Measurement of the Hall Coefficient, Carrier Density, and Mobility in a Hall probe of Bismiuth

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The Hall effect in a semiconductor was investigated to determine its fundamental electronic properties. By measuring the Hall voltage as a function of current under three different transverse magnetic fields, the Hall coefficient (R_H), charge carrier concentration (n), and Hall mobility (μ_H) were calculated. The magnetic field was calibrated against the electromagnet current, yielding a constant of $(3.148 \pm 0.005) \times 10^3$ G/A. The consistently positive sign of the Hall coefficient confirmed the sample is p-type (hole-dominated).

I. INTRODUCTION

When a current flows through a conductor in the presence of a perpendicular magnetic field, a voltage is generated in the direction transverse to both the current and the magnetic field. This phenomenon, known as the Hall effect, is a powerful tool for characterizing the electronic properties of materials, especially semiconductors. The primary objectives of this experiment are to measure the Hall voltage (V_H), determine the Hall coefficient (R_H) to identify the majority charge carriers, and calculate the carrier concentration (n) and Hall mobility (μ_H).

II. THEORY

When an electric current I passes through a semiconductor sample along the x-axis in the presence of an external magnetic field B applied along the z-axis, a transverse potential difference develops across the y-axis. This effect arises due to the Lorentz force acting on the moving charge carriers. The Hall voltage V_H across a sample of thickness z is given by:

$$V_H = R_H \frac{IB}{z} \tag{1}$$

where R_H is the Hall coefficient. R_H is related to the charge carrier concentration n by:

$$R_H = \frac{1}{nq} \tag{2}$$

where q is the elementary charge. The sign of R_H indicates the type of charge carrier. Another crucial parameter is the Hall mobility, μ_H, which describes how quickly charge carriers move in an electric field. It is related to R_H and the material's resistivity, ρ:

$$\mu_H = \frac{|R_H|}{\rho} \tag{3}$$

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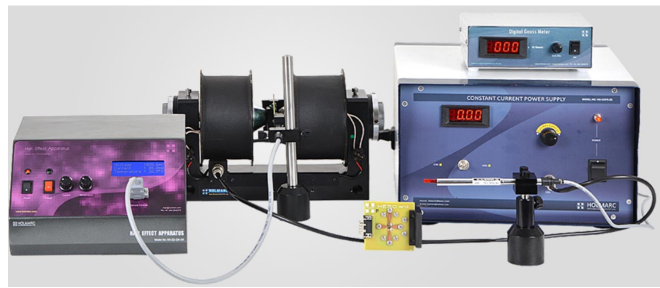


FIG. 1. Picture of the Equipment

III. EXPERIMENTAL SETUP

The setup includes a semiconductor sample of thickness $z = 1.38 \times 10^{-3}$ m, an electromagnet with a power supply, a Gaussmeter, a constant current source for the sample, and a voltmeter. The sample's resistivity was given as $\rho = 1.29 \times 10^{-6}\,\Omega \cdot$ m.

IV. PROCEDURE

First, the electromagnet was calibrated by measuring the magnetic field B for a range of coil currents, I_{coil}. Next, the semiconductor sample was placed in the magnetic field. For three fixed magnetic fields, the sample current I was varied, and the corresponding Hall voltage V_H was recorded. The raw data for these measurements are provided in the Appendix.

V. DATA AND ANALYSIS

A. Calibration of Electromagnet

A linear fit ($y = mx$) to the calibration data (see Appendix, Table II) established the relationship between the coil current and the magnetic field. The slope from the fit gives the calibration constant $m_B = (3.148 \pm 0.005) \times$

