PHYS2170: Investigation of the Hall Effect in Semiconductors

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Contents

Abstract

This report details the observation of the Hall effect in two germanium samples, 3361 and 3375. Hall Voltages were recorded for changing magnetic fields and used to calculate the hall coefficient, carrier type, density and carrier mobility of each material. Sample 3361 was found to be a p-type semiconductor and its carrier density was $3.03 \pm 0.16 \times 10^{13}$. Sample 3375 was found to be an n-type semiconductor with a carrier density of $3.12 \pm 0.16 \times 10^{13}$. The difference in majority carrier types between the two "pure" crystals of germanium suggests that intrinsic semiconductors exhibit extrinsic conductive behaviour.

Introduction

The Hall Effect is phenomenon where in a magnetic field is applied perpendicular to a current passing through a conductor. The charges moving in the magnetic field experience a force deflecting perpendicular to both the magnetic field and current direction (see Figure 1.) The deflection of the carriers creates an accumulation of charges in one place and hence potential difference and associated electric field is created. This potential difference is the "hall voltage".

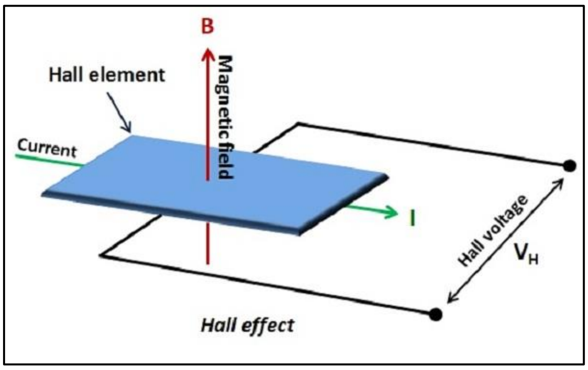

Figure 1: Magnetic field and current applied to a conductor generating a hall voltage (source: dangerousprototypes.com)

By knowing the direction of the magnetic field and current, the direction of the force acting on a charge carrier can be determined (See figure 2). This information in combination with knowing the orientation of the voltmeter terminals measuring the hall voltage can be used to figure out the majority carrier "type" of the sample.

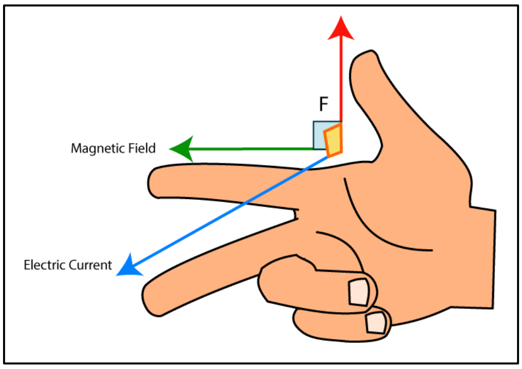

Figure 2: Right-hand rule, indicating the direction of force acting on a positive charge carrier.

The force is calculated as the cross product of the hall voltage (V) and current (I).

$$F = V \text{ x } B$$

$Where\ F, V\ and\ B\ are\ all\ vectors.$

The Hall voltage (V) is related to the magnetic field (B), current (I), charge (q), carrier density (p) and sample conductor thickness (t) by:

$$V = \frac{BI}{pqt} = \frac{BIR_H}{t} \quad (1)$$

If the charges in Figure 1 are positive and the current direction is taken as positive, then $F = V\ x\ B$. If the charges were negative the current direction would be opposite but so would the sign on the charge therefore,

$$V = \frac{B(-I)}{p(-q)t} = \frac{BI}{pqt}$$

and hence $F = V\ x\ B$. That is to say if the moving charge is positive or negative it doesn't matter, they will be deflected in the same direction with the same force [1].

If the magnitude of the magnetic field is increased the hall voltage will either increase or decrease relative to the initial reading. Knowing that positive charges (holes) and negative charges (electrons) must be accumulating at the same terminal the majority charge carrier of the material can be determined.

