Study of Hall effect in semiconductors

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The Hall effect is the production of a potential difference (the Hall voltage) across an electrical conductor that is transverse to an electric current in the conductor and to an applied magnetic field perpendicular to the current. In this experiment, we study the Hall effect in semiconductors (specifically, n-type and p-type Germanium) at room temperature. Then, we try to differentiate n-type and p-type Ge by studying the effect at different temperatures.

I. OBJECTIVES

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

II. THEORY

A. Hall effect

Hall effect is the production of potential in the transverse direction when a magnetic field is applied through a current-carrying conductor. The effect was discovered by E.H. Hall in 1879.
It has a major use in determining the type of charge carriers and their mobilities in the conductor and can be useful in many other property measurements.
In FIG.1, the magnetic field is along the z-direction while the current is along the y-direction. In the case of hall voltage formation, we see that the potential is formed across the x-direction. This is attributed to the Lorentz force on the charge carriers that causes them to be separated and produce an electric field depending on the properties of the conductor. The type of carriers affects the properties of the Hall effect drastically.

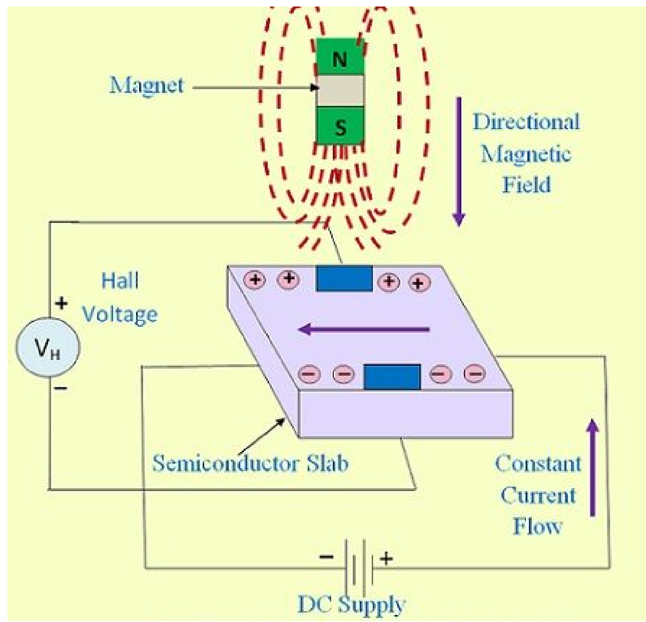

FIG. 1. Diagramatic representation of Hall effect

B. Hall effect in one carrier system

If there is a single carrier in the system, the Lorentz force is given by:

$$\vec{F_m} = e(\vec{v} \times \vec{B}) = e\vec{E_m} \tag{1}$$

This is compensated by the hall voltage and is given by:

$$\vec{F_H} = e\vec{E_H} \tag{2}$$

As $\vec{v}$ is along the x-axis and $\vec{H}$ along the z-axis, the electric field E_m is along the y-axis and is determined by:

$$E_m = vH_m = \mu E_x H \tag{3}$$

where μ is the carrier mobility given by $v = \mu E_x$ and E_x is the applied electric field along the x-axis. This electric field is related to the current density and conductivity:

$$\sigma E_x = J_x \tag{4}$$

The Hall coefficient R_H is defined as:

$$|R_H| = \frac{E_m}{J_x H} = \frac{\mu E_x}{J_x} = \frac{\mu}{\sigma} = \frac{1}{ne} \tag{5}$$

Thus, for a given magnetic field and fixed input current, the hall coefficient is proportional to 1/n.
Experimentally, the Hall coefficient is given by:

$$R_H = \frac{V_y t}{I_x H} \tag{6}$$

where V_y is the Hall voltage and t is the thickness of the sample.
In case the voltage across the input is kept constant, it

is convenient to define the Hall angle as:

$$\phi = \frac{V_y}{V_x} = \mu \frac{b}{l} H \tag{7}$$

where b and l are the width and length of the crystal. The Hall angle is thus proportional to the mobility.

