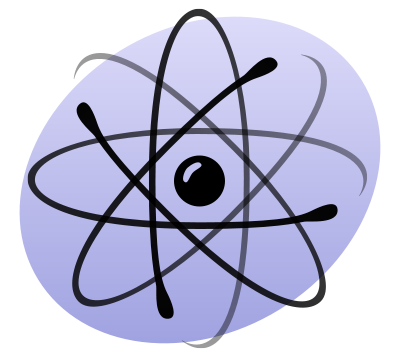
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PHYS2170: Investigation of the Hall Effect in Semiconductors

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# 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 3.03x1013 ± **XX** cm-3. Sample 3375 was found to be an n-type semiconductor with a carrier density of 3.12 x1013 ± **XX** cm-3.

# 

# 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”.

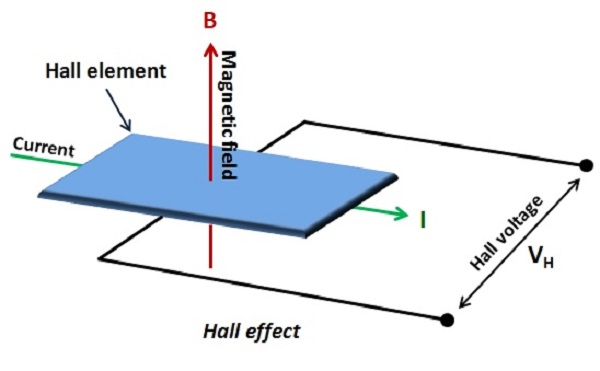


Figure 1: Magnetic field and current applied to a conductor generating a hall voltage (source: dangerousprototypes.com)

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.

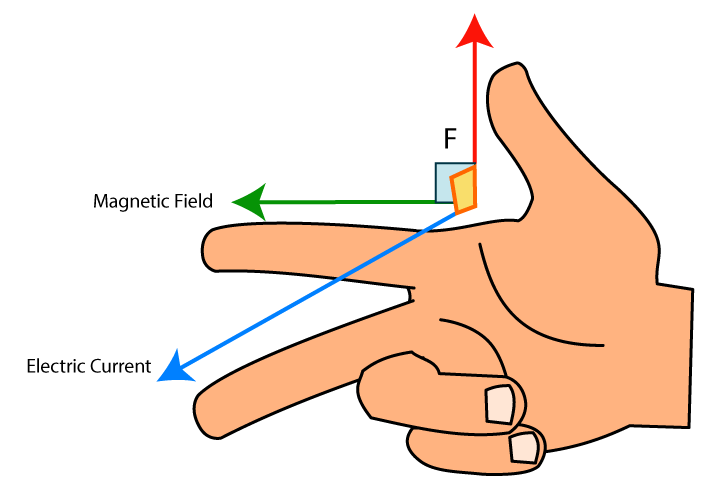


Figure 2: Right-hand rule, indicating the direction of force acting on a positive charge carrier.

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

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

If the charges in Figure 1 are positive and the current direction is taken as positive, then If the charges were negative the current direction would be opposite but so would the sign on the charge therefore,

and hence. 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.

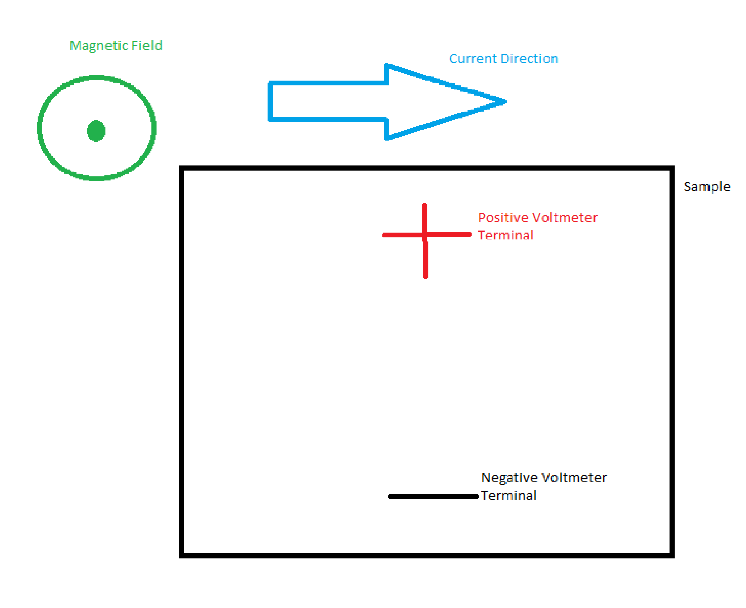


Figure 3: Conducting material experiencing hall effect due to current and magnetic field.

