Studying the Hall effect in Germanium

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ABSTRACT

This report focuses on studying the Hall effect in a Germanium semi-conductor sample. Properties of Germanium such as its sample voltage and Hall voltage were investigated by varying different parameters, including current, temperature, and the magnetic flux density. The concept of energy bands and the role of charge carriers were explored, leading to the calculation of the the Hall coefficient $R_H = (7.99 \times 10^{-3}) \pm (8.12 \times 10^{-4})\, m^3 A^{-1} T^{-1}$, the Hall mobility μ_0 = $142.37 \pm 1.66 \times 10^{-4}\, \mathrm{cm}^2 V^{-1} s^{-1}$, and the carrier density $7.82 \times 10^{20} \pm (8.12 \times 10^{-4})\, \mathrm{cm}^{-3}$.

1 INTRODUCTION

1.1 Theory and Background

The Hall effect takes place once voltage is produced between the two opposite sides of a conducting strip of rectangular section, as a result of a current induced in the strip which leads the strip to be transversed by a magnetic field at 90 degrees to the direction of the current. This is because the Lorentz force deflects the charge carriers in a direction which is perpendicular to both the direction of current I and magnetic field B. The charge carriers determine the current induced in the sample. The Lorentz force **F** is defined in Eq. (1) as

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B}) \tag{1}$$

where q indicates the charge of the charge carriers, **v** the velocity at which the charge carriers travel, and **B** their associated magnetic field.

To determine whether the charge carriers are positive or negative, the flow of the current can be determined from the polarity of the Hall voltage. [1]

1.2 Motivation

Semiconductor materials play a crucial role in various areas, such as nanoeletronics, detectors, and quantum applications because of their distinct electrical properties, which vary with temperature. This experiment aimed to examine how thermal excitation affects the charge carrier concentration and, consequentially the germanium semiconductor's overall conductivity. Conductivity is a fundamental property that measures the ability to conduct an electric current. For a semiconductor material, it is defined as a function of temperature, displayed in Eq. (2) as

$$\sigma = \frac{1}{\rho} = \frac{l}{A}\frac{I}{V} \tag{2}$$

where ρ is the resistivity, l the length of the germanium sample, A the cross sectional area of the germanium sample, I is the current and V is the voltage. [1]

2 METHOD

2.1 Risk Assessment and Apparatus

The 3B 1009934 Hall Effect Console allows control of the induced current by adjusting the knob labeled 'I k', which varies the current in mA. The display can be switched to measure temperature by pressing the 'Tp/°C' button, and temperature adjustments are made using the 'OFF — 170°C' knob. The PHYWE Tesla Meter measures magnetic flux density in mT and was set to a 2000-digit scale, ensuring whole-digit readings. The Hall probe, connected to the Tesla meter port labeled 'probe', was inserted into the magnetic coils to measure the magnetic field by detecting the Hall voltage when current flowed through the Germanium semiconductor sample. The PHYWE 0651.01 Magnetic Coils were used to generate the magnetic field, while the PHYWE DC-Constanter allowed for controlled variation of the magnetic field as displayed on the Tesla meter by adjusting the DC knobs. Voltage measurements were recorded using the Thandar TM356 Digital Multimeter. In Part 1, the multimeter was set to a 20-digit scale, allowing voltage values to be recorded to two decimal places. In Part 2, it was set to a 2-digit scale, enabling measurements to three decimal places for greater precision. A risk assessment was performed. The two main risks identified were electric shock from the power supplies and burning from touching the heating coil. To minimize these risks, touching exposed wires was avoided, and enough time was given for the coils to cool down.

