MAGNETORESISTANCE & HALL EFFECT OF BISMUTH

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Abstract :-

In this experiment, the magnetoresistance & ~~troff~~ hall effect of Bi ~~are~~ were studied using four-probe method under an applied magnetic field. The variation of ~~magnetore~~ resistance with applied magnetic field was studied to understand ~~mto~~ dependence of magnetoresistance on applied field. The Hall coefficients were calculated at two different probe currents, and ~~results~~ measured values had same order of magnitude as literature values for Bismuth. The results confirm the strong magnetoresistive response & Hall effect behaviour of Bi, owing to its semi-metallic nature.

Aim :-

i) To study the magnetoresistance of Bi

ii) To determine the Hall coefficient of Bi

Apparatus required :-

i) Magnetoresistance & Hall probes

ii) Sampes : Bismuth for Magnettoresistance, Bismuth for Hall effect

iii) Constant current Source

iv) Digital Microvoltmeter

v) Electromagnet

vi) Constant current power supply

vii) Digital Gaussmeter

viii) Multipurpose stands.

Theory :-

① Magnetoresistance :

Magnetoresistance refers to the change in electrical resistivity of a material when an external magnetic field is applied.

If R ~~is~~ = resistance in zero magnetic field.

R_m = resistance in presence of magnetic field $\vec{H}$.

Magnetoresistance is defined as, (in terms of resistance).,

$$\frac{\Delta R}{R} = \frac{R_m - R}{R}.$$

When $\vec{E}$ ~~is~~ electric field is applied to a conductor, charge carriers ~~gain~~ a have a drift velocity $\vec{v}$. In presence of magnetic field $\vec{H}$, each carrier experiences a Lorentz force, $\vec{F} = q(\vec{v} \times \vec{H})$

This force bends the carrier trajectories & ~~an~~ ~~intern~~ transverse electric field (Hall field) ~~is~~ develops.

This Hall Voltage $V = E_y t = |\vec{v} \times \vec{H}|$ compensates exactly the Lorentz force for carriers with average velocity. Slow carriers are over-compensated, fast carriers are under-compensated, resulting in trajectories that are not along the applied field. Due to this, mean free path decreases & resistivity increases.

(t = thickness of the crystal).

The change in resistivity is positive for both longitudinal ($\Delta\rho_{\parallel}$) and transverse ($\Delta\rho_{\perp}$). with $\rho_{\perp} > \rho_{\parallel}$.

Depending on the structure of orbitals at Fermi Surface, magnetoresistance can be classified into 3 cases :-

i) Closed Fermi surfaces : Magnetoresistance saturates at high magnetic fields.

ii) Compensated metals (with equal electrons & holes, like Bismuth) : Magnetoresistance increases continuously with magnetic field and does not saturate.

iii) Open Fermi Surfaces : Large, direction-dependent magnetoresistance occurs.

(II) Hall Effect :-

When a current carrying conductor is placed in a magnetic field perpendicular to the direction of current, moving charges experience a Lorentz force, causing a charge accumulation on opposite sides, developing transverse electric field. This field is called the Hall field. It is given by,

$$\vec{E_h} = \vec{R}\,(\vec{J} \times \vec{H}) \quad —① $$

R = Hall coefficient
$\vec{J}$ = current density
$\vec{H}$ = magnetic field.

Consider a rectangular bar with current density $\vec{J}$ is (along $\hat{x}$) & magnetic field $\vec{H}$ (along $\hat{z}$). Then Hall field develops along $\hat{y}$.

Lorentz force on charge carrier, $\vec{F_m} = q(\vec{v} \times \vec{H})$

It is balanced by Hall field, $\vec{F_e} = q\vec{E_h}$

At steady state,

$$q|\vec{E_h}| = q|(\vec{v} \times \vec{H})| \Rightarrow E_h = vH.$$

Current density $\vec{J} = nq\vec{v}$

$$v = \frac{J}{nq}$$

$$\boxed{E_h = \frac{JH}{nq}} \quad —②$$

Comparing ① & ②,

$$\frac{JH}{nq} = RJH \Rightarrow \boxed{R = \frac{1}{nq}}. \quad \therefore R \propto \frac{1}{n}.$$

~~The Hall voltage V_h across the width of the sample. is given by,~~ $\cancel{V_h = E_h y = R\left(\frac{IH}{t}\right)}$

~~I = current through the sample.~~
~~t = thickness of the sample.~~

$$\cancel{\boxed{R = \frac{V_h t}{IH}}}$$

The Hall coefficient of this semi-conductor in the state consider above is given as,

$$R = \frac{V_h/y}{JH} = \frac{V_h z}{IH}$$

V_h = Hall voltage b/w 2 surfaces ⊥ to y.

& $I = J_y z$.

z = thickness of semiconductor

In general, V_h is not a linear function of H. i.e. R is not generally a constant, but a function of applied field. But, if it assumed that all carriers have the same drift velocity, then calculation is easier. We perform it for metals & degenerate (doped) semiconductors.

Magnetic force on carriers, $\vec{F}_m = e(\vec{v} \times \vec{H})$

Hall field compensation $\vec{F}_h = e\vec{E}_h$

$\vec{v}$ = drift velocity of carrier

$E_h = vH$.

We know, current density $\vec{J} = qn\vec{v}$.

$$R = \frac{E_h}{JH} = \frac{vH}{qnvH} = \frac{1}{nq} \Rightarrow \underline{R \propto \frac{1}{n}}.$$

Conductivity of material $\sigma = nq\mu$

μ = mobility of charge carriers.

$$\Rightarrow \boxed{\mu = R\sigma}$$

Mobilities from Hall Effect measurements do not agree with measured values. The reason is that carriers are distributed in energy. those with higher velocities will be deviated to a greater extent for a given field.

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NOTE for observations & plots.

* Magnetoresistance :

i) We took readings for a full loop of coil current values which are plotted. with different markers to show ~~direction~~ sequence of readings. (with a parabola fit) ($\frac{\Delta R}{R}$ v/s H)

ii) Voltage v/s current plot in absence of magnetic field. : Slope provides R (resistance in absence of magnetic field) (Ω)

iii) In the forward positive (increasing I in +ve) readings, we perform a quadratic fit to the $\frac{\Delta R}{R}$ v/s H plot which exhibited a quadratic nature.

iv) For the same points, we plot $\log\left(\frac{\Delta R}{R}\right)$ v/s $\log(H)$ as described in manual. It exhibited an almost linear nature (shown by linear fit).

* Hall Effect

i) Similarly, we took readings for a full loop of coil current values & plot Hall voltage (mV) v/s Magnetic field (Gauss) using different markers to show sequence of readings.

ii) For increasing coil current in +ve, we consider the first (5 datapoints for I = 62.2 mA) & (6 datapoints for I = 134 mA) & perform a linear fitting to calculated the Hall coefficient.

(These points were chosen based on the observation that they fall in the linear region of V_y v/s H plot; further the data exhibits non-linear nature.)

#Observations:-

Table:-

Residual Magnetic field = 112 Gauss.
Constant current = 154.2 mA

(Magnetoresistance of Bi)

S.no.	Magnetic field H (Gauss)	Voltage V_m (mV)	R_m (Ω)	$\frac{\Delta R}{R}$	Log(H)	Log($\frac{\Delta R}{R}$)
1.	120	0.054				
2.	710	0.056				
3.	1380	0.058				
4.	1680	0.059				
5.	2050	0.060				
6.	2710	0.061				
7.	3330	0.063				
8.	3950	0.065				
9.	4280	0.066				
10.	4620	0.067				
11.	4950	0.068				
12.	5080	0.069				
13.	5310	0.070				
14.	5500	0.071				
15.	5690	0.072				
16.	5760	0.071				
17.	5600	0.071				
18.	5320	0.070				
19.	5200	0.069				
20.	5040	0.068				
21.	4790	0.068				
22.	4340	0.066				
23.	4170	0.065				
24.	3850	0.064				

S.no.	Magnetic field H (Gauss)	Voltage V (mV)	R_m (Ω)	$\frac{\Delta R}{R}$	Log(H)	$\text{Log}\left(\frac{\Delta R}{R}\right)$
25.	3500	0.063				
26.	3240	0.062				
27.	2880	0.061				
28.	2620	0.060				
29.	2430	0.060				
30.	1920	0.059				
31.	1740	0.058				
32.	1440	0.057				
33.	1200	0.056				
34.	950	0.056				
35.	740	0.056				
36.	360	0.055.				
37.	120	0.055				
38.	−1600	0.056				
39.	−1480	0.057				
40.	−1760	0.058				
41.	−2050	0.058				
42.	−2270	0.057				
43.	−2550	0.058				
44.	−2810	0.059				
45.	−2970	0.060				
46.	−3180	0.061				
47.	− ~~0~~3560	0.062				
48.	~~0~~ −3760	0.063				
49.	−4200	0.064				

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S.no.	Magnetic field H (Gauss)	Voltage V (mV)	R_m (Ω)	$\frac{\Delta R}{R}$	Log (H)	Log$\left(\frac{\Delta R}{R}\right)$
50.	−4510	0.065				
51.	−4860	0.066				
52.	−5080	0.067				
53.	−5370	0.067				
54.	−5590	0.067				
55.	−5730	0.067				
56.	−5430	0.067				
57.	−4960	0.066				
58.	−4570	0.065				
59.	−4290	0.063				
60.	−3900	0.062				
61.	−3370	0.061				
62.	−3030	0.060				
63.	−2210	0.058				
64.	−1840	0.057				
65.	−1320	0.056				
66.	−780	0.056				
67.	−80	0.0055				

Table:- R in the absence of magnetic field

S.no.	Current (mA)	Voltage (mV)
1.	22.0	0.006
2.	41.6	0.014
3.	57.9	0.020
4.	63.9	0.023
5.	~~8~~92.0	0.033
6.	117.5	0.041
7.	136.0	0.048
8.	151.3	0.055
9.	170.7	0.062
10.		

