Identifying Charge Carrier Type and Density: The Hall Effect in Semiconductors and Copper

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This report focuses on two primary applications of the Hall effect: (1) to distinguish between n-type and p-type conduction in semiconductor samples, and (2) to measure the charge carrier densities in two semi-conductive samples and copper. These measurements are critical in semiconductor industries where precise control over charge carrier properties determines device performance.

I. INTRODUCTION

The Hall effect, an electromagnetic phenomenon arising when a current-carrying conductor is placed in a magnetic field orthogonal to the flow of current, serves as a versatile tool in both fundamental physics and applied technology. This experiment is structured around two central goals. First, the identification of the majority charge carrier type within semiconductor samples using the Hall Effect. Regardless of the experiment's geometry, n-type and p-type semiconductors will generate Hall voltages of opposite signs, within our experiment, a negative Hall voltage indicates n-type (electron) conduction while a positive voltage indicates p-type (hole) conduction. The second goal of the experiment is to use the observed Hall voltages to derive a value for the charge carrier densities of semiconductor materials and in copper – a conventional conductive metal with a high density of free electrons.

The ability to accurately identify and measure the charge carrier types and densities is of paramount importance in semiconductor industries, where the performance and reliability of devices depend critically on precise doping levels and carrier concentrations. The Hall effect is also commonly applied in fields beyond traditional electronics; for instance, modern gaming controllers incorporate Hall effect sensors to mitigate stick drift by providing accurate feedback on joystick position, thus enhancing gaming precision and durability.

A. The Hall Effect

The Hall effect is a phenomenon that arises when an electrical current within a conductor or semiconductor is subjected to a magnetic field perpendicular to its flow. Due to the magnetic force generated by this field, $\vec{F} = q\vec{v} \times \vec{B}$, charge carriers are deflected perpendicularly from their direction of motion and the direction of the magnetic field. The deflection and subsequent build up of charges upon the conductor wall towards which the magnetic force points causes a transverse voltage to arise across the conductor, the direction of charges to one portion of a conductor leads to a variation in charge across the conductor and thus a potential difference. This transverse voltage is the Hall voltage. While it is true that the Lorentz force acts on all charge carriers and that the Lorentz force will direct both electrons (n-type) and holes (p-type) in the same direction, a fact arising from their opposite charges and their opposite directions of flow, the Hall voltage produced by n-type and p-type carriers proves to be opposite in sign, allowing for differentiation. Whereas n-type semiconductors experience a buildup of negative charges upon the conductor wall towards which the Lorentz force points, p-type conductors will experience a buildup of positive charges upon the same wall and thus a Hall voltage opposite in sign to n-type conduction. This characteristic enables the use of the Hall effect to identify the majority charge carriers within a sample.

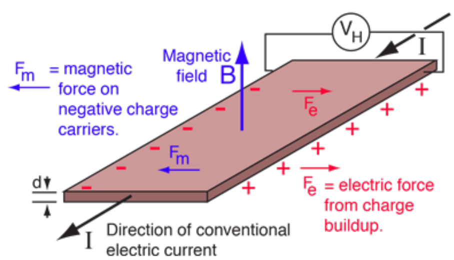

FIG. 1. Illustration of the Hall effect. Current I flows through an n-type semiconductor sample, placed in a perpendicular magnetic field $\mathbf{B}$. The Lorentz force deflects the carriers, leading to a transverse Hall voltage V_H. Figure from ref[1].

B. Determining Charge Carrier Density

Beyond determining carrier type, the Hall effect also provides a pathway to calculate the effective charge carrier density of a sample. Neglecting terms that could arise from sample imperfections, the magnitude of the Hall voltage is given by reference [2] to be:

$$V_{\text{Hall}} = \frac{BI}{qnt} \tag{1}$$

Where B refers to the orthogonal magnetic field strength, I refers to the current through the sample, q refers to the charge carriers' charge, n refers the charge carrier density, and t is the thickness/height of the sample. Following algebraic manipulation, an expression for the effective charge carrier density of a sample can be obtained.

$$n_{\text{eff}} = \frac{B}{q\,|\text{slope}|t} \tag{2}$$

Slope refers to the slope obtained by fitting a linear function to the plot of the Hall voltage versus the current through the sample. The sign of the slope is certainly relevant for determining the primary charge carrier of a sample but only magnitudes are relevant for determining the charge carrier density, illustrated by the use of the slope's absolute value in equation [2].