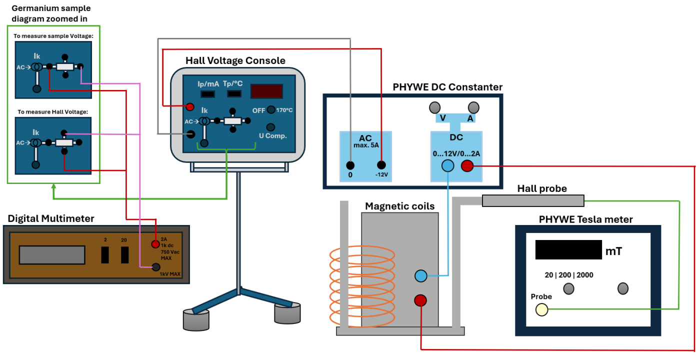

Figure 1. Labeled diagram including the setup and apparatus

2.2 Measurement of conductivity in Germanium

The dimensions of the Germanium sample (20 mm × 10 mm × 1 mm) were recorded before inserting it into the Hall effect console. The multimeter was connected to measure the sample voltage, with the red and black "banana" cords placed on the 2 A port and the 1 kV MAX port, respectively. The sample voltage was measured as a function of temperature, maintaining a constant magnetic flux density of 4 mT and a current of 4 mA via the DC-Constanter. The Hall voltage console was used to raise the temperature to 100°C, then allowed to cool in increments of 10°C to 30°C, recording the voltage at each step.

2.3 Hall effect in Germanium

A Hall probe was inserted into the magnetic coils to generate a magnetic field. The undoped Germanium sample was replaced with a p-type doped Germanium sample, positioned centrally in the coils. The magnetic flux density was set to 250 mT, and the Hall voltage was recorded while varying the current from -35.20 mA to 34.40 mA in 10 mA increments using the 'I K' knob on the Hall effect console. To further analyze the Hall effect, the multimeter was reconfigured to measure sample voltage while maintaining a current of 25.20 mA. The magnetic flux density was varied from 0 mT to 300 mT in 50 mT increments using the DC-Constanter, with corresponding voltage readings recorded. The Hall voltage was then measured with a different configuration. The red and black "banana" cords were reconnected to measure voltage vertically, and the DC-Constanter's DC port connections were reversed to record magnetic flux density on the negative scale. The current was set at 30.3 mA, and the magnetic flux density was varied from -300 mT to 300 mT in 50 mT increments, with voltage measurements recorded accordingly. For the final step, the current was set to 30.70 mA, and the magnetic field strength was maintained at 300 mT. The Hall voltage console was used to increase the temperature to 100°C, then allowed to cool in increments 10°C to 30°C, recording the voltage at each step.

2.4 Direction of the magnetic field

In the experiment, the direction of the magnetic field was determined to be from the south pole to the north pole of the magnet. This orientation of the magnetic field influenced the flow of current and the resulting Lorentz force on the charge carriers. The position of the Hall probe in the magnetic coils was essential in determining the magnetic field's orientation. The probe's sticker, which was facing the left side of the wall it was placed on, indicated the direction of the magnetic field. If the Hall probe were rotated by 180 degrees, the magnetic field direction would reverse, resulting in negative voltage values being recorded. Using the right-hand rule, the direction of the current of the charge carriers was deduced. The current flowed from left to right, and as a result, the Lorentz force acted downward. This was consistent with the experimental setup, where the movement of charge carriers was influenced by both the magnetic field and the applied current, leading to the downward force observed.

3 RESULTS

3.1 Analysis

Figure 2 illustrates the conductivity of the undoped Germanium sample as a function of the inverse of the applied temperature. The conductivity was calculated using Eq. (2), with temperature values converted to Kelvin. Origin Pro was used to determine the natural logarithm of conductivity and the reciprocal of temperature. The band gap energy was calculated using Eq. (3) as

$$b = -\frac{E_g}{2k_B} \tag{3}$$

where b corresponds to the instantaneous rate of the change of the conductivity with temperature, C indicates the band energy gap and k_B refers to the Boltzmann constant [1].
From this analysis a value of 0.74 eV was obtained, which is consistent with the literature value of 0.70 eV for Germanium at room temperature. A strong linear relationship can be denoted as the temperature increases, the conductivity of the sample increases, showcasing its intrinsic behavior. An intrinsic semiconductor is a pure

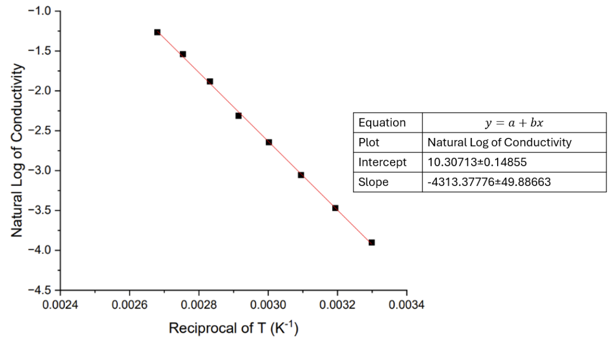

Figure 2. Natural log of conductivity ln_{σ} as a function of the inverse of the temperature T (K^{-1}).