Say that things are oriented as in Figure 3 and the current direction is describing positive charges. Assume also that as magnetic field is increased the hall voltage decreases. This implies that the majority carrier is negative charges accruing at the positive terminal OR the majority carrier is positive charges accruing at the negative terminal.

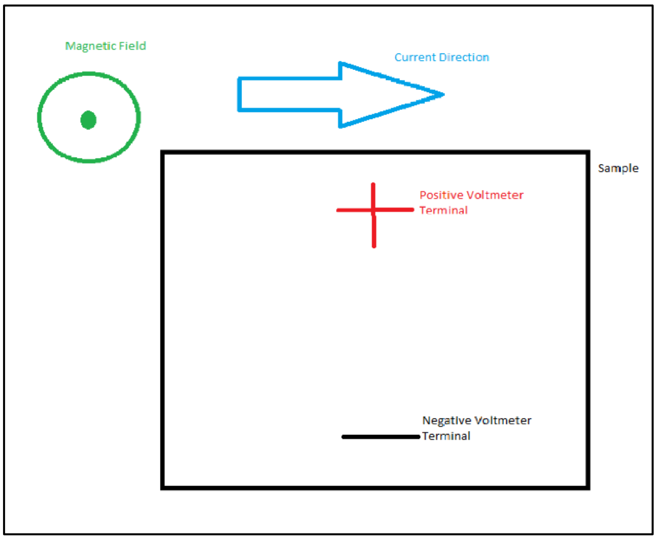

Figure 3: Conducting material experiencing hall effect due to current and magnetic field.

Applying the right-hand-rule (and left-hand rule) to Figure 3 indicates that both positive and negative charges are accumulating at the negative terminal. As the voltage is decreasing with increased magnetic field strength then the majority charge carrier must be positive holes.

Furthermore, the *carrier density* may be calculated, knowing the hall coefficient of the material (See Equation 1 – R_H), by:

(2) $$n = \frac{1}{R_H q}$$

$Where\ density\ is\ n, hall\ coeffienct\ is\ R_H\ and\ carrier\ charge\ is\ q.$

$NB: Charge\ will\ be\ negative\ for\ an\ n-type\ material.$

The mobility of the charge carrier (μ) may be determined, knowing the conductivity of the material (σ), its carrier density (n) and charge (q).

(3) $$\mu = \frac{\sigma}{\mathrm{nq}}$$

Procedure

The magnetic field strength of an electromagnet was recorded at increments of 0.25 A from 0 to 4A using a Gauss Probe. A conductive sample was placed between the poles of the calibrated electromagnet. A current of 5mA was passed through the sample perpendicular to the magnetic field and the terminals of a voltmeter that contacted the sample (See Figure 3).

The strength of the magnetic field experienced by the sample was varied by increasing the current through the electromagnet at increments of 0.25A. The voltage was recorded across the sample for each current through the electromagnet and its associated magnetic field strength in Tesla. The magnetic field direction was reversed the process repeated to account for electromagnet misalignment. The offset voltage for each magnetic field strength was calculated using the following formula:

$$V_{offset} = \frac{1}{2}(V_{H1} - V_{H2}) \qquad (4)$$

The apparatus was as shown in Figure 4.