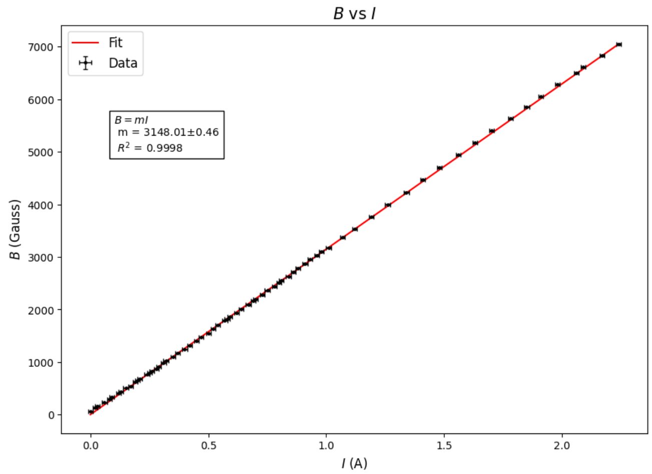


FIG. 2. Magnetic field callibration

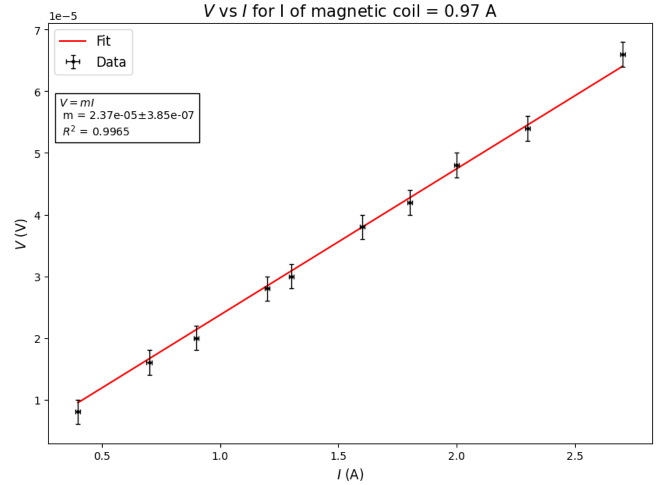


FIG. 4. V vs I for first data

10^3 G/A, where the error is the square root of the single element in the covariance matrix from the fit.

FIG. 3. Calibration curve of the electromagnet, showing magnetic field B as a function of coil current I_{coil}.

B. Calculation of R_H, n, and μ_H

For each fixed magnetic field, a plot of V_H vs. I was created. The slope of the linear fit, $m = V_H/I$, was used to find R_H. The magnetic field for each case is calculated as $B = m_B \times I_{coil}$, with error $\Delta B = \Delta m_B \times I_{coil}$.

1. *Case 1: $I_{coil} = 0.97$ A*

The measured parameters are:

- Magnetic Field: $B_1 = (3.054 \pm 0.005) \times 10^{-1}\,\mathrm{T}$
- Slope: $m_1 = (2.372 \pm 0.039) \times 10^{-5}\,\mathrm{V/A}$

Hall Coefficient (R_{H1})

$$R_{H1} = \frac{m_1 z}{B_1} = \frac{(2.372 \times 10^{-5})(1.38 \times 10^{-3})}{3.054 \times 10^{-1}} = 1.072 \times 10^{-7}\,\mathrm{m^3/C}$$

$$\Delta R_{H1} = |R_{H1}|\sqrt{\left(\frac{\Delta m_1}{m_1}\right)^2 + \left(\frac{\Delta B_1}{B_1}\right)^2} = |1.072 \times 10^{-7}|\sqrt{(0.0162)^2 + (0.00015)^2} = 1.74 \times 10^{-9}\,\mathrm{m^3/C}$$

Result: $R_{H1} = (1.072 \pm 0.002) \times 10^{-7}\,\mathrm{m^3/C}$.

Carrier Density (n_1)

$$n_1 = \frac{1}{|R_{H1}|q} = \frac{1}{(1.072 \times 10^{-7})(1.602 \times 10^{-19})} = 5.83 \times 10^{25}\,\mathrm{m^{-3}}$$

$$\Delta n_1 = |n_1|\left(\frac{\Delta R_{H1}}{|R_{H1}|}\right) = |5.83\text{e}25|\left(\frac{1.74\text{e-}9}{1.072\text{e-}7}\right) = 9.46 \times 10^{23}\,\mathrm{m^{-3}}$$

Result: $n_1 = (5.83 \pm 0.09) \times 10^{25}\,\mathrm{m^{-3}}$.