C. Hall effect in two carrier system

For the same electric field E_x, the Hall voltage for p carriers (holes) will have the opposite sign from that for n carriers (electrons). (That is, the Hall coefficient R has a different sign.) Thus, the Hall field E_y will not be able to compensate for the magnetic force on both types of carriers and there will be a transverse motion of carriers; however, the net transverse transfer of charge will remain zero since there is no current through the 3, 4 contacts. The equation for the Hall coefficient in this case would be:

$$R_H = \frac{{\mu_h}^2 p - {\mu_e}^2 p}{e(\mu_h p + \mu_e n)^2} \tag{8}$$

Since the mobilities μ_h and μ_e are not constants but functions of T, the Hall coefficient given by Eq. 8 is also a function of T and it may become zero and even change sign when the electron concentration becomes more than hole concentrations.
This is caused due to the shift of valence electrons to the conduction band and causes a change in the overall concentration of charge carriers.
Hall coefficient inversion is characteristic property of only "p-type" semiconductors since the majority of carriers in n-types are electrons and do not see inversion. At the point of zero Hall Coefficient, it is possible to determine the ratio of mobilities μ_e/μ_h in a simple manner

III. EXPERIMENTAL SETUP

The experimental setup is shown in FIG.2 and 3.

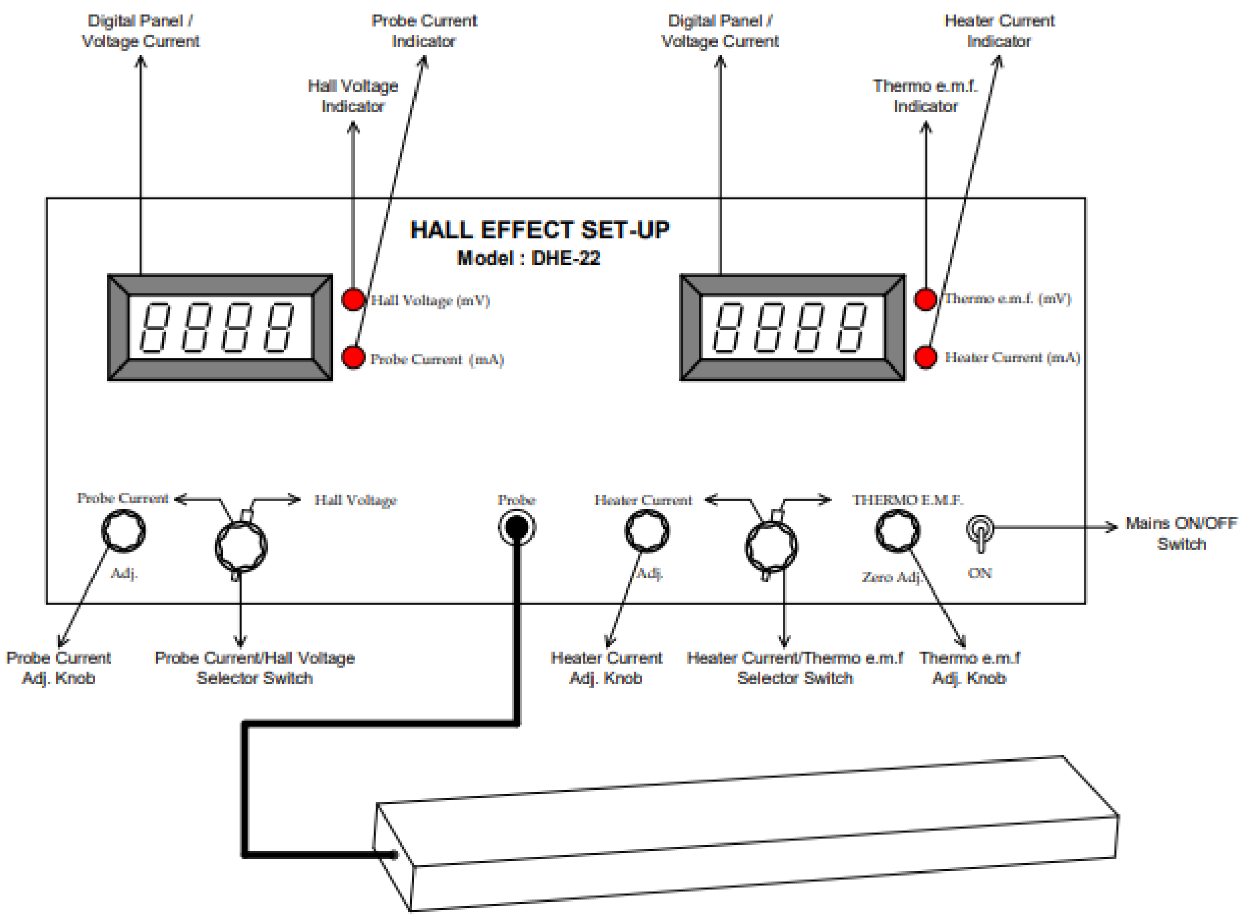

FIG. 2. Panel diagram of Hall effect setup

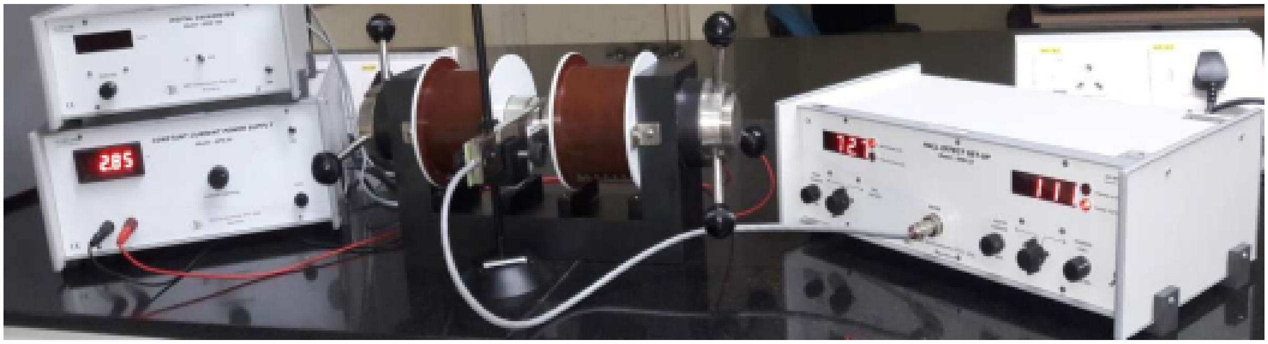

FIG. 3. Experimental setup

IV. OBSERVATIONS AND CALCULATIONS

Table 1: Calibration of current vs magnetic field

CALIBRATION	
Current (A)	Magnetic field (Gauss)
0	0
0.1	85
0.21	171
0.3	246
0.41	328
0.51	418
0.61	494
0.7	576
0.8	659
0.9	746
1.01	836
1.11	941
1.21	1016
1.3	1084
1.4	1177
1.51	1268
1.61	1379
1.7	1444
1.8	1527
1.89	1600
2	1697
2.1	1783
2.2	1873
2.3	1954
2.4	2030
2.5	2120
2.6	2210
2.7	2285
2.8	2370
2.91	2460
3.01	2550
3.1	2630
3.2	2700
3.3	2780
3.4	2860
3.5	2950

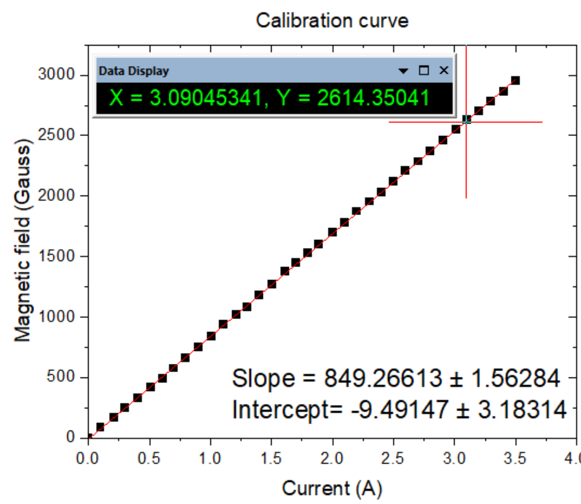

FIG. 4. Calibration curve

From the calibration curve, we get the magnetic field corresponding to the current of 3.09 A to be 2614.35 Gauss at room temperature.
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Now the hall coefficient of the semiconductors given i.e. n-type and p-type Germanium can be calculated using the following equation:

$$R_H = m \times \left(\frac{t}{H}\right) \tag{9}$$

where m is the slope of the Hall voltage vs probe current plots.
In the above equation, we have the thickness of the sample, t = 0.5 mm, and the magnetic field, H = 2614.35 Gauss.