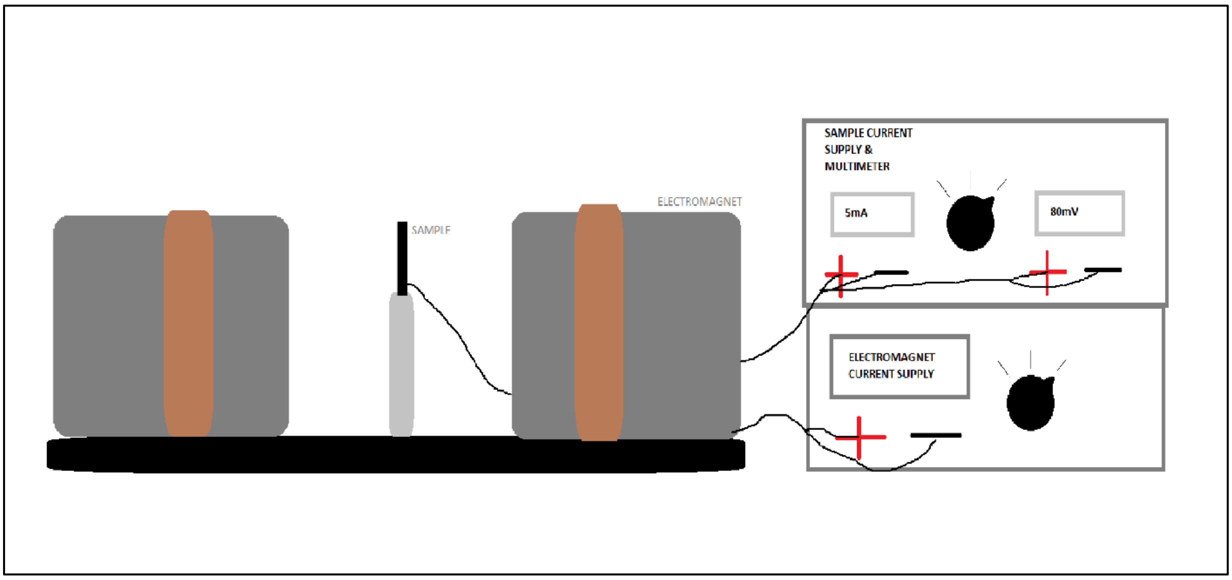

Figure 4: Semiconducting sample placing between electromagnetic poles having current passed through it to induce a hall voltage.

Two samples were tested and both germanium. The plot of the offset voltage vs the magnetic field was used to calculate the Hall Coefficient (see Equation 1) and hence carrier density (See Equation 2) and carrier mobility (see Equation 3).

Results

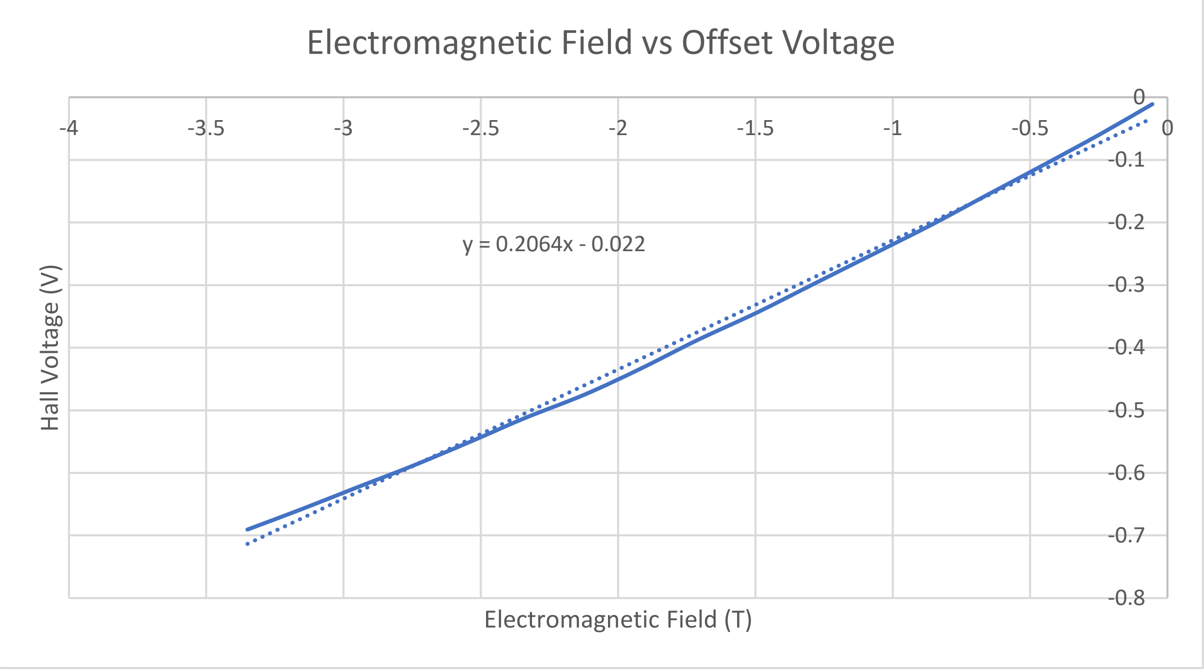

Figure 5: Plot of magnetic field against offset hall voltage for germanium sample 3361 placed in an electromagnet and experiencing a current.