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slope ↑

$$R_H = \frac{V_y}{H}\frac{t}{I_x}$$

$$R_H = \frac{(\text{slope}) \times t}{I_x} \approx \frac{10 \times \frac{V}{T} \times 10^{-3}\,m}{10^{-3}A} \approx 10 \frac{V\,m}{TA}$$

$t = 0.5$ mm

$I_x = \sim$ mA

$$\text{slope} \approx \frac{mV}{\text{Gauss}} \approx \frac{\times 10^{-3}\,V}{\times 10^{-4}\,T} \approx 10\,\frac{V}{T}$$

I = 92.5 mA

S.no.	Magnetic field H (Gauss)	Voltage V (mV)	Rm	$\left(\frac{\Delta R}{R}\right)$	log (H)	Log$\left(\frac{\Delta R}{R}\right)$
1.	730	0.034				
2.	1190	0.034				
3.	1620	0.035				
4.	2100	0.036				
5.	2370	0.036				
6.	2740	0.037				
7.	3160	0.038				
8.	3510	0.039				
9.	3970	0.039				
10.	4280	0.039				
11.	4510	0.040				
12.	4950	0.041				
13.	5350	0.042				
14.	5760	0.043				
15.	5230	0.041				
16.	4840	0.040				
17.	4580	0.039				
18.	4010	0.038				
19.	3640	0.038				
20.	3150	0.037				
21.	2410	0.036				
22.	1820	0.035				
23.	1500	0.035				
24.	1140	0.034				
25.	810	0.034				

S. no.	Magnetic field H (Gauss)	Voltage V (mV)	R_m	$\left(\frac{\Delta R}{R}\right)$	Log (H)	$\log\left(\frac{\Delta R}{R}\right)$
26.	400	0.033				
27.	−430	0.033				
28.	−890	0.034				
29.	−1130	0.034				
30.	−1590	0.035				
31.	−1910	0.035				
32.	−2540	0.036				
33.	−2990	0.036				
34.	−3450	0.037				
35.	−3820	0.037				
36.	−4110	0.038				
37.	−4540	0.039				
38.	−4950	0.039				
39.	−5210	0.040				
40.	−5400	0.041				
41.	−5730	0.041				
42.	−5380	0.041				
43.	−4990	0.039				
44.	−4340	0.038				
45.	−3920	0.037				
46.	−3190	0.036				
47.	−2900	0.036				
48.	−2480	0.035				
49.	−2320	0.034				
50.	−2050	0.034				
51.	−1730	0.034				
52.	−1240	0.034				
53.	−620	0.034				
54.	−130	0.033.				

NOTE :-

* The tables attached for magnetoresistance have corrected values of magnetic field (after subtracting the residual H).

* A few values of $\frac{\Delta R}{R}$ are negative, & hence the $\log\left(\frac{\Delta R}{R}\right)$ is left 'empty'. Since log( ) is not defined for negative inputs.

*
$$\frac{\Delta R}{R} = \frac{R_m - R}{R}$$

where R = resitance in absence of mag. field (obtained from V v/s I plot) linear fit.

$$R_m = \frac{\text{Hall voltage (mV)}}{\text{Probe current (mA)}}$$

$$\boxed{R_m = \frac{V_y}{I_x}}$$

(in presence of magnetic field).

$R = 0.000370 \pm 0.000005\ \Omega$

$R = (0.370 \pm 0.005)\ m\Omega$

(tables & plot are attached).

(Hall Effect of Bi)

Probe current = 134.0 mA

S. no.	Magnetic field H (Gauss)	Hall Voltage (mV)	S. no.	Magnetic field H (Gauss)	Hall Voltage (mV)
1.	440	-0.010	32.	7470	-0.072
2.	800	-0.018	33.	7320	-0.071
3.	1160	-0.025	34.	7190	-0.069
4.	1510	-0.032	35.	7020	-0.067
5.	1800	-0.038	36.	6870	-0.067
6.	2210	-0.044	37.	6680	-0.068
7.	2560	-0.047	38.	6500	-0.068
8.	3000	-0.051	39.	6240	-0.069
9.	3340	-0.055	40.	5980	-0.070
10.	3640	-0.057	41.	5650	-0.070
11.	4020	-0.061	42.	5340	-0.068
12.	4350	-0.064	43.	5010	-0.066
13.	4670	-0.067	44.	4720	-0.062
14.	4960 5350	-0.069 -0.071	45.	4350	-0.059
15.	5620	-0.072	46.	4010	-0.055
16.	5910	-0.074	47.	3660	-0.052
17.	6200	-0.075	48.	3310	-0.048
18.	6450	-0.076	49.	2910	-0.045
19.	6670	-0.075	50.	2510	-0.040
20.	7750	-0.079	51.	2160	-0.036
21.	7810	-0.079	52	1840	-0.030
22.	7890	-0.079	53.	1480	-0.023
23.	7990	-0.079	54.	1040	-0.015
24.	8120	-0.080	55.	730	-0.010
25.	8150	-0.080	56.	370	-0.002
26.		-0.080	57.	-160	0.002
27.	8010		58.	-510	0.009
28.	7910	-0.079	59.	~~-1170~~ -810	0.013
29.	7810	-0.078	60.	~~-1530~~ -1170	0.020
30.	7700	-0.076	61.	-1530	0.026
31.	7590	-0.075	62.		
			63.	-1870	0.032
			64.	-2310	0.038
			65.	-2610	0.043
			66.	-2920	0.048

S.no.	Magnetic field H (Gauss)	Hall voltage (mV)	S.no.	Magnetic field H (Gauss)	Hall voltage (mV)
66.	-3300	0.053	94.	-6790	0.089
67.	-3800	0.061	95.	-6~~0~~630	0.086
68.	-4130	0.065	96.	-6400	0.08~~0~~3
69.	-4490	0.070	97	-6220	0.080
70	-4770	0.074	98.	-6020	0.078
71.	-5080	0.079	99.	-~~0~~5740	0.076
72.	-5310	0.081	100.	-5460	0.074
73.	-5560	0.083	101.	-5200	0.072
74.	-5890	0.086	102.	-4880	0.071
75.	-6110	0.087	103.	-~~4090~~4430	0.065
76.	-6350	0.089	104.	-4090	0.064
77.	-6550	0.091	105.	-3750	0.060
78.	-6730	0.093	106.	-3370	0.054
79.	-6920	0.094	107.	-3110	0.051
80.	-7100	0.095	108.	-2710	0.045
81.	-7260	0.096	109.	-2400	0.040
82.	-7410	0.099	110.	-2090	0.035
83.	-7500	0.102	111.	-1780	0.028
84.	-7600	0.104	111.	-1420	0.024
85.	-7740	0.104	112.	-1020	0.017
86.	-7800	0.102	113.	-770	0.013
87.	-7690	0.102	114.	-250	0.005
88.	-7570	0.100	115.	-80	0.002
89.	-7400	0.098			
90.	-7360	0.097			
91.	-7230	0.095			
92.	-7100	0.094			
93.	-6990	0.092			

Probe current = 62.2 mA

S.no.	Magnetic field (H) (Gauss)	Hall Voltage (mV)	S.no.	Magnetic field H (Gauss)	Hall voltage (mV)
1.	180	0	25.	~~729~~ 7300	−0.030
2.	790	−0.005	26.	7420	−0.030
3.	920	−0.006	27.	7550	−0.031
4.	1310	−0.009	28.	7670	−0.031
5.	1620	−0.012	29.	7790	−0.032
6.	1980	−0.014	30.	7900	−0.032
7.	2460	−0.017	31.	7980	−0.032
8.	2680	−0.018	32.	8120	−0.032
9.	3040	−0.020	33.	8040	−0.032
10.	3380	−0.021	34.	7880	−0.030
11.	3760	−0.021	35.	7770	−0.029
12.	4100	−0.022	36.	7620	−0.029
13.	4430	−0.023	37.	7500	−0.028
14.	4750	−0.024	38.	7380	−0.028
15.	5110	−0.026	39.	7240	−0.027
16.	5410	−0.027	40.	7090	−0.027
17.	5700	−0.028	41.	6890	−0.027
18.	5970	−0.029	42.	6750	−0.026
19.	6210	−0.029	43.	6530	−0.026
20.	6500	−0.029	44.	6310	−0.025
21.	6670	−0.029	45.	6050	−0.024
22.	6860	−0.028	46.	5780	−0.024
23.	7030	−0.029	47.	5440	−0.024
24.	7180	−0.030	48.	5120	−0.023
			49.	4790	−0.022
			50.	4460	−0.022

S.no.	Magnetic field H (Gauss)	Hall voltage (V) (mV)
51.	4120	−0.021
52.	3690	−0.020
53.	3390	−0.016
54.	3040	−0.014
55.	2680	−0.013
56.	2330	−0.012
57.	1970	−0.009
58.	1620	−0.007
59.	1260	−0.005
60.	900	−0.002
61.	460	−0.001
62.	410	~~−0.000~~
63.	−110	0.006
64.	−500	0.009
65.	−720	0.011
66.	−900	0.013
67.	−1160	0.014
68.	−1560	0.019
69.	−1860	0.020
70.	−2210	0.023
71.	−2560	0.026
72.	−2900	0.029
73.	−3320	0.033
74.	−3660	0.036