Hall Mobility (μ_{H1})

$$\mu_{H1} = \frac{|R_{H1}|}{\rho} = \frac{1.072 \times 10^{-7}}{1.29 \times 10^{-6}} = 8.31 \times 10^{-2}\,\mathrm{m^2/(V \cdot s)}$$

$$\Delta \mu_{H1} = |\mu_{H1}|\left(\frac{\Delta R_{H1}}{|R_{H1}|}\right) = |8.31\text{e-}2|\left(\frac{1.74\text{e-}9}{1.072\text{e-}7}\right) = 1.35 \times 10^{-3}\,\mathrm{m^2/(V \cdot s)}$$

Result: $\mu_{H1} = (8.31 \pm 0.14) \times 10^{-2}\,\mathrm{m^2/(V \cdot s)}$.

2. *Case 2: $I_{coil} = 1.53$ A*

- Magnetic Field: $B_2 = (4.816 \pm 0.008) \times 10^{-1}\,\mathrm{T}$
- Slope: $m_2 = (2.527 \pm 0.041) \times 10^{-5}\,\mathrm{V/A}$

Hall Coefficient (R_{H2})

$$R_{H2} = 7.24 \times 10^{-8}\,\mathrm{m^3/C}$$
$$\Delta R_{H2} = 1.19 \times 10^{-9}\,\mathrm{m^3/C}$$

Result: $R_{H2} = (7.24 \pm 0.12) \times 10^{-8}\,\mathrm{m^3/C}$.

Carrier Density (n_2)

$$n_2 = 8.63 \times 10^{25}\,\mathrm{m^{-3}}$$
$$\Delta n_2 = 1.41 \times 10^{24}\,\mathrm{m^{-3}}$$

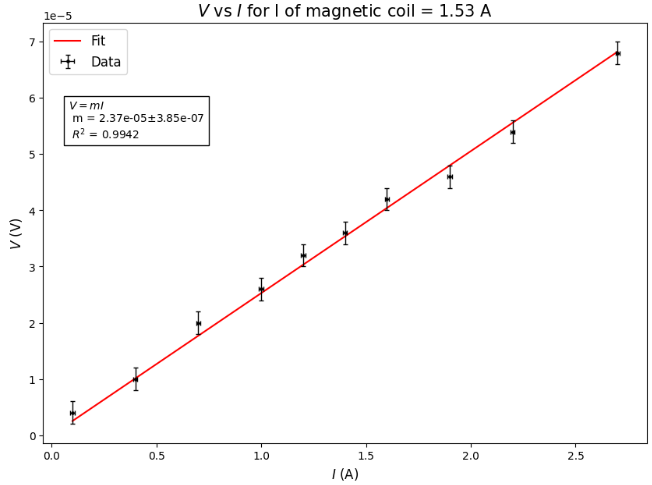


FIG. 5. V vs I for second data

Result: $n_2 = (8.63 \pm 0.14) \times 10^{25}\,\mathrm{m}^{-3}$.

Hall Mobility (μ_{H2})

$$\mu_{H2} = 5.61 \times 10^{-2}\,\mathrm{m}^2/(\mathrm{V}\cdot\mathrm{s})$$
$$\Delta\mu_{H2} = 9.19 \times 10^{-4}\,\mathrm{m}^2/(\mathrm{V}\cdot\mathrm{s})$$

Result: $\mu_{H2} = (5.61 \pm 0.09) \times 10^{-2}\,\mathrm{m}^2/(\mathrm{V}\cdot\mathrm{s})$.

3. Case 3: $I_{coil} = 1.21$ A

- Magnetic Field: $B_3 = (3.809 \pm 0.006) \times 10^{-1}\,\mathrm{T}$
- Slope: $m_3 = (2.594 \pm 0.043) \times 10^{-5}\,\mathrm{V/A}$

Hall Coefficient (R_{H3})

$$R_{H3} = 9.40 \times 10^{-8}\,\mathrm{m}^3/\mathrm{C}$$
$$\Delta R_{H3} = 1.56 \times 10^{-9}\,\mathrm{m}^3/\mathrm{C}$$

Result: $R_{H3} = (9.40 \pm 0.16) \times 10^{-8}\,\mathrm{m}^3/\mathrm{C}$.