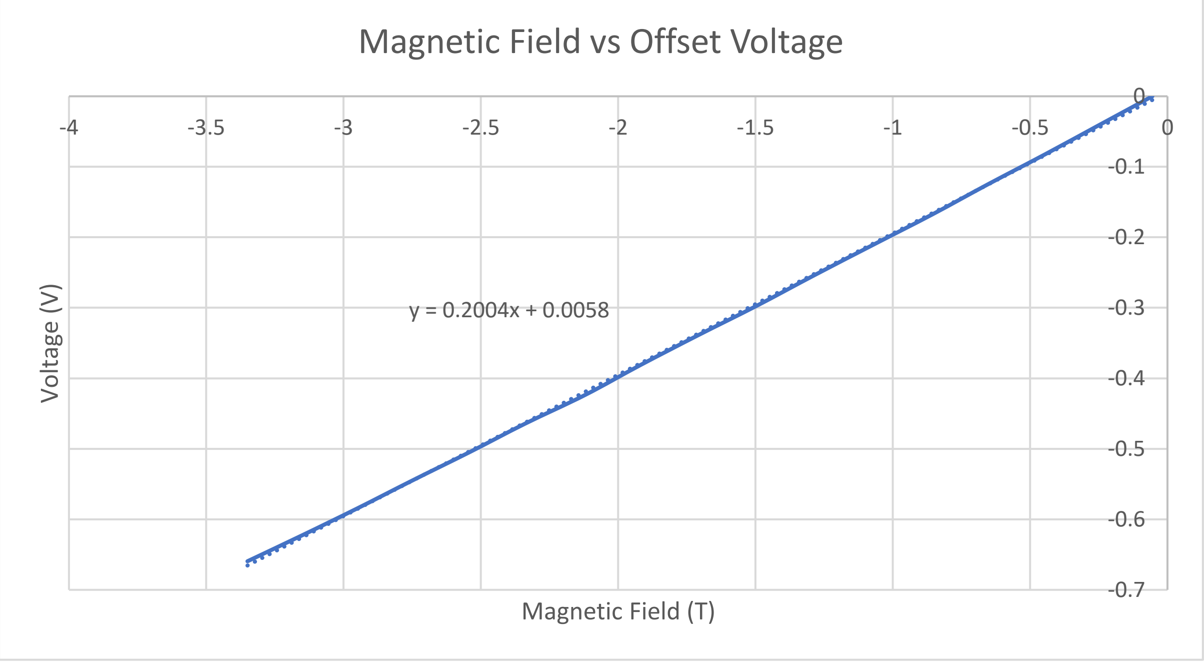

Figure 6: Plot of magnetic field against offset hall voltage for germanium sample 3375 placed in an electromagnet and experiencing a current.

Sample	**Majority Carrier Type**	**Hall Coefficient (cm^3C^{-1})**	**Carrier Density (cm^{-3})**	**Carrier Mobility ($cm^2V^{-1}s^{-1}$)**
3361	p-type	20600 ± 1080	$3.03 \pm 0.16 \times 10^{13}$	$2.943 \pm 0.17 \times 10^{3}$
3375	n-type	20000 ± 1080	$3.12 \pm 0.16 \times 10^{13}$	$3.333 \pm 0.17 \times 10^{3}$

Table 1: Properties of the tested germanium samples as determined using Equations 1, 2 & 3.

Discussion

Inaccuracy

The experiment has a number of sources of inaccuracy. The instruments themselves have intrinsic inaccuracies. The voltmeter and current sources are accurate to ±0.1mV and ±0.1mA respectively. The Gauss probe had an accuracy of ±0.1 Gs.

The gradient of the plots in Figure 5 & 6 were not perfectly linear and so an inaccuracy of ±5% was applied to the gradient and carried through the results calculations. The inaccuracy for the Hall Coefficient is ±1080, the carrier density is ±0.16x10E13 and the carrier mobility is ±0.17x10E3.