S.no.	Magnetic field (H) (Gauss)	Hall voltage (V) (mV)
75.	−3910	0.038
76.	−4270	0.041
77.	−4600	0.042
78.	−4910	0.043
79.	−5220	0.045
80.	−5540	0.047
81.	−5810	0.048
82.	−6060	0.048
83.	−6280	0.048
84.	−6510	0.047
85.	−6710	0.047
86.	−6860	0.047
87.	−7000	0.048
88.	−7180	0.047
89.	−7310	0.048
90.	−7430	0.047
91.	−7530	0.047
92.	−7680	0.048
93.	−7790	0.049
94.	−7660	0.050
95.	−7540	0.051
96.	−7480	0.051
97.	−7400	0.051
98.	−7280	0.052
99.	−7130	0.052
100.	−7000	0.051
101.	−6870	0.050

S.no.	Magnetic Field H (Gauss)	Hall voltage V (mV)	
102.	−6720	0.048	
103.	−6510	0.047	
104.	−6340	0.046	
105.	−6100	0.046	
106.	−5870	0.046	
107.	−5640	0.045	
108.	−5270	0.043	
109.	−5000	0.042	
110.	−4670	0.038	
111.	−4340	0.036	
112.	−3960	0.033	
113.	−3620	0.031	
114.	−3280	0.030	
115.	−2840	0.027	
116.	−2480	0.024	
117.	−2220	0.023	
118.	−1910	0.021	
119.	−1550	0.019	
120.	−1100	0.016	
121.	−840	0.015	
122.	−480	0.013	
123.	−210	0.012	
124.	−40	0.010	

Calculations & Error Analysis :-

(error in least square fitting is explained later)

* Hall coefficient from Hall effect plots.

(I) Probe current $I_x = 62.2\ mA$

From the attached plots of Hall voltage (V_y) v/s Magnetic field (H), we obtain the slope,

slope, $a_1 = -0.0000082 \pm 0.0000002$

Hall coefficient,

$t = 0.5\ mm$ (given)

$$R_{H_1} = \frac{V_y t}{H I_x} = \frac{(\text{slope}) \times t}{I_x} = \frac{a_1 t}{I_x}$$

$$R_{H_1} = \frac{-0.0000082 \times 0.5 \times 10}{62.2} \ \frac{m^3}{C},$$

$$R_{H_1} = -6.62 \times 10^{-7} \ \frac{m^3}{C}.$$

Error in R_{H_1},

$$\Delta R_{H_1} = \sqrt{\left(\frac{\partial R_{H_1}}{\partial a_1}.\Delta a_1\right)^2 + \left(\frac{\partial R_{H_1}}{\partial I_x}.\Delta I_x\right)^2}$$

$$= \sqrt{\left(\frac{t}{I_x}.\Delta a_1\right)^2 + \left(-\frac{a_1 t}{I_x^2}.\Delta I_x\right)^2} = \sqrt{\left(\frac{a_1 t}{I_x}.\frac{\Delta a_1}{a_1}\right)^2 + \left(\frac{a_1 t}{I_x}.\frac{\Delta I_x}{I_x}\right)^2}$$

$$\Delta R_{H_1} = |R_{H_1}| \sqrt{\left(\frac{\Delta a_1}{a_1}\right)^2 + \left(\frac{\Delta I_x}{I_x}\right)^2}$$

$\Delta I_x = 0.01\ mA$ (least count)

$$\Delta R_{H_1} = 6.62 \times 10^{-7} \sqrt{\left(\frac{2 \times 10^{-7}}{82 \times 10^{-7}}\right)^2 + \left(\frac{0.01}{62.2}\right)^2}$$

$$\Delta R_{H_1} = 0.16 \times 10^{-7} \ \frac{m^3}{C}.$$

(II) Probe current I_x = 134.0 mA

From attached plots of Hall voltage (V_y) v/s Magnetic field (H), we obtain, slope.

slope, $a_2 = -0.0000191 \pm 0.0000005$

Hall coefficient, $R_{H_2} = \frac{a_2 t}{I_x}$

$$R_{H_2} = \frac{-0.0000191 \times 0.5 \times 10}{134} \; \frac{m^3}{C}.$$

$$\underline{R_{H_2} = -7.14 \times 10^{-7} \; \frac{m^3}{C}}.$$

Error in R_{H_2}, similarly,

$\Delta I_x = 0.1$ mA (least count)

$$\Delta R_{H_2} = |R_{H_2}| \sqrt{\left(\frac{\Delta a_2}{a_2}\right)^2 + \left(\frac{\Delta I_x}{I_x}\right)^2}$$

$$\Delta R_{H_2} = +7.14 \times 10^{-7} \sqrt{\left(\frac{5 \times 10^{-7}}{191 \times 10^{-7}}\right)^2 + \left(\frac{0.1}{134.0}\right)^2}$$

$$\underline{\Delta R_{H_2} = 0.19 \times 10^{-7} \; \frac{m^3}{C}}.$$

* <u>Least squared fitting</u> error :-

The linear fitting using least squares method of data points into an equation of the form $y = ax + b$.

Loss function minimized is.

$$\mathcal{L}(a, b) = \sum_{i=1}^{N} (\hat{y}_i - (ax_i + b))^2$$

$\hat{y}_i$ = true value
a, b - parameters.

Choosing optimal parameters a, b to minimize the loss function,

$$\frac{\partial \chi}{\partial a} = -2\sum_{i=1}^{N} x_i \left(y_i - (ax_i + b)\right)^2 = 0$$

N = no. of observations

$$\frac{\partial \chi}{\partial b} = -2\sum_{i=1}^{N} \left(y_i - (ax_i + b)\right)^2 = 0$$

$\{x_i, y_i\}_{i=1}^{N}$ - Data points

$$\Rightarrow \left\{ \begin{array}{l} a\sum_{i=1}^{N} x_i^2 + b\sum_{i=1}^{N} x_i = \sum_{i=1}^{N} x_i y_i \\ a\sum_{i=1}^{N} x_i + bN = \sum_{i=1}^{N} y_i \end{array} \right\}$$

Solving the system of linear equations & two unknowns gives a & b.

Error in y, $\sigma_y = \sqrt{\frac{1}{(N-2)} \sum_{i=1}^{N} \left(y_i - (ax_i + b)\right)^2}$

Error in a, $\sigma_a = \sigma_y \sqrt{\frac{N}{\Delta}}$

where $\Delta = N\sum_{i=1}^{N} x_i^2 - \left(\sum_{i=1}^{N} x_i\right)^2$

~~Er~~ Error in b, $\sigma_b = \sigma_y \sqrt{\frac{\sum_{i=1}^{N} x_i^2}{\Delta}}$

Results & Discussion :-

i) The Hall Coefficient of Bi was determined experimentally by analysing the slope of linear region of ~~the~~ Hall voltage vs Magnetic field plot.

for I_x = 62.2 mA, $R_{H_1} = (-6.62 \pm 0.16) \times 10^{-7} \frac{m^3}{C}$

for I_x = 134.0 mA, $R_{H_2} = (-7.14 \pm 0.19) \times 10^{-7} \frac{m^3}{C}$

ii) The order of magnitude of above values matches the typical literature values of Bi & the -ve sign indicates electrons to be the ~~ma~~ dominant carriers.

iii) A parabolic fit was performed over the cycle of applied Magnetic field in the $\left(\frac{\Delta R}{R}\right)$ (relative change in resistance) v/s H (applied magnetic field) since a quadratic nature of change was observed.

iv) A quadratic fit over the first quarter of the cycle shows the nature of dependence of $\left(\frac{\Delta R}{R}\right)$ on H.

v) The $\log\left(\frac{\Delta R}{R}\right)$ v/s $\log(H)$ plot exhibits an almost linear nature with minor deviations attributed to the sources of error discussed below:

