx4;
    covariance_matrix_I_Vx4 = inv(curvature_matrix_I_Vx4);

    % Calculate CHI_squared
    min_chi2_I_Vx4 = goF_I_Vx4.sse;
    dof_I_Vx4 = goF_I_Vx4.dfe;

    reduced_chi2_I_Vx4 = min_chi2_I_Vx4/dof_I_Vx4;

    err_R4 = covariance_matrix_I_Vx4(1,1);
    err_resistivity4 = sqrt(((err_R4*b*c)/a)^2 + ((R4*c*err_ab)/a)^2 +
((R4*b*err_ab)/a)^2 + ((R4*b*c*err_ab)/(a*a))^2);

    %0.5 Tesla Error Prpogation
     % Extract weighted jacobian
    J_I_Vx5 = Fit_output_I_Vx5.Jacobian;

    %Get the covariance and curvature matrix and extract the errors on F
    %parameters from there.
    curvature_matrix_I_Vx5 = J_I_Vx5'*J_I_Vx5;
    covariance_matrix_I_Vx5 = inv(curvature_matrix_I_Vx5);

    % Calculate CHI_squared
    min_chi2_I_Vx5 = goF_I_Vx5.sse;
    dof_I_Vx5 = goF_I_Vx5.dfe;

    reduced_chi2_I_Vx5 = min_chi2_I_Vx5/dof_I_Vx5;

    err_R5 = covariance_matrix_I_Vx5(1,1);
    err_resistivity5 = sqrt(((err_R5*b*c)/a)^2 + ((R5*c*err_ab)/a)^2 +
((R5*b*err_ab)/a)^2 + ((R5*b*c*err_ab)/(a*a))^2);

 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 % calculating Net resistivity
 resistivity = (resistivity3 + resistivity4 + resistivity5)/3;
 err_resistivity = ((err_resistivity3)^2) + ((err_resistivity4)^2) +
((err_resistivity5)^2);
 err_resistivity = sqrt(err_resistivity);
 err_resistivity = err_resistivity/3;
 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 %Plot Figure 3
  F3_3 = plot(I_Vx3,'r',I3,Vx3); hold on;
  F3_4 = plot(I_Vx4,'g',I4,Vx4);
  F3_5 = plot(I_Vx5,'b',I5,Vx5);
```

```
 F3 =[F3_3;F3_4;F3_5];
 xlabel('Applied Current- Ix (A)','FontSize',18);
 ylabel('Applied Potential-Vx (V)','FontSize',18);
 title ('Variation in Potential as the applied current is Varied at a constant
magnetic field','FontSize',18)

  legend('Data for 0.3 Tesla', 'Resistivity = (18.1 +/- 4.1)E-04','Data for 0.4
Tesla','Resistivity = (18.3 +/- 4.1)E-04','Data for 0.5 Tesla','Resistivity = (18.7
+/- 4.2)E-04','FontSize',18)
  errorbar(I3 ,Vx3, I_err,'horizontal',"k.",'HandleVisibility','off');
  errorbar(I3 ,Vx3, V_err,"k.",'HandleVisibility','off');
  errorbar(I4 ,Vx4, I_err,'horizontal',"k.",'HandleVisibility','off');
  errorbar(I4 ,Vx4, V_err,"k.",'HandleVisibility','off');
  errorbar(I5 ,Vx5, I_err,'horizontal',"k.",'HandleVisibility','off');
  errorbar(I5 ,Vx5, V_err,"k.",'HandleVisibility','off');
  hold off
```

Part II: Hysteresis Curve

```
% Import data
time = Data2(:,1);
time = table2array(time);
%time = abs(time);
I = Data2(:,2);
I = table2array(I);
%I = abs(I);
Vx = Data2(:,3);
Vx = table2array(Vx);
%Vx = abs(Vx);
Vh = Data2(:,4);
Vh = table2array(Vh);
%Vh = abs(Vh);
Vh = 0.001*Vh;

% Standard Values
a = 0.0159;
b = 0.0095;
c = 0.00089;
err_abc = 0.0002;
q = 1.6E-19;
I_high_err = 5.5E-03;
V_err = 3.1E-03;
Ix = 0.350;
err_Ix = 0.002;
u = 5000;
err_u = 0.02*u;
Rh = 7.12E-04;
err_Rh = 0.14E-04;


%Fit for ratio of N/L
H = [0.3,0.4,0.5];
H = transpose(H);
```

```
Ic = [0.899,1.369,2.028];
Ic = transpose(Ic);
err_H = 0.025*H;
err_Ic = 0.025*Ic;

[Ic_H,goF_Ic_H,Fit_output_Ic_H] = fit(Ic,H,'(m*x)+b','Weight',err_H.^(-2));
N_L = Ic_H.m;

    % Extract weighted jacobian
    J_Ic_H = Fit_output_Ic_H.Jacobian;

    %Get the covariance and curvature matrix and extract the errors on F
    %parameters from there.
    curvature_matrix_Ic_H = J_Ic_H'*J_Ic_H;
    covariance_matrix_Ic_H = inv(curvature_matrix_Ic_H);