Table 2: Hall voltage vs probe current for n-type Ge

n-type Ge	
Probe current (mA)	Hall voltage (mV)
0	0
0.57	-10.7
1.06	-19.5
1.45	-26.9
1.97	-36.1
2.45	-44.9
3.02	-55.4
3.51	-63.8
4.08	-73.9
4.53	-81.7
5.04	-90.2
5.52	-98
6.08	-107
6.46	-112.2
7.05	-121.3
7.52	-128
8.1	-136.6
8.48	-141.8

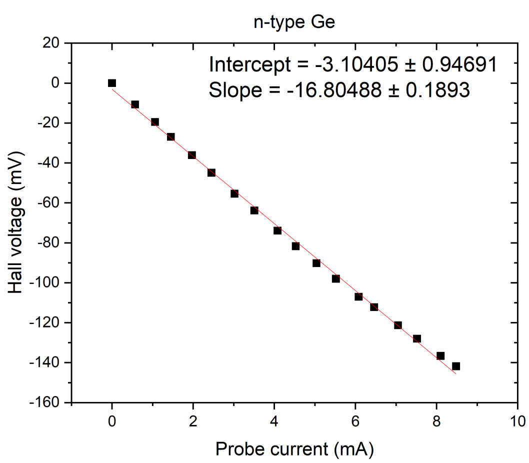

FIG. 5. Plot of Hall voltage vs probe current for n-type Ge

The Hall coefficient for n-type Ge at room temperature,

$$R_H = -16.80488 \times \frac{0.5 \times 10^{-3}}{0.261435} = -0.03214 m^3 C^{-1}$$

Error:

$$\frac{\delta R_H}{R_H} = \sqrt{\left(\frac{\delta slope}{slope}\right)^2 + \left(\frac{\delta H}{H}\right)^2} = 0.01127$$

$$\delta R_H = 0.00036$$

Carrier density:

$$n = \frac{1}{R_H e} = 1.945 \times 10^{20} m^{-3}$$

Error:

$$\frac{\delta n}{n} = \frac{\delta R_H}{R_H} = 0.01127$$

$$\delta n = 0.022 \times 10^{20} m^{-3}$$

Table 3: Hall voltage vs probe current for p-type Ge

p-type Ge	
Probe current (mA)	Hall voltage (mV)
0	0
0.5	6.4
1.13	14
1.59	19.7
1.89	23.2
2.43	30
2.88	35.5
3.43	43.2
3.96	50.1
4.44	55.6
4.93	62.5
5.5	69.3
6.02	75.8
6.51	82.2
6.92	87.2
7.46	93.9
7.95	100.2
8.4	105.8
8.95	112.6
9.42	118.5
10.1	128.3

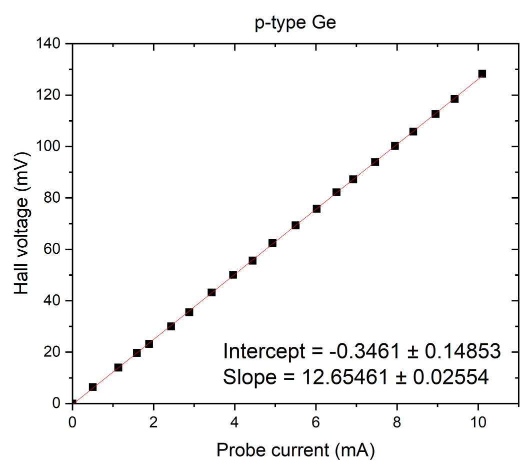

FIG. 6. Plot of Hall voltage vs probe current for p-type Ge

The Hall coefficient for p-type Ge at room temperature,

$$R_H = 12.65461 \times \frac{0.5 \times 10^{-3}}{0.261435} = 0.0242 m^3 C^{-1}$$