vi) Resistance (R) calculated in absence of magnetic field

$$R = (0.370 \pm 0.005)\ m\Omega$$

Sources of Error :-

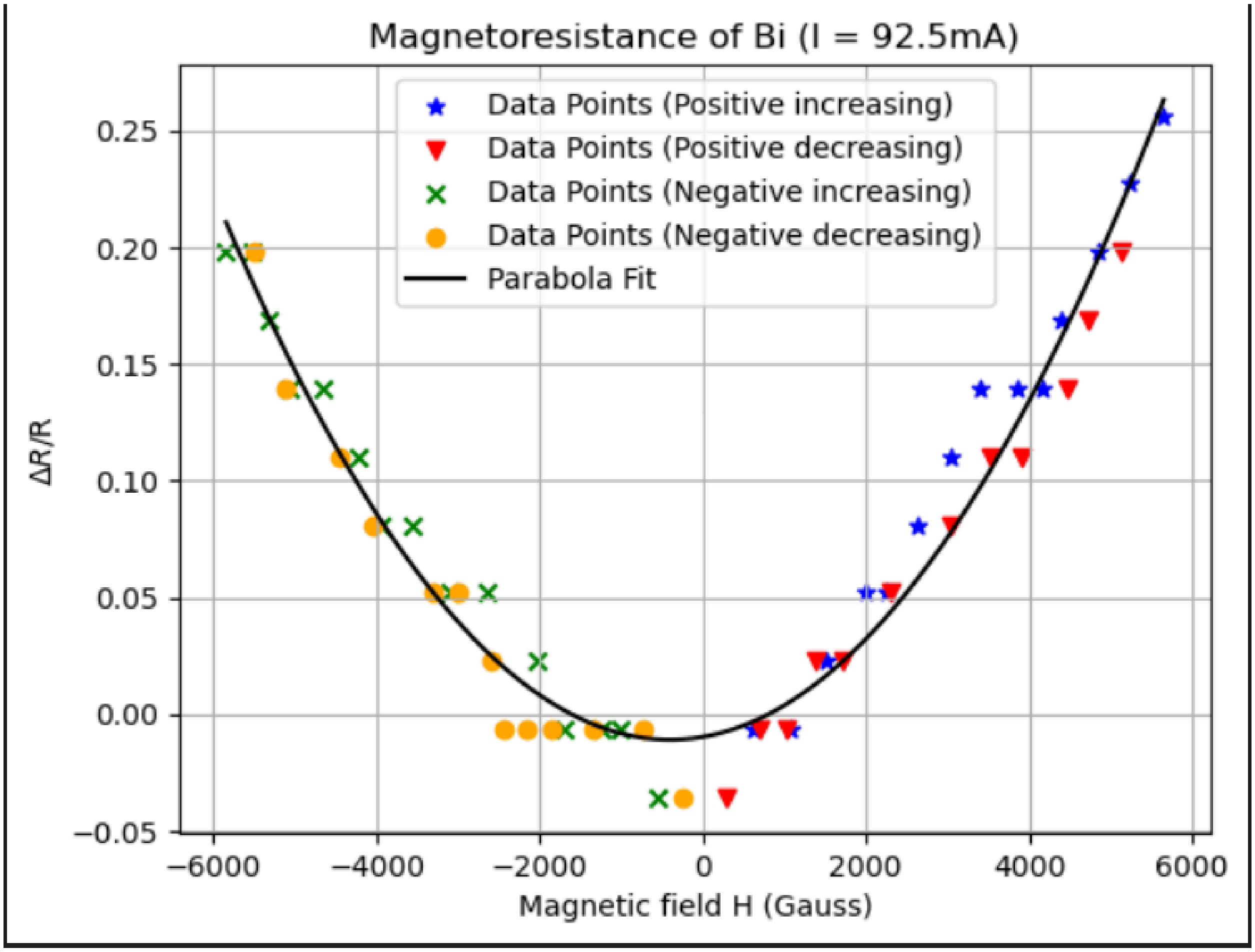
i) At high fields, deviations can be caused due to sample heating up, affecting carrier mobility.

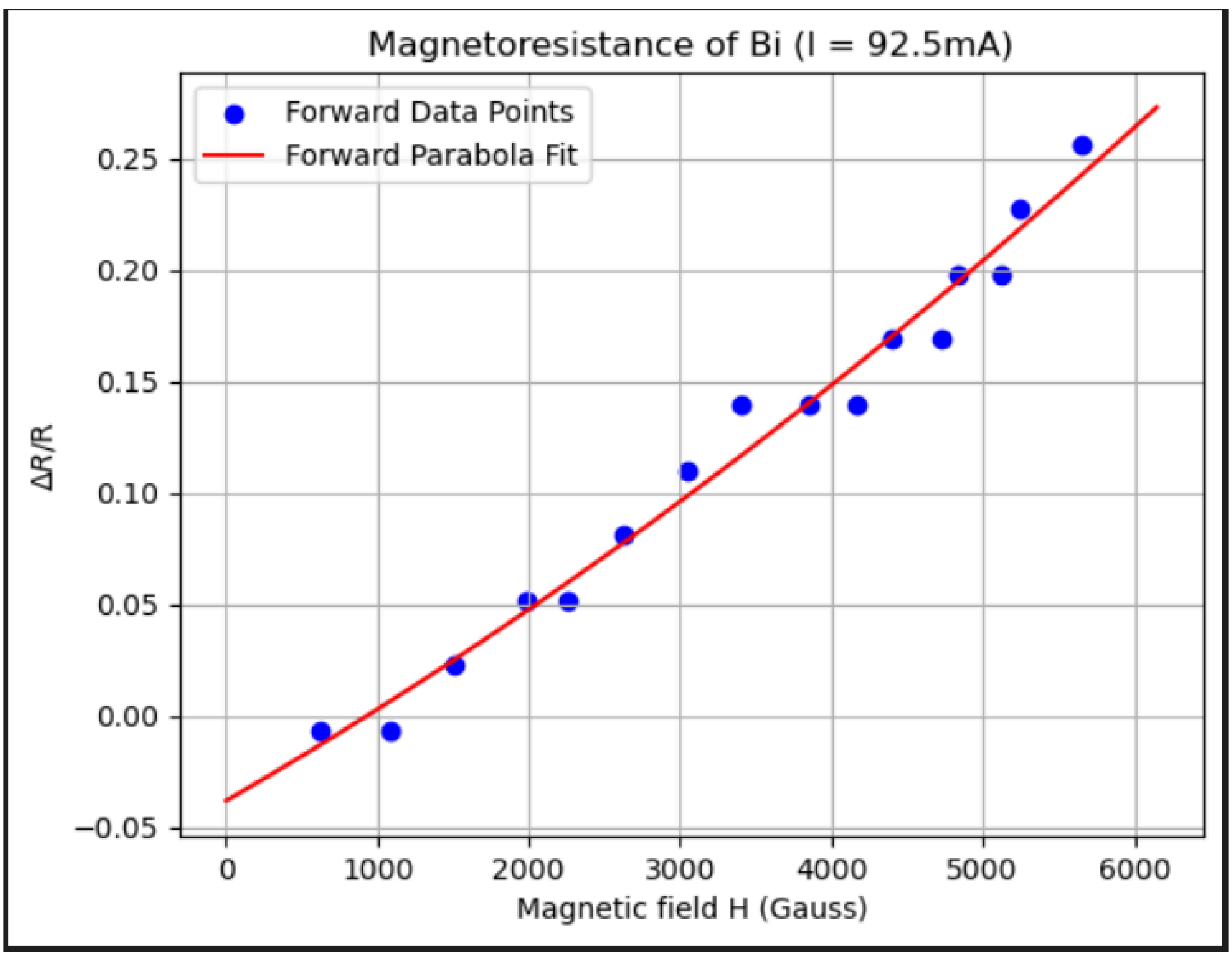
ii) Misalignment of probe wrt. magnetic field (must be exactly perpendicular)

iii) Assuming a dominant single carrier (e^-) in calculating Hall coefficient. We neglect hole contributions, even though Bi has equal e^- & hole densities.

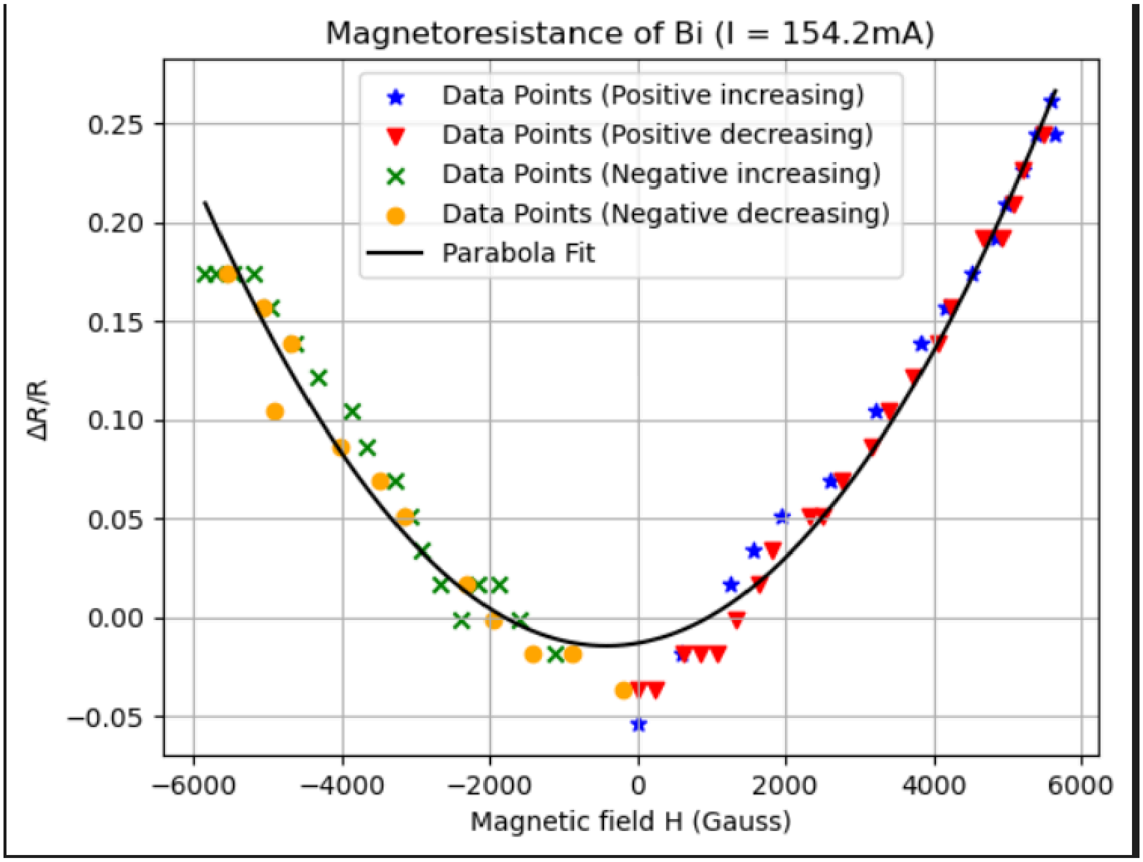
iv) Inhomogeneity in sample can cause errors, since in calculations, we assume a homogeneous sample.