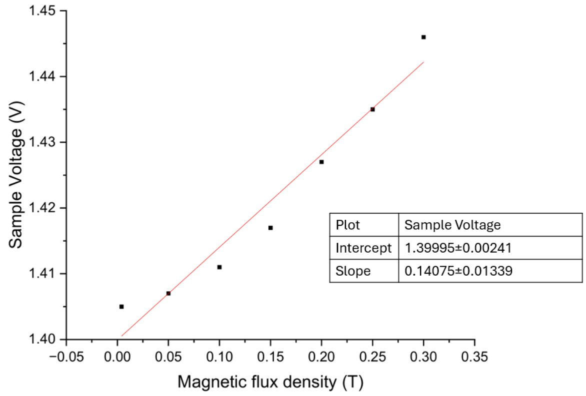

Figure 3. Sample Voltage V_s (V) as a function of the magnetic flux density B (T).

undoped material in which conduction occurs as a result of the thermal generation of electron-hole pairs. When an electric field is applied, electrons move into the conduction band, while the corresponding positive charge carriers (holes) migrate in the opposite direction within the valence band. As the temperature increases, more electrons gain enough energy to cross the band gap and transition into the conduction band. This process results in an increase in the semiconductor's conductivity with rising temperature [2].

Figure 3 displays the recorded sample voltage of the p-type undoped Germanium sample as a function of the magnetic flux density. As the magnetic flux density increases, the sample voltage also increases proportionally. However, the plotted data points exhibit deviations from the fitted line, indicating potential errors in the recorded voltage measurements. One source of error arises from the adjustment of the DC knobs on the DC-Constanter, as the magnetic flux density values were not precisely set due to fluctuations of ±1 mT in the Tesla meter. This fluctuation introduced an instrumental error that contributed to the weak linear correlation observed in the plotted data.
In addition, a resistive component inherent in the material may have influenced the recorded sample voltage. The resistance of the material affects the voltage V_R which impacts the measurement of the total voltage. This resistance was then calculated using Eq. (4) as

$$V_R = I \times R \tag{4}$$

This is referred to as Ohm's first law and it states that V_R represents the sample's voltage, I denotes the current induced in the sample, and R corresponds to the sample's resistance. When the magnetic flux density was set to zero, the measured current was 25.20 mA, resulting in a calculated resistance of 55.67 Ω. Furthermore, the

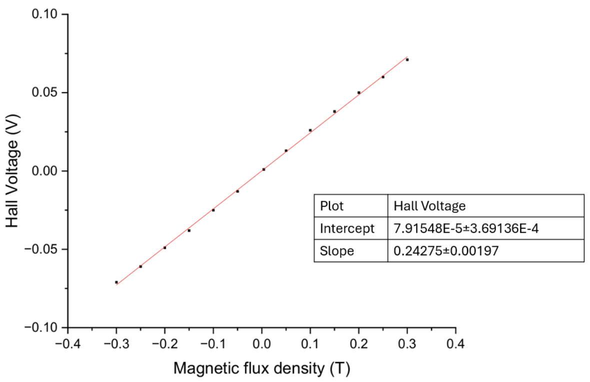

Figure 4. Hall Voltage V_H (V) as a function of the magnetic flux density B (T).

resistivity of the material was determined using Eq. (5) as

$$\rho = \frac{RA}{l} \tag{5}$$

where R is the resistance of the undoped germanium sample, A represents the cross-sectional area of the sample, and l is its length. The calculated resistivity was found to be 0.55 $\Omega\, m^{-1}$, which closely aligns with the literature value of 0.60 $\Omega\, m^{-1}$ for Germanium.

