Hall effect of semiconductors

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In this experiment, we investigate the Hall effect of semiconductors, specifically the value of the Hall coefficient for both n- and p-type germanium samples at room temperature. The observed values are found to be $2.01 \pm 0.017\text{cm}^3$ coulomb^{-1} and $3.02 \pm 0.041\text{cm}^3$ coulomb^{-1} for p-type and n-type germanium, respectively. In the second part of the experiment, we examine the dependence of the Hall coefficient on temperature for p-type germanium, and observe an inversion in the Hall coefficient at high temperatures. Furthermore, we find that the Hall coefficient exhibits a nonlinear decrease with increasing temperature. These results have important implications for the understanding and characterization of semiconductors and their electronic properties.

I. AIM:

1. To determine the Hall coefficient of semiconductor at room temperature
2. To study the variation of the Hall coefficient with temperature

II. THEORY

Measurements of conductivity in semiconductors are insufficient for distinguishing between the presence of one or both types of carriers. In contrast, Hall effect measurements, a fundamental method for determining mobilities, can be utilized to obtain this information.

Consider a simple crystal, as depicted in Figure 1, with contacts 1, 2, and 3 perpendicular to a magnetic field H in the z-direction. When a voltage V_x is applied between contacts 1 and 2 to induce current flow through the crystal in the x-direction, a voltage will arise across contacts 3 and 4 in the y-direction. Assuming all carriers possess equal drift velocity, it is easy to compute this (Hall) voltage. To do so, we make two assumptions: (a) that there is only one kind of carrier present, and (b) that both types of carriers are present.

A. One type of carrier:

The magnetic force on the carriers is $\vec{F_m} = e\vec{E_m} = e(\vec{v} \times \vec{H})$ and is compensated by the force $\vec{F_h}$ due to the Hall fields $\vec{E_h}$. The electric field $\vec{E_m}$ is along the y-axis and is provided by $E_m = vH = \mu E_x H$, where the carrier mobility μ is determined by $v = E_x$, and E_x is the applied electric field along the x-axis. This is because v is along the x-axis, and H is along the z-axis. $E_x = J_x$ describes the relationship between the electric field, current density, and conductivity. The Hall coefficient R_H is given by:

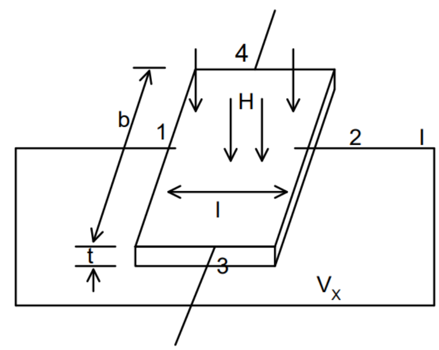

FIG. 1: Schematic arrangement for the measurement of the Hall Effect of a crystal.

$$|R_H| = \frac{E_m}{J_x H} = \frac{1}{ne} = \frac{V_y t}{I_x H} \tag{1}$$

where t is the thickness of the sample. Thus, for a fixed magnetic field and input current, the Hall voltage is proportional to $1/n$.

B. Two Types of Carriers

We observe that the Hall voltage for p-type carriers (holes) has the opposite sign from that for n-type carriers (electrons) for the same electric field E_x. Consequently, the sign of the Hall coefficient R_H is also different for the two types of carriers. Both types of carriers experience a transverse motion due to the Hall field E_y, which fails to counteract the magnetic force acting on them. However, since no current flows through contacts 3, 4, and 5, the net transverse transfer of charge remains zero.