Carrier Density (n_3)

$$n_3 = 6.65 \times 10^{25}\,\mathrm{m}^{-3}$$
$$\Delta n_3 = 1.11 \times 10^{24}\,\mathrm{m}^{-3}$$

Result: $n_3 = (6.65 \pm 0.11) \times 10^{25}\,\mathrm{m}^{-3}$.

Hall Mobility (μ_{H3})

$$\mu_{H3} = 7.28 \times 10^{-2}\,\mathrm{m}^2/(\mathrm{V}\cdot\mathrm{s})$$
$$\Delta\mu_{H3} = 1.21 \times 10^{-3}\,\mathrm{m}^2/(\mathrm{V}\cdot\mathrm{s})$$

Result: $\mu_{H3} = (7.28 \pm 0.12) \times 10^{-2}\,\mathrm{m}^2/(\mathrm{V}\cdot\mathrm{s})$.

VI. LIMITATIONS

1. **Experimental setup constraints:** Variations in the coil current did not produce significant changes in the probe current, suggesting possible limitations due to coupling or the power supply.

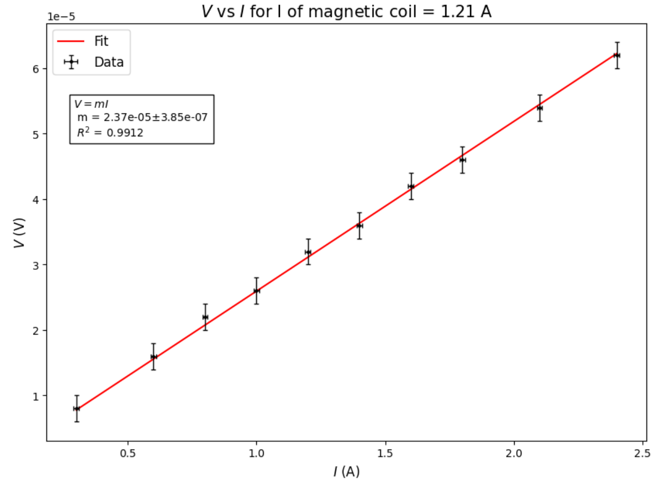


FIG. 6. V vs I for the third data

2. **Magnetic field uniformity:** Any non-uniformity of the magnetic field across the sample can introduce systematic deviations in the measured Hall voltage.
3. **Contact quality:** Imperfect ohmic contacts may add unwanted resistance or cause voltage offsets, thereby affecting the accuracy of the measurement.
4. **Temperature sensitivity:** Since semiconductor properties are highly temperature dependent, self-heating during measurements can alter carrier mobility and concentration.
5. **Geometrical accuracy:** The sample thickness is a major source of uncertainty, as it directly influences the calculation of the Hall coefficient R_H.

VII. RESULTS AND CONCLUSION

The experiment successfully characterized a p-type semiconductor sample. The results from the three trials are consistent and are summarized in Table I.

TABLE I. Summary of final calculated values with uncertainties.

B ($\times 10^{-1}$ T)	R_H ($10^{-8}\mathrm{m}^3/\mathrm{C}$)	n ($10^{25}\mathrm{m}^{-3}$)	μ_H ($10^{-2}\mathrm{m}^2/\mathrm{Vs}$)
3.054	10.72 ± 0.17	5.83 ± 0.09	8.31 ± 0.14
4.816	7.24 ± 0.12	8.63 ± 0.14	5.61 ± 0.09
3.809	9.40 ± 0.16	6.65 ± 0.11	7.28 ± 0.12

The positive Hall coefficient confirms that holes are the majority charge carriers. The weighted average values for the Hall coefficient, carrier density, and Hall mobility provide a robust characterization of the material. In conclusion, the experiment validates the theoretical model of the Hall effect and demonstrates its practical application in determining key semiconductor parameters.

[1] IISER Pune Lab Manual

Appendix A: Data Tables

TABLE II. Raw data for the calibration of the electromagnet.