Figure 4 displays the recorded Hall voltage of the p-type undoped Germanium sample as a function of the magnetic flux density. A strong linear relationship between the Hall voltage and the magnetic flux density can be observed. The recorded voltage is solely dependent on the Hall effect, driven by the Lorentz force, and indicates that the Hall voltage directly reflects the behavior of the positive charge carriers, as expected from a p-type semiconductor. The Hall coefficient, R_H, was calculated to be $7.99 \times 10^{-3}\, m^3 A^{-1} T^{-1}$ using Eq. 6 as

$$R_H = \frac{Vd}{IB} \tag{6}$$

where $\frac{V}{B}$ is taken to be the instantaneous change of the Hall voltage with the magnetic flux density, I corresponds to the current set to 30.30mA and d indicates the width of the sample. The Hall coefficient measures the extent to which the charge carriers respond to the applied magnetic field. The positive value of R_H confirms that the germanium sample used is a p-type semiconductor [3]. Next, the Hall mobility, μ_0, was computed, yielding a value of $142.37\, \mathrm{cm}^2 V^{-1} s^{-1}$. This was achieved through Eq. 7 as

$$\mu_0 = R_H \times \sigma_0 \tag{7}$$

The Hall mobility describes how easily the positive charge carriers move through the semiconductor under the influence of the electric and magnetic fields. The value obtained for the Hall mobility is considered to be high, suggesting that the charge carriers experience less resistance to motion, leading them to move more freely. Finally, the carrier density , n, was calculated using Eq. 8 as

$$n = \frac{1}{eR_H} \tag{8}$$

where e is the charge of the charge-carriers.

A value of $7.82 \times 10^{20}\, \mathrm{cm}^{-3}$ was computed from this analysis. The carrier density reflects the number of free charge carriers per unit volume in the semiconductor. The large value of n, in the range of 10^{20}, indicates that the sample contains a significant number of positive charge carriers, which contributes to the higher conductivity observed in the material [1].

3.2 Error propagation

A main source of error in this procedure was the recording of the parameters at the exact time at which the value would appear on the multimeter, therefore it introduced perceptual error in the findings obtained. The propagation of errors was carried out using Eq. 9 as

$$\frac{\sigma_C}{C} = \sqrt{(\frac{\sigma_A}{A})^2 + (\frac{\sigma_B}{B})^2} \tag{9}$$

where σ in this case, it represents the uncertainty [4]. Eq. 9 was adapted and the following uncertainties were calculated for each finding.

$$p = 0.55 \pm (5.88 \times 10^{-3})\, \Omega\, m^{-1}$$
$$R_H = (7.99 \times 10^{-3}) \pm (8.12 \times 10^{-4})\, m^3 A^{-1} T^{-1}$$
$$\mu_0 = 142.37 \pm 1.66 \times 10^{-4}\, \mathrm{cm}^2 V^{-1} s^{-1}$$
$$\mathrm{n} = 7.82 \times 10^{20} \pm (8.12 \times 10^{-4})\, \mathrm{cm}^{-3}$$

The same uncertainty was attributed to the carrier as the Hall coefficient, since the charge of the charge carriers is a constant, the elementary charge. The uncertainties obtained were very small, highlighting the accuracy of the findings.

4 CONCLUSION

In this experiment, the Hall effect in Germanium was studied and it led to understanding different properties of the semiconductor and its effects. Energy gaps which are a key characteristic of semi conductors were also discussed, and to determine the direction of the charge carriers, Fleming's right-hand rule was used to first determine the direction of the magnetic field. To further understand the crucial role of charge carries, various quantities including the Hall coefficient $R_H = (7.99 \times 10^{-3}) \pm (8.12 \times 10^{-4})\, m^3 A^{-1} T^{-1}$, the Hall mobility $\mu_0 = 142.37 \pm 1.66 \times 10^{-4}\, \mathrm{cm}^2 V^{-1} s^{-1}$, and the carrier density $7.82 \times 10^{20} \pm (8.12 \times 10^{-4})\, \mathrm{cm}^{-3}$, were calculated. The main source of error throughout this procedure was the way the data was recorded, which lead to the introduction of perceptual error. Next time, a better way to record the data would be to carry out a video documentation so it could be paused or rewinded.

References

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