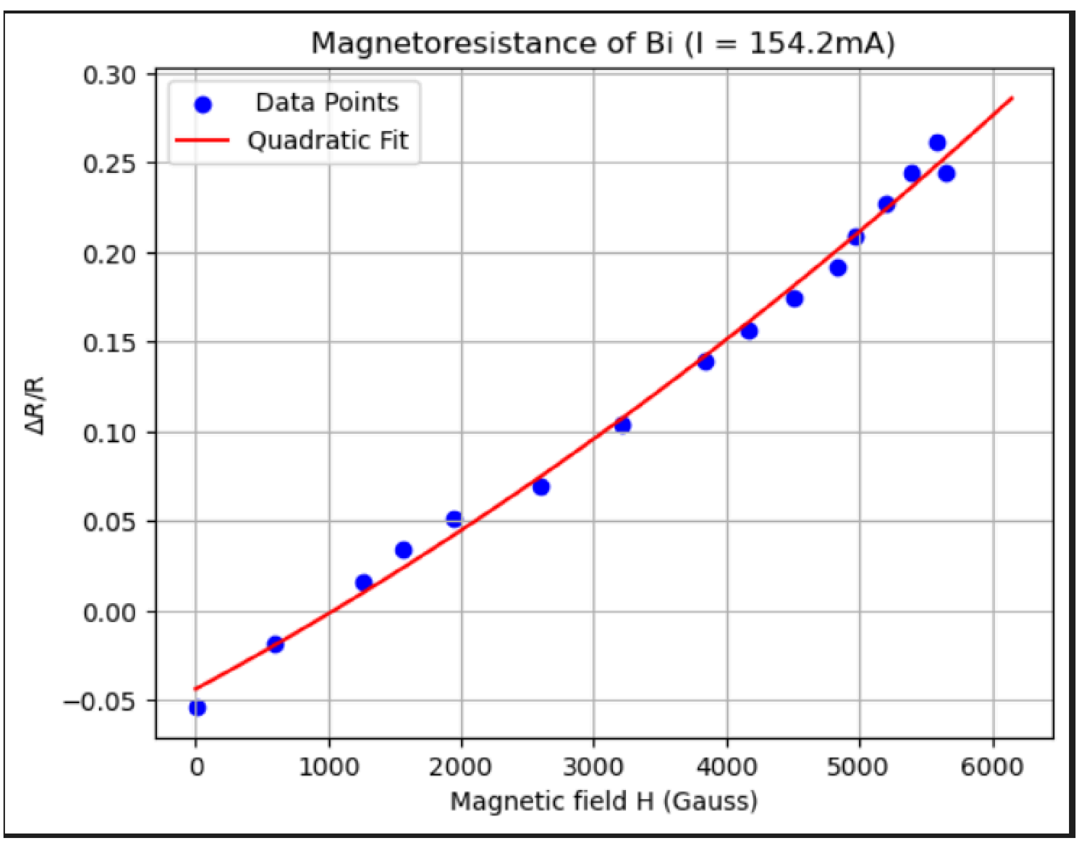
S.no.	Magnetic field (Gauss)	Hall Voltage (mV)	Rm (ohm)	ΔR/R	log(H)	log(ΔR/R)
1	618	0.034	0.0003675675676	-0.006574141709	617.966	
2	1078	0.034	0.0003675675676	-0.006574141709	1077.966	
3	1508	0.035	0.0003783783784	0.02264426589	1507.965	-3.787848621
4	1988	0.036	0.0003891891892	0.05186267348	1987.964	-2.959155948
5	2258	0.036	0.0003891891892	0.05186267348	2257.964	-2.959155948
6	2628	0.037	0.0004	0.08108108108	2627.963	-2.512305624
7	3048	0.038	0.0004108108108	0.1102994887	3047.962	-2.204555988
8	3398	0.039	0.0004216216216	0.1395178963	3397.961	-1.969562397
9	3858	0.039	0.0004216216216	0.1395178963	3857.961	-1.969562397
10	4168	0.039	0.0004216216216	0.1395178963	4167.961	-1.969562397
11	4398	0.04	0.0004324324324	0.1687363039	4397.96	-1.779418115
12	4838	0.041	0.0004432432432	0.1979547115	4837.959	-1.619717004
13	5238	0.042	0.0004540540541	0.2271731191	5237.958	-1.482042913
14	5648	0.043	0.0004648648649	0.2563915267	5647.957	-1.361049602
15	5118	0.041	0.0004432432432	0.1979547115	5117.959	-1.619717004
16	4728	0.04	0.0004324324324	0.1687363039	4727.96	-1.779418115
17	4468	0.039	0.0004216216216	0.1395178963	4467.961	-1.969562397
18	3898	0.038	0.0004108108108	0.1102994887	3897.962	-2.204555988
19	3528	0.038	0.0004108108108	0.1102994887	3527.962	-2.204555988
20	3038	0.037	0.0004	0.08108108108	3037.963	-2.512305624
21	2298	0.036	0.0003891891892	0.05186267348	2297.964	-2.959155948
22	1708	0.035	0.0003783783784	0.02264426589	1707.965	-3.787848621
23	1388	0.035	0.0003783783784	0.02264426589	1387.965	-3.787848621
24	1028	0.034	0.0003675675676	-0.006574141709	1027.966	
25	698	0.034	0.0003675675676	-0.006574141709	697.966	
26	288	0.033	0.0003567567568	-0.03579254931	287.967	
27	-542	0.033	0.0003567567568	-0.03579254931	-542.033	
28	-1002	0.034	0.0003675675676	-0.006574141709	-1002.034	
29	-1242	0.034	0.0003675675676	-0.006574141709	-1242.034	
30	-1702	0.034	0.0003675675676	-0.006574141709	-1702.034	
31	-2022	0.035	0.0003783783784	0.02264426589	-2022.035	-3.787848621
32	-2652	0.036	0.0003891891892	0.05186267348	-2652.036	-2.959155948
33	-3102	0.036	0.0003891891892	0.05186267348	-3102.036	-2.959155948
34	-3562	0.037	0.0004	0.08108108108	-3562.037	-2.512305624
35	-3932	0.037	0.0004	0.08108108108	-3932.037	-2.512305624
36	-4222	0.038	0.0004108108108	0.1102994887	-4222.038	-2.204555988
37	-4652	0.039	0.0004216216216	0.1395178963	-4652.039	-1.969562397
38	-5062	0.039	0.0004216216216	0.1395178963	-5062.039	-1.969562397
39	-5322	0.04	0.0004324324324	0.1687363039	-5322.04	-1.779418115
40	-5512	0.041	0.0004432432432	0.1979547115	-5512.041	-1.619717004
41	-5842	0.041	0.0004432432432	0.1979547115	-5842.041	-1.619717004
42	-5492	0.041	0.0004432432432	0.1979547115	-5492.041	-1.619717004
43	-5102	0.039	0.0004216216216	0.1395178963	-5102.039	-1.969562397
44	-4452	0.038	0.0004108108108	0.1102994887	-4452.038	-2.204555988
45	-4032	0.037	0.0004	0.08108108108	-4032.037	-2.512305624
46	-3302	0.036	0.0003891891892	0.05186267348	-3302.036	-2.959155948
47	-3012	0.036	0.0003891891892	0.05186267348	-3012.036	-2.959155948
48	-2592	0.035	0.0003783783784	0.02264426589	-2592.035	-3.787848621
49	-2432	0.034	0.0003675675676	-0.006574141709	-2432.034	
50	-2162	0.034	0.0003675675676	-0.006574141709	-2162.034	
51	-1842	0.034	0.0003675675676	-0.006574141709	-1842.034	
52	-1352	0.034	0.0003675675676	-0.006574141709	-1352.034	
53	-732	0.034	0.0003675675676	-0.006574141709	-732.034	
54	-242	0.033	0.0003567567568	-0.03579254931	-242.033	

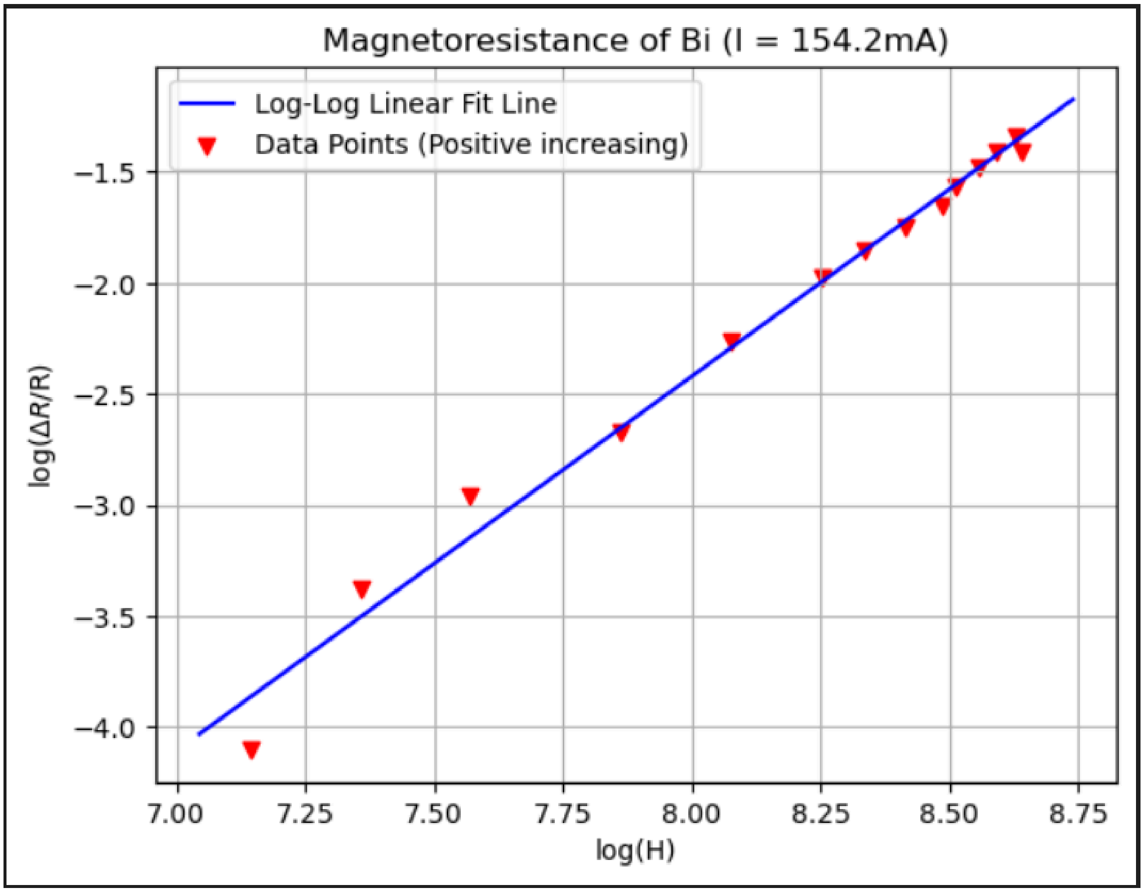

Magnetoresistance of Bi (I = 92.5mA)
Data Points (Positive increasing)
Data Points (Positive decreasing)
Data Points (Negative increasing)
Data Points (Negative decreasing)
Parabola Fit
ΔR/R
Magnetic field H (Gauss)