I (A)	B (G)	I (A)	B (G)	I (A)	B (G)	I (A)	B (G)
0.00	55	0.47	1474	0.93	2950	1.56	4940
0.02	126	0.50	1549	0.96	3030	1.63	5170
0.03	160	0.52	1627	0.98	3100	1.70	5400
0.06	227	0.54	1703	1.01	3180	1.78	5630
0.08	298	0.57	1784	1.07	3370	1.85	5860
0.09	332	0.58	1820	1.12	3530	1.91	6050
0.12	401	0.59	1858	1.19	3760	1.98	6280
0.13	437	0.62	1936	1.26	4000	2.06	6500
0.15	508	0.64	2010	1.34	4230	2.09	6610
0.17	543	0.67	2090	1.41	4470	2.17	6830
0.19	617	0.69	2170	1.48	4700	2.24	7050
0.20	652	0.70	2200				
0.21	686	0.73	2280				
0.24	760	0.75	2360				
0.25	796	0.78	2440				
0.26	831	0.80	2510				
0.28	871	0.81	2550				
0.29	907	0.84	2630				
0.31	980	0.86	2710				
0.32	1020	0.88	2790				
0.35	1094	0.91	2870				
0.37	1169						
0.40	1244						
0.42	1320						
0.45	1396						

TABLE III. Observed values of Hall Voltage V_H at a constant coil current $I_{coil} = 0.97\,\mathrm{A}$.

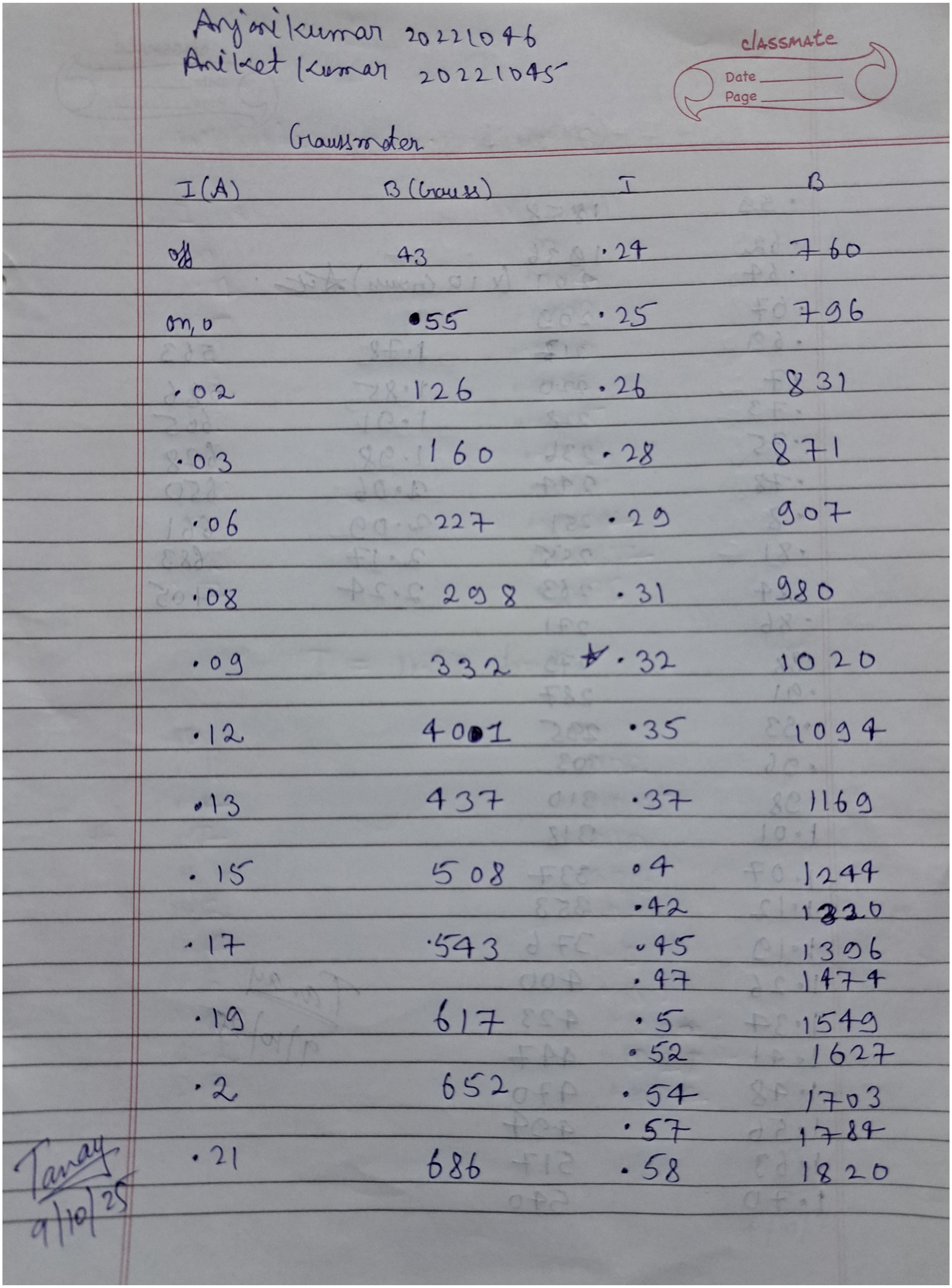
I (A)	$V_{(\mathrm{x2mV})}$	V_H (V)
0.0	0.000	0.000000
0.4	0.004	0.000008
0.7	0.008	0.000016
0.9	0.010	0.000020
1.2	0.014	0.000028
1.3	0.015	0.000030
1.6	0.019	0.000038
1.8	0.021	0.000042
2.0	0.024	0.000048
2.3	0.027	0.000054
2.7	0.033	0.000066