In the x-direction, we have:

$$e(v_x^+ p - v_x^- n) = J_x, \tag{2}$$

where v_x^+ has the opposite sign from v_x^-. The carrier mobility μ is always a positive number, and the total current density σ is given by:

$$e(\mu^+ p + \mu^- n) = \sigma. \tag{3}$$

The velocity of carriers in the y-direction is defined as:

$$v_y^- = \frac{F\tau}{2m^*}, \tag{4}$$

where m^* is the effective mass of carriers, and τ is the mean time between collisions. The Hall coefficient is given by:

$$R_H = \frac{E_H}{J_x H} = \frac{E_H}{\sigma E_x H} = \frac{(\mu_h^2 p - \mu_e^2 n)}{e(\mu_h p + \mu_e n)^2}, \tag{5}$$

where E_H is the Hall electric field, and H is the magnetic field strength.

Since the mobilities μ_h and μ_e are functions of temperature, the Hall coefficient is also a function of temperature and may become zero and even change sign. In general, $\mu_e > \mu_h$, so Hall coefficient inversion can only occur if $p > n$. Therefore, Hall coefficient inversion is characteristic of only p-type semiconductors. At the point of zero Hall coefficient, it is possible to determine the ratio of mobilities.

III. OBSERVATION AND CALCULATION

A. Magnetic field calibration

We used an electromagnet coil of 500 turns. Then we gradually increased the current in the coil and measured the magnetic field using a Hall probe. The data is shown in Table I. The graph of B vs I is shown in Fig 2.

I (A)	B (gauss)	I (A)	B (gauss)	I (A)	B (gauss)
0.00	0	0.40	372	2.0	1953
0.01	8	0.45	428	2.2	2140
0.04	36	0.50	474	2.4	2330
0.07	67	0.55	521	2.6	2520
0.10	92	0.65	601	2.8	2720
0.13	119	0.70	653	3.0	2910
0.17	155	0.80	762	3.2	3090
0.20	187	0.90	855	3.4	3277
0.23	216	1.00	955	3.6	3450
0.27	250	1.21	1162	3.8	3620
0.30	280	1.40	1360	4.0	3790
0.33	309	1.60	1559	4.1	3880
0.36	345	1.81	1761	-	-

TABLE I: Magnetic fields and current calibration data

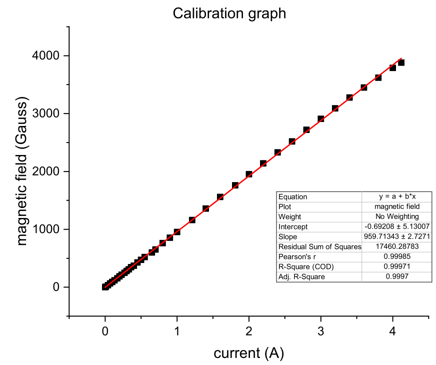

FIG. 2: B vs I (coil current)

B. Constant temperature

1. *Ge n-type*

- sample thickness $= t = 0.5mm$
- coil current $= I = 3.21A$
- $H = 3277G$

We measured the Hall voltage at different probe current. The data is shown in Table II. The graph of Hall voltage vs probe current is shown in Fig 3.

from Graph 3, we have $slope = {}^{V_y}/_{I_x} = -19.8$. Thus, using Equation 1 $R_H = -3.02cm^3coulomb^{-1}$

I (mA)	Hall Voltage (mV)	offset voltage (mV)	Voltage (mV)
0.00	0.0	0.0	0.0
0.55	-12.7	0.0	-12.7
1.00	-22.9	0.4	-23.3
1.50	-34.7	0.5	-35.2
2.00	-46.5	0.5	-47.0
2.50	-57.5	0.6	-58.1
3.03	-69.7	0.9	-70.6
3.48	-79.7	1.0	-80.7
4.00	-90.1	1.0	-91.1
4.50	-100.8	1.2	-102.0
5.00	-109.5	1.4	-110.9
5.45	-118.9	1.4	-120.3
6.00	-129.0	1.5	-130.5
6.50	-137.7	1.7	-139.4
7.04	-147.5	1.9	-149.4
7.53	-155.6	2.1	-157.7
8.00	-163.4	2.1	-165.5
8.46	-169.5	2.2	-171.7
9.00	-177.2	2.3	-179.5
9.50	-184.2	2.4	-186.6