    % Calculate CHI_squared
    min_chi2_Ic_H = goF_Ic_H.sse;
    dof_Ic_H = goF_Ic_H.dfe;
    reduced_chi2_Ic_H = min_chi2_Ic_H/dof_Ic_H;

    err_N_L = covariance_matrix_Ic_H(1,1);

%Calculate Bz = Vh*(c*Rh/Ix)

Bz = Vh.*(c*Rh/Ix);
err_Bz = (((Rh*c*V_err)/Ix).^2) + (((Vh*c*err_Rh)/Ix).^2) +
(((Vh*Rh*c*err_Ix)/(Ix^2)).^2) + (((Vh*Rh*err_abc)/Ix).^2);
err_Bz = sqrt(err_Bz);

%Calculating H = (N_L)*I;
H = (u*I*(N_L)) + 60;
err_H = sqrt( ((N_L*u*I_high_err).^2) + ((I*u*err_N_L).^2) + ((I*N_L*err_u).^2) );

plot (H, Bz)
hold on
 xlabel('Magnetic Field Strength at the center of the Iron Core
(A/m)','FontSize',18);
 ylabel('Magnetic Flux Density (T)','FontSize',18);
 grid on
 title ('Hysterisis Curve: Variation in Magnetic Flux Density and Magnetic Field
Strength Based on direction of current ','FontSize',18)
 errorbar(H ,Bz, err_Bz,"k.",'HandleVisibility','off');
 errorbar(H ,Bz, err_H,'horizontal',"k.",'HandleVisibility','off');
 legend('Coresive Force is 60A/m, Remanent Flux Density is (1.42E-
08)T','FontSize',18)
 hold off
```

APPENDIX III: Error Propagation Formulae

Function: $F(x_1 + x_2 + x_3 + \ldots\ldots + x_n)$

$$\sigma_F = \sqrt{\frac{dF}{dx_1} + \frac{dF}{dx_2} + \frac{dF}{dx_3} + \cdots + \frac{dF}{dx_n}}$$

APPENDIX IV: Extra Results

Figure 10 represents the hysteresis curve with the error bars.

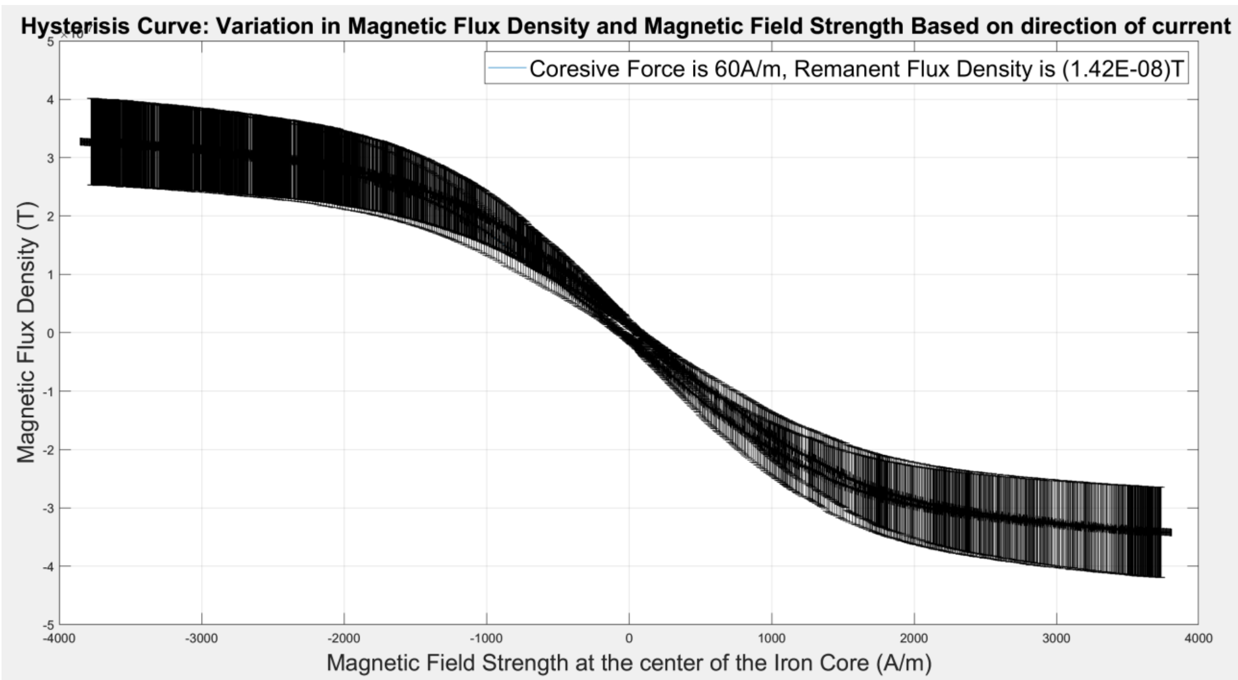

Figure 10: Hysteresis Curve for Ferromagnetic behavior of iron with Error Bars