TABLE IV. Observed values of Hall Voltage V_H at a constant coil current $I_{coil} = 1.53\,\mathrm{A}$.

I (A)	$V_{(\mathrm{x2mV})}$	V_H (V)
0.0	0.000	0.000000
0.1	0.002	0.000004
0.4	0.005	0.000010
0.7	0.010	0.000020
1.0	0.013	0.000026
1.2	0.016	0.000032
1.4	0.018	0.000036
1.6	0.021	0.000042
1.9	0.023	0.000046
2.2	0.027	0.000054
2.7	0.034	0.000068

TABLE V. Observed values of Hall Voltage V_H at a constant coil current $I_{coil} = 1.21\,\mathrm{A}$.

I (A)	$V_{(\mathrm{x2mV})}$	V_H (V)
0.0	0.000	0.000000
0.3	0.004	0.000008
0.6	0.008	0.000016
0.8	0.011	0.000022
1.0	0.013	0.000026
1.2	0.016	0.000032
1.4	0.018	0.000036
1.6	0.021	0.000042
1.8	0.023	0.000046
2.1	0.027	0.000054
2.4	0.031	0.000062



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Gaussmeter

I(A)	B (Gauss)	I	B
off	43	.24	760
on, 0	55	.25	796
.02	126	.26	831
.03	160	.28	871
.06	227	.29	907
.08	298	.31	980
.09	332	.32	1020
.12	401	.35	1094
.13	437	.37	1169
.15	508	.4	1244
		.42	1320
.17	543	.45	1396
		.47	1474
.19	617	.5	1549
		.52	1627
.2	652	.54	1703
		.57	1784
.21	686	.58	1820

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FIG. 7. Data

.59	1858		
.62	1936		
.64	201 (x 10 Gauss) Att.		
.67	209		
.69	217	1.78	563
.7	220	1.85	586
.73	228	1.91	605
.75	236	1.98	628
.78	244	2.06	650
.8	251	2.09	661
.81	255	2.17	683
.84	263	2.24	705
.86	271		
.88	279		
.91	287		
.93	295		
.96	303		
.98	310		
1.01	318		
1.07	337		
1.12	353		
1.19	376		
1.26	400		
1.34	423		
1.41	447		
1.48	470		
1.56	494		
1.63	517		
1.70	540		