II. EXPERIMENTAL OVERVIEW

The experiment was performed using a TeachSpin Hall effect apparatus that allowed for convenient manipulation of the current through a sample, observation of voltage across each sample, and application of a strong magnetic field of fixed magnitude through the sample. Our experiment involved the analysis of three types of samples:

1. Chip 1: Found to exhibit electron conduction (n-type) after a negative Hall voltage was observed.
2. Chip 2: Found to exhibit hole conduction (p-type) after a positive Hall voltage was observed.
3. Copper: A very small Hall voltage was observed, consistent with copper's high charge carrier density.

For each sample, the Hall voltage was recorded as the current was varied, and a linear fit of the graph resultant from plotting the various values of voltage (V_H) observed for each current versus I provided the slope (in V/A) used for calculating the effective charge carrier density from equation [2].

III. RESULTS AND ANALYSIS

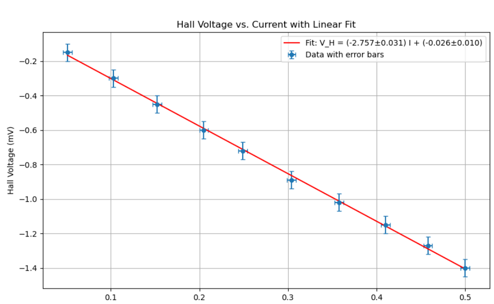

FIG. 2. Hall Voltage versus Current for Chip 1. The observed negative relationship of linearity between input current and induced Hall voltage is indicative of n-type conduction. The linear fit yields a slope of -2.76 ± 0.15 V/A.

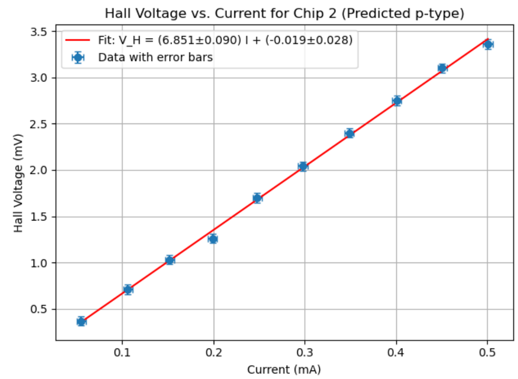

FIG. 3. Hall Voltage versus Current for Chip 2 (p-type). The observed positive relationship between input current and induced Hall voltage is indicative of p-type conduction. The linear fit yields a slope of 6.9 ± 0.3 V/A.

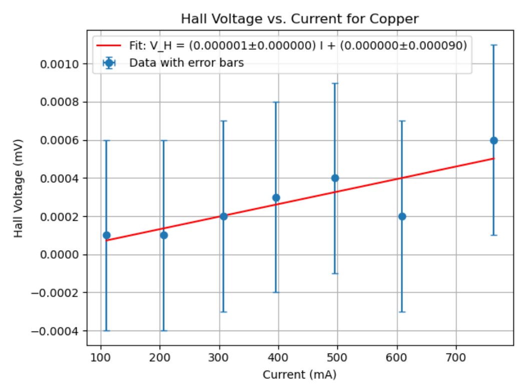

FIG. 4. Hall Voltage versus Current for Copper. The linear fit yields a very small slope of $(6.74 \pm 1.9) \times 10^{-7}$ V/A.

Using equation [2], the accepted value for the charge of free electrons and holes (q) $q = 1.602 \times 10^{-19}$ C (with negligible uncertainty), the given value for the magnetic field magnitude, $0.7{\pm}0.1$ T, and the given values for sample thicknesses, $500 \pm 10\mu m$ for the semiconductors and $17.5 \pm 0.3\mu m$ for the copper sample, the effective charge carrier densities were calculated with their relevant uncertainties.