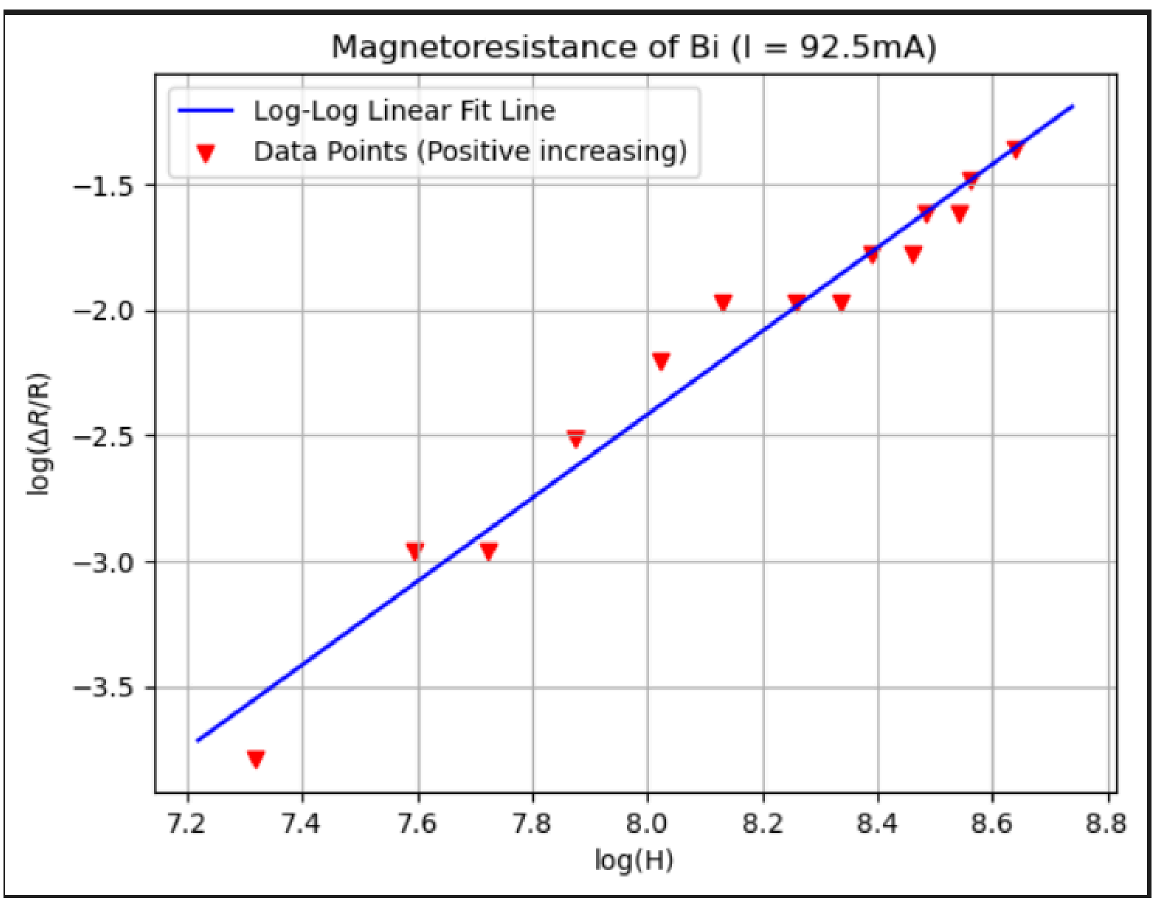

Magnetoresistance of Bi (I = 92.5mA)
Forward Data Points
Forward Parabola Fit
ΔR/R
Magnetic field H (Gauss)

S.no.	Magnetic field H (Gauss)	Hall Voltage (mV)	Rm (ohm)	ΔR/R	log(H)	log(ΔR/R)
1	8	0.054	0.0003501945525	-0.05352823641	7.946	
2	598	0.056	0.0003631647211	-0.01847372664	597.944	
3	1268	0.058	0.0003761348898	0.01658078312	1267.942	-4.099510898
4	1568	0.059	0.0003826199741	0.034108038	1567.941	-3.378222204
5	1938	0.06	0.0003891050584	0.05163529288	1937.94	-2.96354987
6	2598	0.061	0.0003955901427	0.06916254776	2597.939	-2.67129578
7	3218	0.063	0.0004085603113	0.1042170575	3217.937	-2.261279463
8	3838	0.065	0.0004215304799	0.1392715673	3837.935	-1.97132953
9	4168	0.066	0.0004280155642	0.1567988222	4167.934	-1.852791683
10	4508	0.067	0.0004345006485	0.174326077	4507.933	-1.746827727
11	4838	0.068	0.0004409857328	0.1918533319	4837.932	-1.651024095
12	4968	0.069	0.0004474708171	0.2093805868	4967.931	-1.563601693
13	5198	0.07	0.0004539559014	0.2269078417	5197.93	-1.483211328
14	5388	0.071	0.0004604409857	0.2444350966	5387.929	-1.408805459
15	5578	0.072	0.00046692607	0.2619623515	5577.928	-1.339554482
16	5648	0.071	0.0004604409857	0.2444350966	5647.929	-1.408805459
17	5488	0.071	0.0004604409857	0.2444350966	5487.929	-1.408805459
18	5208	0.07	0.0004539559014	0.2269078417	5207.93	-1.483211328
19	5088	0.069	0.0004474708171	0.2093805868	5087.931	-1.563601693
20	4928	0.068	0.0004409857328	0.1918533319	4927.932	-1.651024095
21	4678	0.068	0.0004409857328	0.1918533319	4677.932	-1.651024095
22	4228	0.066	0.0004280155642	0.1567988222	4227.934	-1.852791683
23	4058	0.065	0.0004215304799	0.1392715673	4057.935	-1.97132953
24	3738	0.064	0.0004150453956	0.1217443124	3737.936	-2.105832233
25	3388	0.063	0.0004085603113	0.1042170575	3387.937	-2.261279463
26	3178	0.062	0.000402075227	0.08668980264	3177.938	-2.445419019
27	2768	0.061	0.0003955901427	0.06916254776	2767.939	-2.67129578
28	2508	0.06	0.0003891050584	0.05163529288	2507.94	-2.96354987
29	2318	0.06	0.0003891050584	0.05163529288	2317.94	-2.96354987
30	1808	0.059	0.0003826199741	0.034108038	1807.941	-3.378222204
31	1628	0.058	0.0003761348898	0.01658078312	1627.942	-4.099510898
32	1328	0.057	0.0003696498054	-0.00094647176:	1327.943	
33	1088	0.056	0.0003631647211	-0.01847372664	1087.944	
34	838	0.056	0.0003631647211	-0.01847372664	837.944	
35	628	0.056	0.0003631647211	-0.01847372664	627.944	
36	248	0.055	0.0003566796368	-0.03600098153	247.945	
37	8	0.055	0.0003566796368	-0.03600098153	7.945	
38	-1112	0.056	0.0003631647211	-0.01847372664	-1112.056	
39	-1592	0.057	0.0003696498054	-0.00094647176:	-1592.057	
40	-1872	0.058	0.0003761348898	0.01658078312	-1872.058	-4.099510898
41	-2162	0.058	0.0003761348898	0.01658078312	-2162.058	-4.099510898
42	-2382	0.057	0.0003696498054	-0.00094647176:	-2382.057	
43	-2662	0.058	0.0003761348898	0.01658078312	-2662.058	-4.099510898
44	-2922	0.059	0.0003826199741	0.034108038	-2922.059	-3.378222204
45	-3082	0.06	0.0003891050584	0.05163529288	-3082.06	-2.96354987
46	-3292	0.061	0.0003955901427	0.06916254776	-3292.061	-2.67129578
47	-3672	0.062	0.000402075227	0.08668980264	-3672.062	-2.445419019
48	-3872	0.063	0.0004085603113	0.1042170575	-3872.063	-2.261279463
49	-4312	0.064	0.0004150453956	0.1217443124	-4312.064	-2.105832233
50	-4622	0.065	0.0004215304799	0.1392715673	-4622.065	-1.97132953
51	-4972	0.066	0.0004280155642	0.1567988222	-4972.066	-1.852791683
52	-5192	0.067	0.0004345006485	0.174326077	-5192.067	-1.746827727
53	-5482	0.067	0.0004345006485	0.174326077	-5482.067	-1.746827727
54	-5702	0.067	0.0004345006485	0.174326077	-5702.067	-1.746827727
55	-5842	0.067	0.0004345006485	0.174326077	-5842.067	-1.746827727
56	-5542	0.067	0.0004345006485	0.174326077	-5542.067	-1.746827727
57	-5072	0.066	0.0004280155642	0.1567988222	-5072.066	-1.852791683
58	-4682	0.065	0.0004215304799	0.1392715673	-4682.065	-1.97132953
59	-4902	0.063	0.0004085603113	0.1042170575	-4902.063	-2.261279463
60	-4012	0.062	0.000402075227	0.08668980264	-4012.062	-2.445419019
61	-3482	0.061	0.0003955901427	0.06916254776	-3482.061	-2.67129578
62	-3142	0.06	0.0003891050584	0.05163529288	-3142.06	-2.96354987
63	-2322	0.058	0.0003761348898	0.01658078312	-2322.058	-4.099510898
64	-1952	0.057	0.0003696498054	-0.00094647176:	-1952.057	
65	-1432	0.056	0.0003631647211	-0.01847372664	-1432.056	
66	-892	0.056	0.0003631647211	-0.01847372664	-892.056	
67	-192	0.055	0.0003566796368	-0.03600098153	-192.055	