TABLE II: Ge n-type hall voltage at different probe current

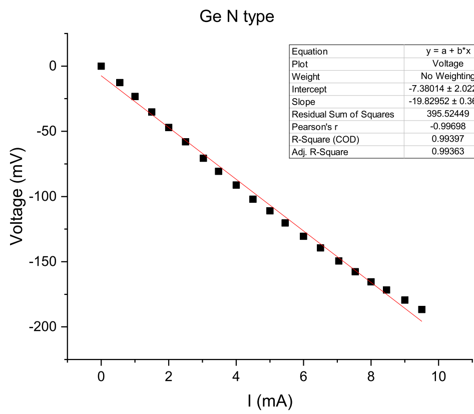

FIG. 3: Hall voltage vs. probe current for Ge n-type

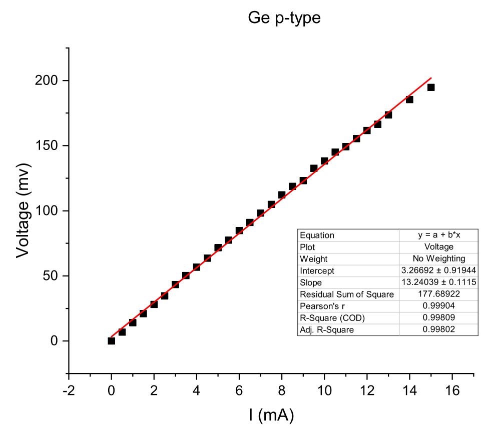

FIG. 4: Hall voltage vs probe current for Ge p-type

2. Ge p-type

- sample thickness $= t = 0.5mm$
- coil current $= I = 3.21A$
- $H = 3277G$

I (mA)	Hall Voltage (mV)	Offset Voltage (mV)	Voltage (mV)
0.0	0	0	0
0.5	3.6	-3.2	6.8
1.0	7.3	-6.8	14.1
1.5	10.8	-10.2	21.0
2.0	14.4	-13.6	28.0
2.5	17.9	-16.8	34.7
3.0	22.4	-20.9	43.3
3.5	25.8	-24.4	50.2
4.0	29.1	-27.5	56.6
4.5	32.4	-31.1	63.5
5.0	36.3	-35.3	71.6
5.5	38.9	-38.5	77.4
6.0	42.4	-42.4	84.8
6.5	44.8	-46.2	91.0
7.0	48.0	-50.3	98.3
7.5	50.9	-54.0	104.9
8.0	53.9	-58.3	112.2
8.5	56.0	-62.7	118.7
9.0	58.3	-64.9	123.2
9.5	62.5	-70.1	132.6
10.0	64.5	-73.8	138.3
10.5	67.8	-77.2	145.0
11.0	69.6	-79.5	149.1
11.5	72.3	-83.1	155.4
12.0	70.7	-90.9	161.6
12.5	72.1	-94.3	166.4
13.0	74.6	-99.0	173.6
14.0	77.6	-107.8	185.4
15.0	77.5	-117.2	194.7

TABLE III: Ge-P type hall voltage at different probe current

We measured the Hall voltage at different probe current. The data is shown in Table III. The graph of Hall voltage vs probe current is shown in Fig 4.

from Graph 4, we have $slope = {}^{V_y}/_{I_x} = -13.24$. Thus, using Equation 1 $R_H = 2.02cm^3coulomb^{-1}$

C. Temperature dependence of hall coefficient

- sample thickness $= t = 0.5mm$
- coil current $= I = 3.07A$
- $H = 2910G$
- probe current $= 4.0mA$
- Room temperature $= 300K$

We measured the Hall voltage at different temperature. The data is shown in Table IV and V. The graph of Hall coefficient vs temperature is shown in Fig 5.