As expected, plotting Hall voltage verses current led to a negative slope in the case of Chip 1, as seen in Figure [2], and a positive slope in the case of Chip 2, as seen in Figure [3]. These results provide support to the predictions made regarding the primary charge carrier of chips 1 and 2. Further in line with expectation, a very slight slope was associated with the copper sample and thus a much larger effective charge carrier density.

The provided values and their respective uncertainties for all values of slope were attained through linear regression of the V_{Hall} versus I data. Conversely, error propagation of the linear regression's uncertainty and the uncertainty of the provided magnetic field strength, taken from reference [3] and defined by equation 3, was used to find uncertainties for all charge carrier density values.

Recorded Slope and Effective Carrier Density Values

Chip	*slope* (V/A)	n_{eff} (C/m^3)
1	-2.76 ± 0.15	$(3.16 \pm 0.17) \times 10^{21}$
2	6.9 ± 0.3	$(1.26 \pm 0.05) \times 10^{21}$
Copper	$(6.74 \pm 1.9) \times 10^{-7}$	$(3.7 \pm 1.0) \times 10^{29}$

TABLE I. Provides the observed slopes and effective charge carrier densities for the semiconductor chips and the copper sample. Recorded values of slope were attained from linear regressions of the Hall voltage vs input current data, as outlined in Figures 2, 3, and 4. The charge carrier density was then calculated using equation 2, as outlined in Section IB. Values of uncertainty are assigned according to instrument precision and error propagation convention, equation 3

Due to the incredibly minute magnitude of the Hall voltages induced in copper samples and sensitivity limitations of available devices at lower voltages, the relative uncertainty for copper was expected and observed to be significantly higher than that observed for observations carried out for the other two chips.

$$\delta n_{eff} = n_{eff}\sqrt{\left(\frac{\delta_{slope}}{slope}\right)^2 + \left(\frac{\delta_B}{B}\right)^2 + \left(\frac{\delta_t}{t}\right)^2} \tag{3}$$

These results underscore the stark contrast between the low free-carrier densities in semiconductors (on the order of 10^{18} C/m^3) and the high density in copper (on the order of 10^{24} C/m^3). It is evident that uncertainties in the slope measurements, as provided by the linear regression, directly propagate into the carrier density estimates, emphasizing the need for precise instrumentation and careful data analysis.

IV. ERROR ANALYSIS

In this experiment, uncertainties within the measurements of voltage and current and the uncertainty of the linear regression used to determine the slope of the V_H versus I relationship serve as the primary sources of error. While uncertainties within the regression certainly carry weight in the error propagation, the uncertainty within the applied magnetic field strength, on the order of 14%, is more than double the linear regression's uncertainty, on the order of 6%, and contributes notably to the error within calculated values of charge carrier density. As aforementioned, values attached to the observation of the copper possess relatively higher values of uncertainties, observable in Figure [4]. This is primarily resultant from the extreme precision required to accurately record minute voltages. Through the use of higher precision instruments and the conduction of multiple trials to average out random errors could both be used to find a more precise estimation of a sample's charge carrier density could be made.

V. CONCLUSION

This report demonstrates the dual utility of the Hall effect in both identifying the type of charge carriers in semiconductors and measuring the effective charge carrier densities in semiconductors and copper. The experimental findings are summarized as follows: Chip 1 (n-type) and Chip 2 (p-type) were successfully distinguished based on the sign of the Hall voltage, with effective carrier densities of $(3.16 \pm 0.17) \times 10^{21}$ C/m^3 and $(1.26 \pm 0.05) \times 10^{21}$ C/m^3, respectively, and a significantly higher carrier density of $(3.7 \pm 1.0) \times 10^{29}$ C/m^3 was determined for the copper sample.

These measurements are critical in the semiconductor industry where precise control over doping and carrier density is vital for device optimization. Furthermore, the application of the Hall effect in curing stick drift in gaming controllers illustrates its broader technological relevance, showcasing its role in enhancing the reliability of modern consumer electronics.

[1] Georgia State University, The hall effect (n.d.), accessed: 2025-03-30.
[2] LibreTexts, The hall effect (n.d.), accessed: 2025-03-23.
[3] W. F. Polik, Error propagation (n.d.), accessed: 2025-03-23.