Additional sources of inaccuracy are the misalignment of voltmeter probe terminals though this should have been accounted for by calculating the offset voltage (see Equation 4).

The Ettingshausen and Nernst (Righi-Leduc) Effects also contribute to errors in the data collected. The Ettingshausen Effect is where charge carriers with a greater velocity are deflected more than others creating a temperature gradient that induces an additional voltage which affects the hall voltage. The Nernst effect is also due to a temperature gradient which generates current perpendicular to the hall voltage and magnetic field, this also alters the reading of the hall voltage.

The Ettingshausen effect cannot be corrected by calculating an offset voltage for reversed magnetic field or current however the Nernst effect can be accounted for by reversing current. This process could be used to improve the experimental data in the future.

The magnitude of these effects on the data for this experiment have however been deemed negligible.

Hall Effect Applications

The data obtained can and has been used to calculate the conductive properties of a semiconducting material. This is useful as the information can be used to determine the possible applications of a material for certain tasks, such transistors in small electronics.

The hall effect can also be used in sensors. Many pedal systems for vehicles use this effect to generate a voltage due to a moving magnetic field. A magnet is attached to a pedal and when the pedal moves the induced voltage magnitude determines the angle that the pedal has been pushed to. Often switches in integrated circuits are triggered by a moving magnetic field inducing a voltage i.e. the Hall Effect.

Intrinsic Semiconductors

Intrinsic semiconductors do exhibit extrinsic conduction. Extrinsic conduction is caused by having free holes or electrons, intrinsic conduction is caused by thermal agitation exciting electrons from the valence band to the conduction band of a material (see Figure 7).

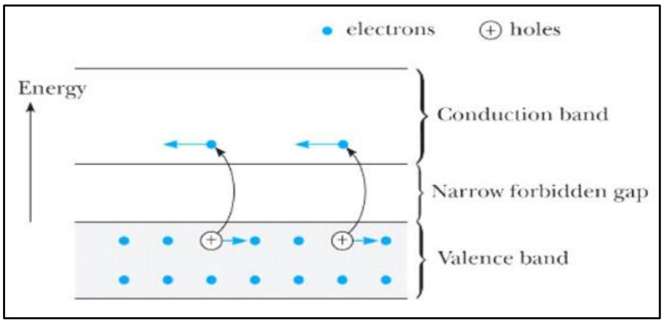

Figure 7: Thermal agitation of electrons in a semiconductor to the conduction band form the valence band (aka intrinsic conduction).

The samples of germanium in this experiment were kept at a relatively constant temperature. The increase in temperature due to heat dissipation in the material was negligible as the current was only 5mA. Therefore, the hall voltage generated must be attributed to extrinsic conduction and hence was observed for a intrinsic semiconductor.

Based on the analysis of force direction described in the introduction of this report (see Figure 2) the materials, though undoped, exhibited a clear majority charge carrier. This occurred despite pure semiconductors being modelled as having an equal number of holes and electrons. The results may be explained by crystallographic defects and imperfections in the material.

Furthermore, the change in hall voltage with increasing magnetic field in combination with the right-hand rule demonstrated that germanium sample 3361 had positive majority charge carriers. This is as it is known that both positive and negative charge carriers are deflected in the same direction and hence it could be determined which carrier was influences the change in voltage. Similarly, the sample 3375 was determined to be an n-type material.

Conclusion

The hall effect was effectively used to determine the conductive properties of two samples of germanium. Most notably sample 3361 was found to be a p-type material with carrier density 3.03 ± 0.16 x 10^{13} cm^{-3}, validating the presence of positive charge carriers. Sample 3375 was found to be an n-type material with carrier density 3.12 ± 0.16 x 10^{13} cm^{-3}. This means that despite both samples being “intrinsic” materials there was a difference majority charge carrier for both hence even pure semiconductors exhibit extrinsic properties.

Bibliography

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[2] M. Design, "Energy band structure of germanium," materials design, 2018. [Online]. Available: http://www.materialsdesign.com/appnote/energy-band-structure-germanium.