Magnetoresistance of Bi (I = 154.2mA)
Data Points (Positive increasing)
Data Points (Positive decreasing)
Data Points (Negative increasing)
Data Points (Negative decreasing)
Parabola Fit
ΔR/R
Magnetic field H (Gauss)
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
−6000
−4000
−2000
0
2000
4000
6000


Magnetoresistance of Bi (I = 154.2mA)
Data Points
Quadratic Fit
ΔR/R
Magnetic field H (Gauss)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
0
1000
2000
3000
4000
5000
6000

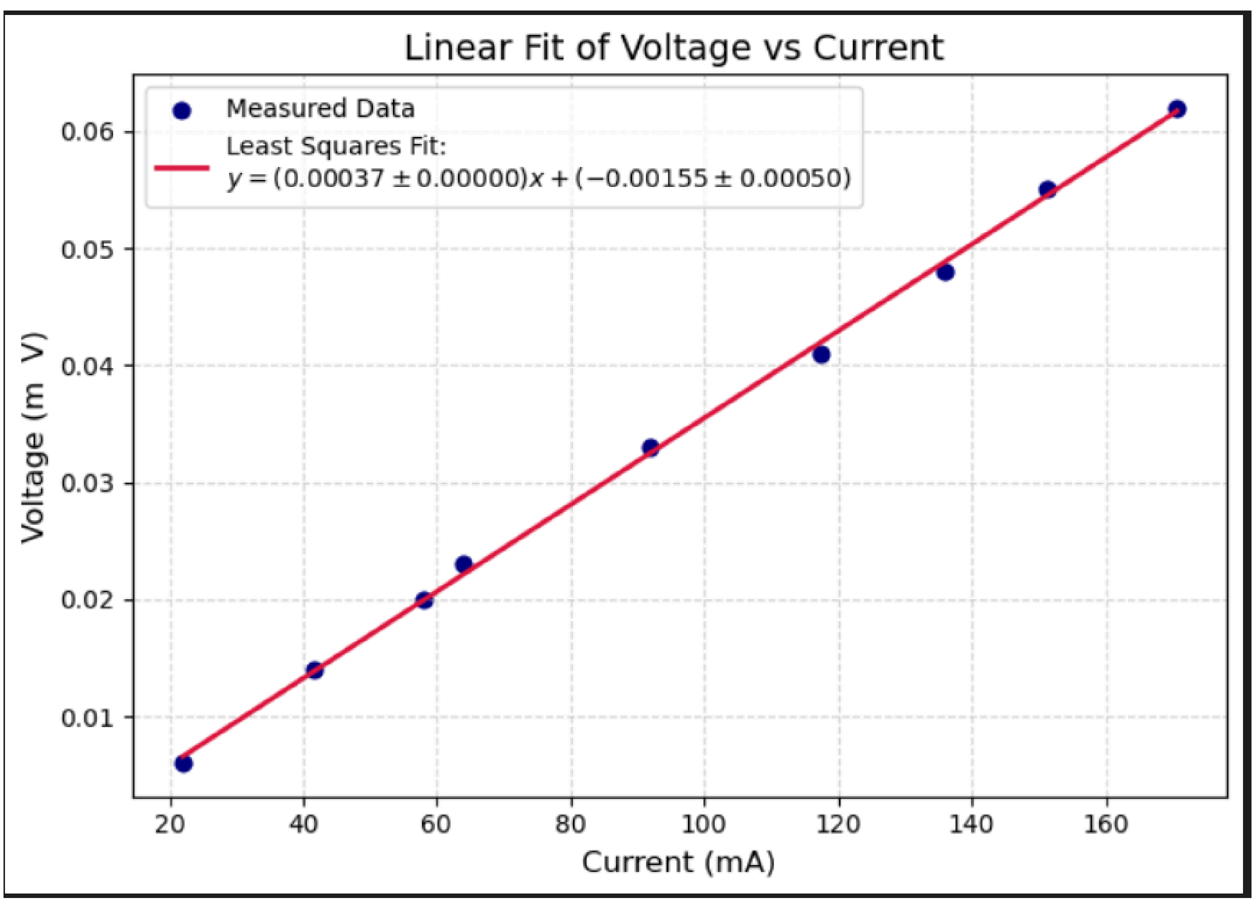

Magnetoresistance of Bi (I = 154.2mA)
Log-Log Linear Fit Line
Data Points (Positive increasing)
log(ΔR/R)
log(H)
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
7.00
7.25
7.50
7.75
8.00
8.25
8.50
8.75

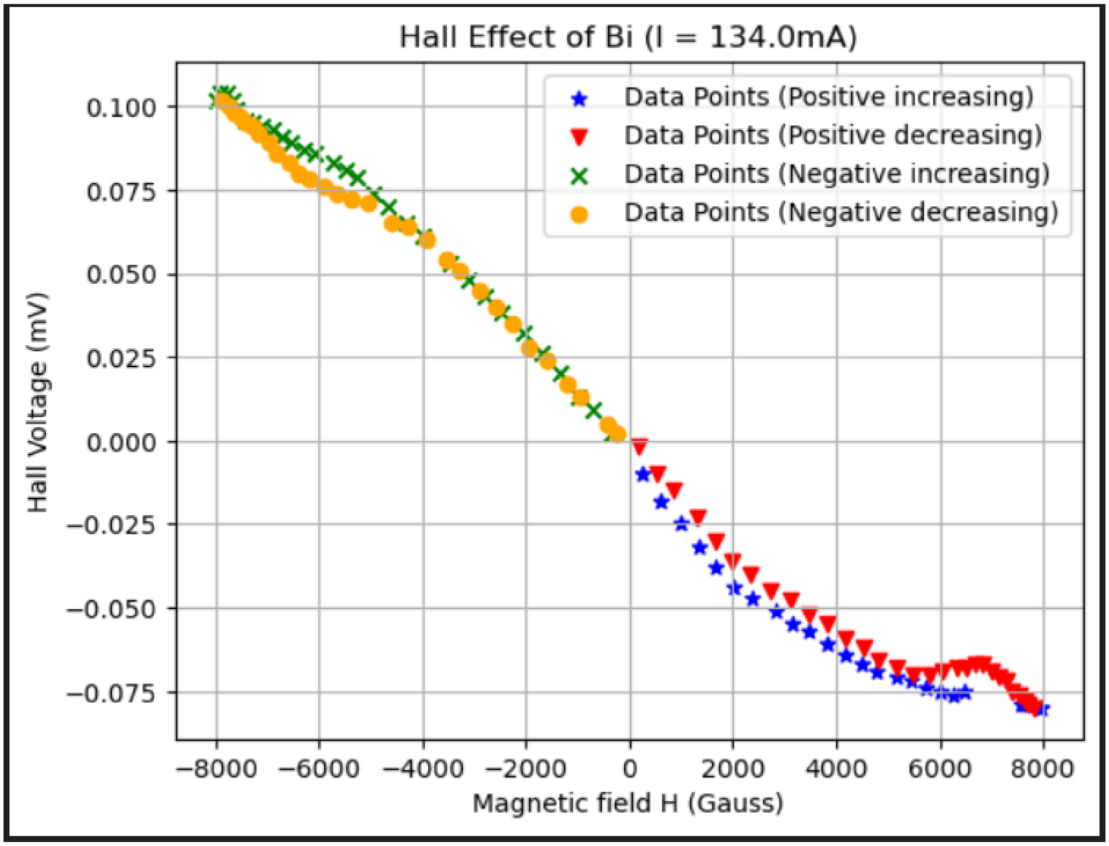

Magnetoresistance of Bi (I = 92.5mA)
Log-Log Linear Fit Line
Data Points (Positive increasing)
log(ΔR/R)
log(H)
−1.5
−2.0
−2.5
−3.0
−3.5
7.2
7.4
7.6
7.8
8.0
8.2
8.4
8.6
8.8