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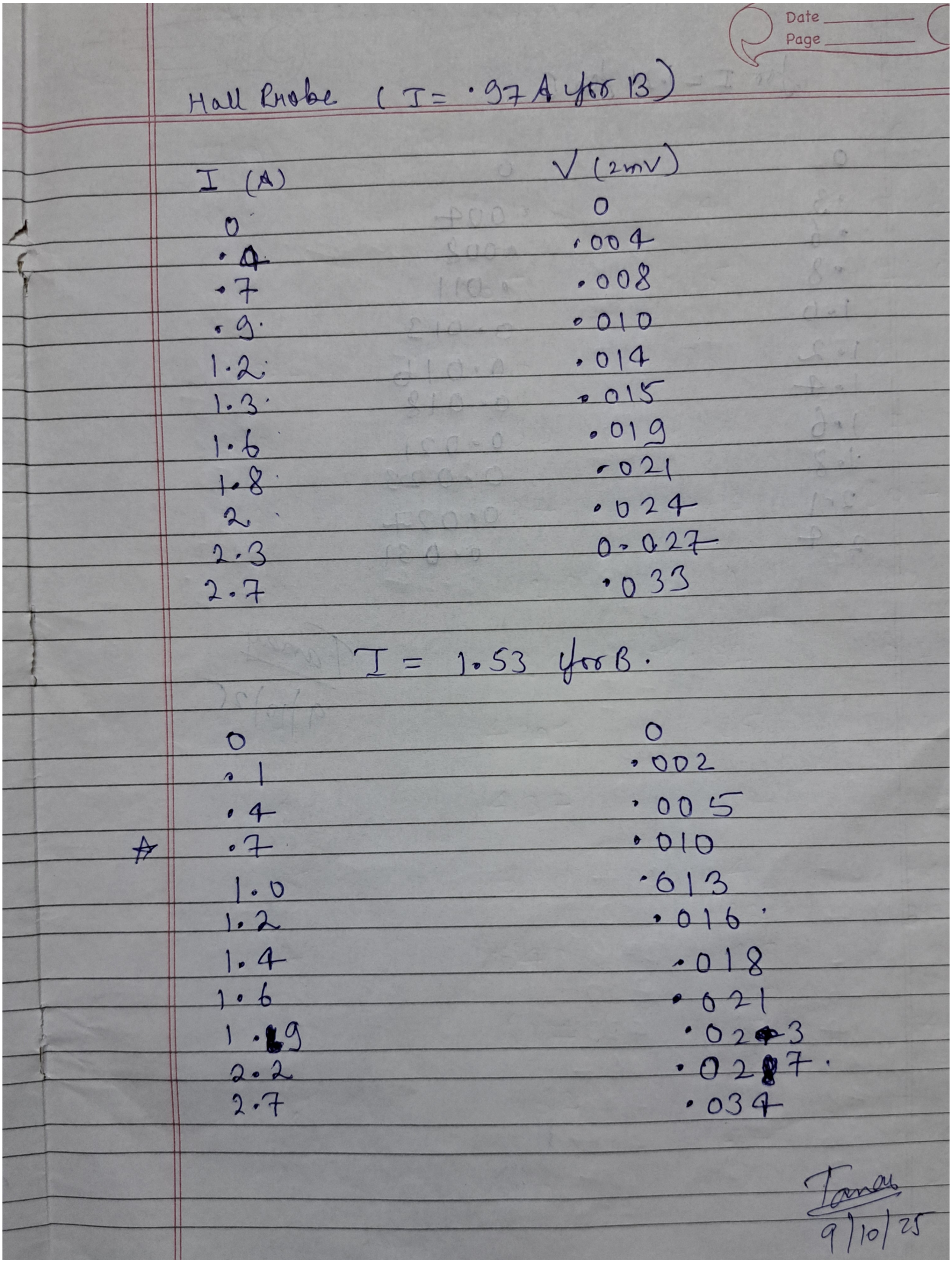
FIG. 8. Data



Hall Probe (I = .97 A for B)

I (A)	V (2mV)
0	0
.4	.004
.7	.008
.9	.010
1.2	.014
1.3	.015
1.6	.019
1.8	.021
2	.024
2.3	0.027
2.7	.033

I = 1.53 for B.

0	0
.1	.002
.4	.005
.7	.010
1.0	.013
1.2	.016
1.4	.018
1.6	.021
1.9	.023
2.2	.027
2.7	.034

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FIG. 9. Data

for I = 1.21 for B

0	0
.3	.004
.6	.008
.8	.011
1.0	0.013
1.2	0.016
1.4	0.018
1.6	0.021
1.8	0.023
2.1	0.027
2.4	0.031

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FIG. 10. Data