Error:

$$\frac{\delta R_H}{R_H} = \sqrt{\left(\frac{\delta slope}{slope}\right)^2 + \left(\frac{\delta H}{H}\right)^2} = 0.01175$$

$$\delta R_H = 0.000284$$

Carrier density:

$$n = \frac{1}{R_H e} = 2.5826 \times 10^{20} m^{-3}$$

Error:

$$\frac{\delta n}{n} = \frac{\delta R_H}{R_H} = 0.01175$$

$$\delta n = 0.03 \times 10^{20} m^{-3}$$

Table 4: Temperature dependence of Hall coefficient

Probe current=3.99mA Const. current=3.04 A					
Sl.No.	**Heater current (mA)**	**Thermo emf (mV)**	**Temperature (C)**	**Hall voltage (mV)**	**Hall coefficient** (cm^3/C)
1	0	0	26	47.7	—
2	101	0.06	28.5	47.4	912.5521
3	200	0.32	35	46.3	450.1442
4	300	0.72	45	44.8	290.3738
5	400	1.28	59	38.6	187.6411
6	501	1.83	72.5	31.3	121.4807
7	600	2.46	86.5	18.3	59.30626
8	701	3.18	104	4.1	11.37278
9	802	3.89	122	-2	-4.84905
10	900	4.55	138	-2.8	-6.04945

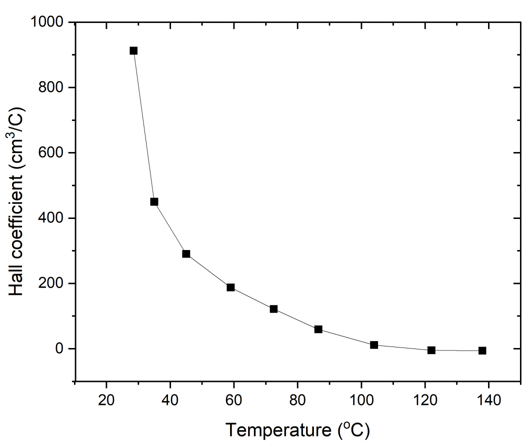

FIG. 7. Temperature dependence of Hall coefficient for p-type Ge

V. RESULTS

- For n-type Ge:

  Hall coefficient:

  $$R_H = (-3.214 \pm 0.036) \times 10^{-2} m^3 C^{-1}$$

  Carrier density:

  $$n_n = (1.945 \pm 0.022) \times 10^{20} m^{-3}$$

- For p-type Ge:

  Hall coefficient:

  $$R_H = (2.42 \pm 0.0284) \times 10^{-2} m^3 C^{-1}$$

  Carrier density:

  $$n_n = (2.5826 \pm 0.03) \times 10^{20} m^{-3}$$

VI. CONCLUSIONS AND DISCUSSIONS

- The Hall Effect experiment on semiconductors reveals important details about the inherent properties of these substances.
  - We obtained a negative hall coefficient with the n-Ge sample, indicating that electrons are the dominant charge carriers.
  - With the p-Ge sample, we obtained a positive hall coefficient, indicating that holes are the predominant charge carriers there.
- We saw that for the p-Ge sample, the hall coefficient gradually turned negative at some higher temperatures, the process called the **Hall coefficient inversion**. This occurs because as the temperature rises, more electrons enter the conduction band, and as $\mu_e > \mu_h$, the electrons take over as the dominant charge carrier, inverting hall voltage and subsequently hall coefficient.

VII. SOURCES OF ERRORS AND PRECAUTIONS

- Degaussing should be done properly before each part of the experiment.
- The sample should be kept stable by mounting it to a stand to get stable readings.
- The errors could be due to the presence of impurities in the sample.
- Least count errors, personal errors, etc.

VIII. REFERENCES

- NISER Lab Manual
- Wikipedia
- https://electronicscoach.com/hall-effect-sensor.html
- ORIGIN Lab