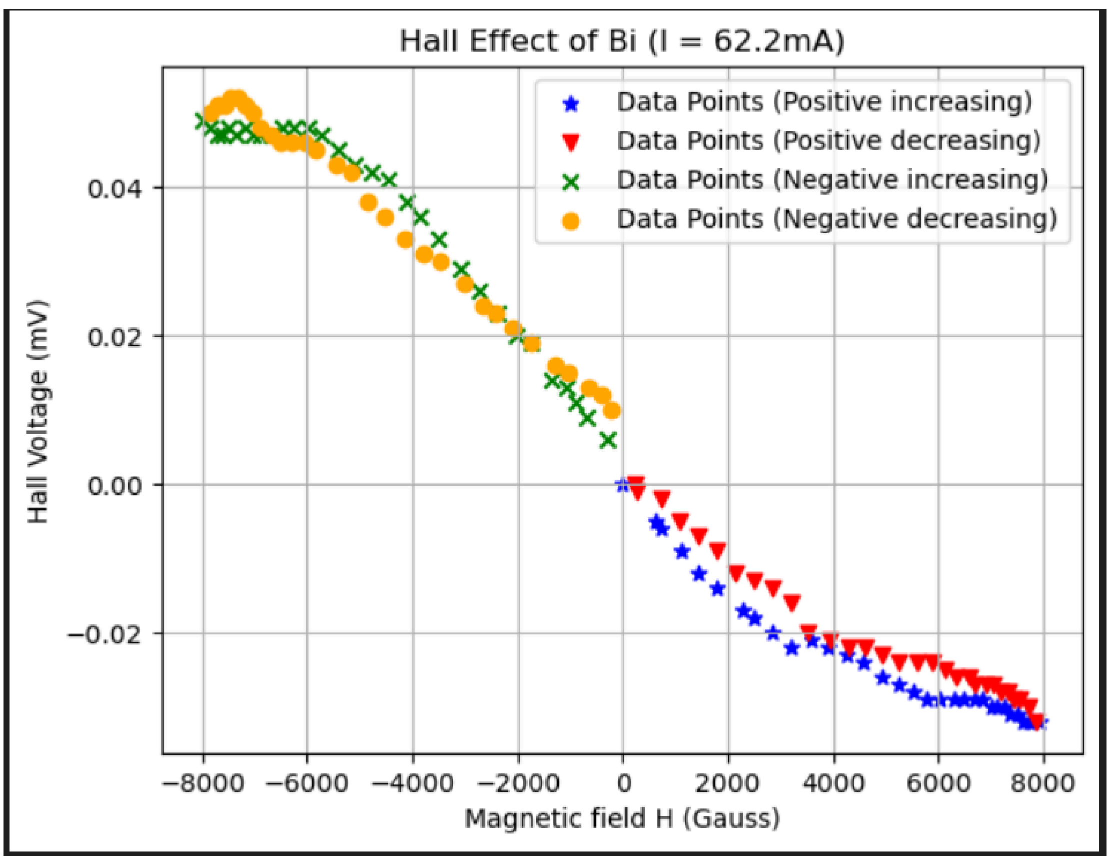
Input Data				
i	x	y	x^2	xy
1	22.0	0.006	484.0	0.132
2	41.6	0.014	1730.56	0.582
3	57.9	0.02	3352.41	1.158
4	63.9	0.023	4083.21	1.47
5	92.0	0.033	8464.0	3.036
6	117.5	0.041	13806.25	4.818
7	136.0	0.048	18496.0	6.528
8	151.3	0.055	22891.69	8.322
9	170.7	0.062	29138.49	10.583
Σ	852.9	0.302	102446.61	36.628

Measured vs Fitted Values		
x	y (measured)	y (fit)
22.0	0.006	0.007
41.6	0.014	0.014
57.9	0.02	0.02
63.9	0.023	0.022
92.0	0.033	0.033
117.5	0.041	0.042
136.0	0.048	0.049
151.3	0.055	0.054
170.7	0.062	0.062

Fit Results & Statistical Errors		
Parameter	Value	Uncertainty
Slope (a_1)	0.00037	±0.00000
Intercept (a_0)	-0.00155	±0.00050
σ_y (Std. Error)	0.00069	
Δ (delta)	194581.08000	



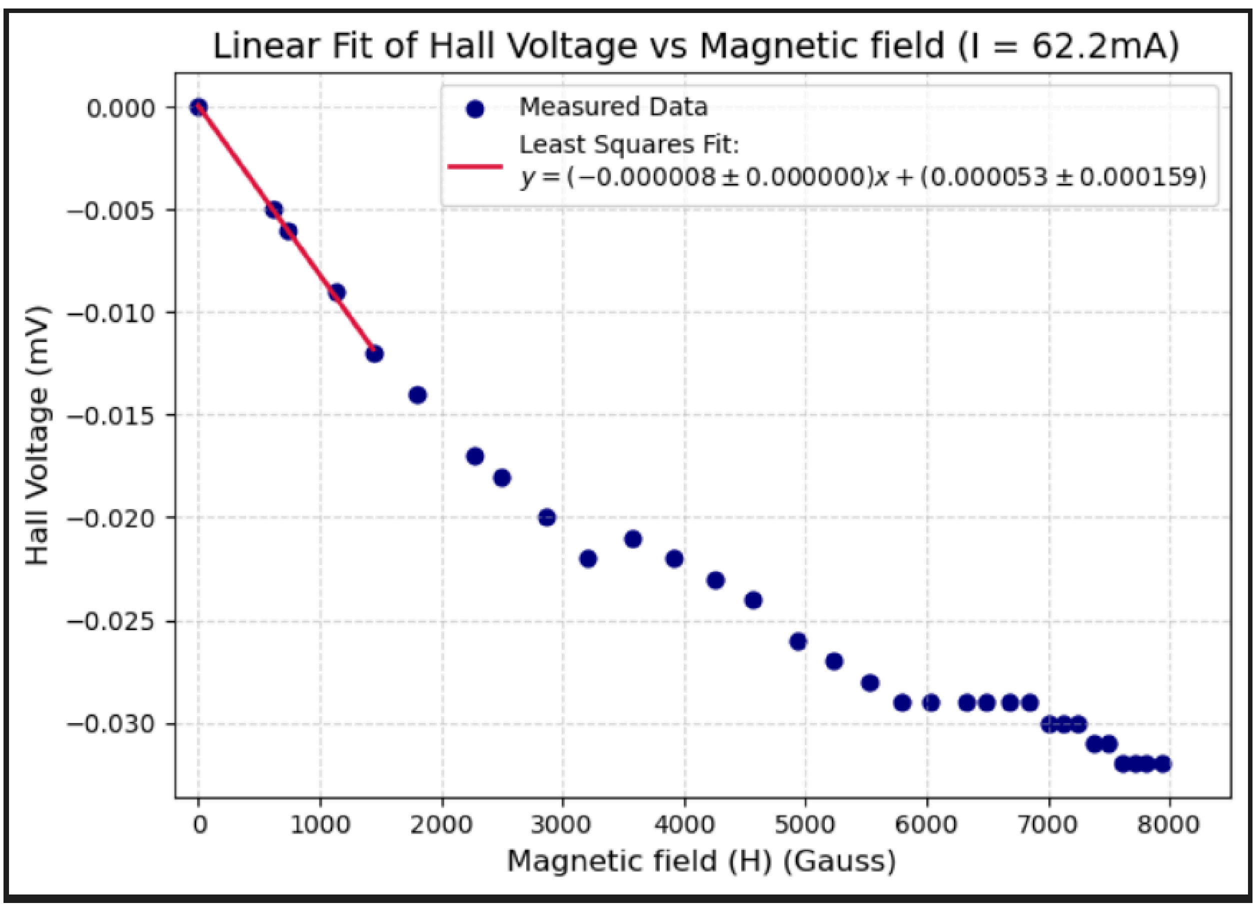

Hall Effect of Bi (I = 134.0mA)
Data Points (Positive increasing)
Data Points (Positive decreasing)
Data Points (Negative increasing)
Data Points (Negative decreasing)
Hall Voltage (mV)
0.100
0.075
0.050
0.025
0.000
−0.025
−0.050
−0.075
−8000
−6000
−4000
−2000
0
2000
4000
6000
8000
Magnetic field H (Gauss)


Hall Effect of Bi (I = 62.2mA)
Data Points (Positive increasing)
Data Points (Positive decreasing)
Data Points (Negative increasing)
Data Points (Negative decreasing)
Hall Voltage (mV)
0.04
0.02
0.00
−0.02
−8000
−6000
−4000
−2000
0
2000
4000
6000
8000
Magnetic field H (Gauss)

Input Data				
i	x	y	x^2	xy
1	0	0.0	0	0.0
2	610	-0.005	372100	-3.05
3	740	-0.006	547600	-4.44
4	1130	-0.009	1276900	-10.17
5	1440	-0.012	2073600	-17.28
Σ	3920	-0.032	4270200	-34.94

Measured vs Fitted Values		
x	y (measured)	y (fit)
0	0.0	0.0
610	-0.005	-0.005
740	-0.006	-0.006
1130	-0.009	-0.009
1440	-0.012	-0.012

Fit Results & Statistical Errors		
Parameter	Value	Uncertainty
Slope (a_1)	-0.000008	±0.000000
Intercept (a_0)	0.000053	±0.000159
σ_y (Std. Error)	0.000189	
Δ (delta)	5984600.000000	



Input Data				
i	x	y	x^2	xy
1	260	-0.01	67600	-2.6
2	620	-0.018	384400	-11.16
3	980	-0.025	960400	-24.5
4	1330	-0.032	1768900	-42.56
5	1680	-0.038	2822400	-63.84
6	2030	-0.044	4120900	-89.32
Σ	6900	-0.167	10124600	-233.98

Measured vs Fitted Values		
x	y (measured)	y (fit)
260	-0.01	-0.011
620	-0.018	-0.018
980	-0.025	-0.025
1330	-0.032	-0.031
1680	-0.038	-0.038
2030	-0.044	-0.045

Fit Results & Statistical Errors		
Parameter	Value	Uncertainty
Slope (a_1)	-0.000019	±0.000000
Intercept (a_0)	-0.005811	±0.000603
σ_y (Std. Error)	0.000687	
Δ (delta)	13137600.000000