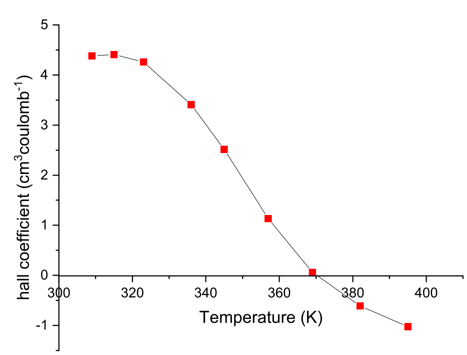

FIG. 5: Hall coefficient vs. Temperature for Ge n-type

Heater Current	Thermal EMF (mV)	Hall voltage (mV)	Offset voltage (mV)	Voltage (mV)
304	0.35	145.4	43.4	102
405	0.6	146	43.4	102.6
501	0.91	142.6	43.4	99.2
605	1.43	122.7	43.4	79.3
706	1.8	102	43.4	58.6
802	2.32	69.8	43.4	26.4
900	2.81	44.8	43.4	1.4
1000	3.33	29.2	43.4	-14.2
1100	3.9	19.5	43.4	-23.9

TABLE IV: Hall voltage at different temperature

Temperature	Rh
309	4.3814433
315	4.40721649
323	4.26116838
336	3.40635739
345	2.51718213
357	1.13402062
369	0.06013746
382	-0.60996564
395	-1.0266323

TABLE V: hall coefficient temperature dependance

IV. ERROR

For R_H value calculation at a constant temperature:

$$\frac{\delta R_H}{R_H} = \sqrt{\left(\frac{\delta slope}{slope}\right)^2 + \left(\frac{\delta B}{B}\right)^2}$$

For Ge n type $\delta R_H = 0.041 cm^3 coulomb^{-1}$
For Ge p type $\delta R_H = 0.017 cm^3 coulomb^{-1}$
The error in the measured value of R_H was found to be small and can be considered negligible. However, the observed variation in the obtained value of R_H could be attributed to several factors, including:

- Fluctuations in the coil current during the experiment, which may result in variations in the magnetic field strength experienced by the sample. Such fluctuations could be caused by external disturbances or instabilities in the power supply.

- Variations in the ambient temperature of the room, which could affect the electrical properties of the sample and lead to variations in the measured value of R_H. Such variations could be due to fluctuations in air conditioning or heating systems, or other environmental factors.

- Thermal effects on the sample, caused by high probe current or non-zero thermal EMF. These effects could cause changes in the temperature of the sample, leading to variations in the measured value of R_H. The magnitude of such effects may depend on the specific characteristics of the sample and the experimental setup.

- Impurities in the sample, which could introduce additional sources of scattering and lead to variations in the measured value of R_H. Such impurities may be present in the bulk of the material or at the interfaces between different layers or regions of the sample.

It is important to note that these factors may not be the only sources of error in the experiment, and that other uncontrolled variables could also contribute to the observed variations in the measured value of R_H. Therefore, a careful analysis of the experimental conditions and possible sources of error is crucial for the interpretation of the results and the assessment of their reliability.

V. CONCLUSION

In conclusion, our experiments for measuring the Hall coefficient have shown that the polarity of the Hall voltage is opposite for p-type and n-type samples, resulting in a change in the sign of R_H. We found that the calculated absolute value of R_H for n-type germanium is higher than that of p-type germanium, indicating a lower charge density in the former. This is because the absolute value of R_H is inversely proportional to the charge density, which is in turn proportional to the number of charge carriers.

Moreover, we observed that the graph of V_H vs I_P is not linear for both p-type and n-type samples at high probe current, which can be attributed to the heating of the sample. Our temperature-dependent measurements revealed that the value of R_H decreases with increasing temperature for the p-type sample and eventually becomes negative, as expected due to an increase in the number of negative charge carriers with an increase in temperature. The decrease is not linear because of the significant difference between the mobilities of the two types of charge carriers at low temperatures.

[1] SPS, Lab manual, Website (2022), https://www.niser.ac.in/sps/sites/default/files/basic_page/p347_2023/3.Halleffect_semiconductors.pdf.