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 – RH), by:

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

# 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:

The apparatus was as shown in Figure 4.

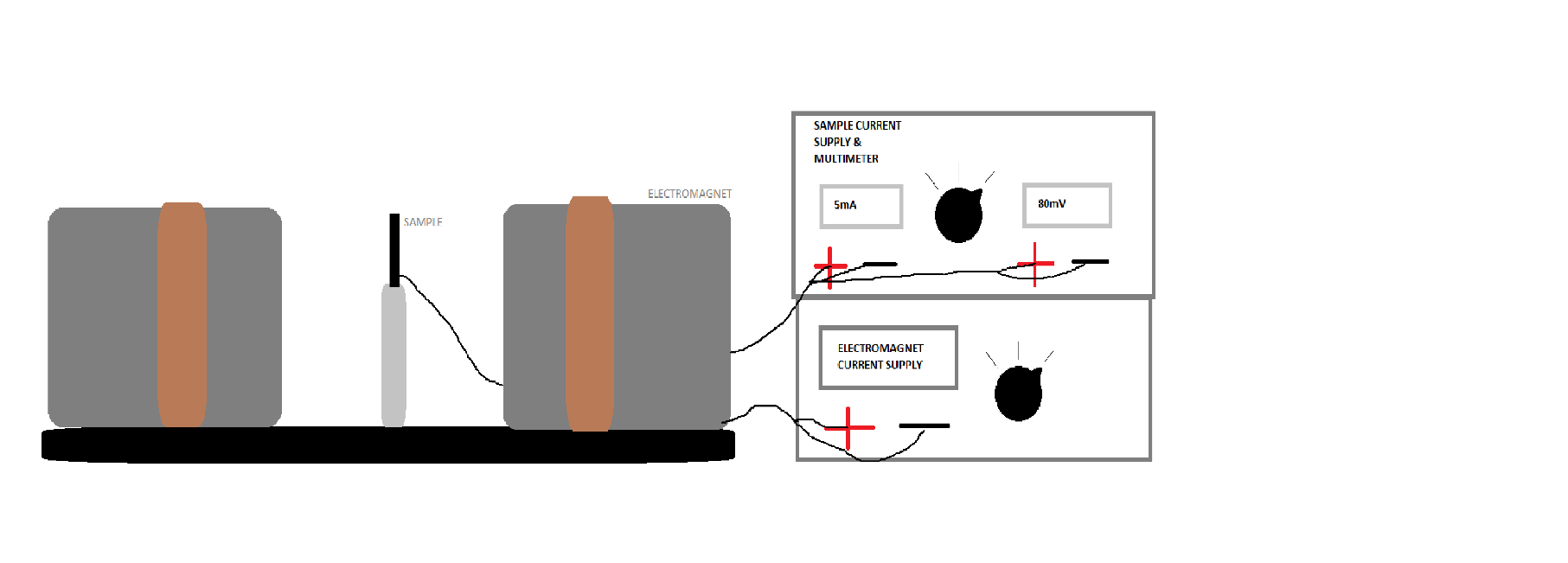


Figure : Semiconducting sample placing between electromagnetic poles having current passed through it to induce a hall voltage.

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

Figure : 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 (cm3C-1)** | **Carrier Density (cm-3)** | **Carrier Mobility (cm2V-1s-1)** |
| 3361 | p-type | 20600 ± **XX** | 3.03 x 1013 ± **XX** | 2.943 x 103 ± **XX** |
| 3375 | n-type | 20000 ± **XX** | 3.12 x 1013 ± **XX** | 3.333 x 103 ± **XX** |

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

# Discussion

## Inaccuracy

This experiment was conducted affected by several inaccuracies. The instruments used all had associated inaccuracies, for example the thermometer±1 °C. The four-probe method assumes a number of parameters are correctly setup such as alignment of the probes and perfect contact of the probes. These things are easily executed imperfectly due to human error additionally the instrument has an associated inaccuracy of ±0.1% and ±0.1mV for the voltmeter and ±0.25% and ±0.1mA for the current generator.

In the calculation phase as the results did not produce an exactly linear plot (see Figure 5) the data was linearly fitted. The approximation affected the basis of the calculation to obtain the energy gap of the germanium sample (see Appendix- Calculations 1). Unsurprisingly the results obtained, 0.5160 eV for experimental data and 0.4429 eV for calculated data, were some 20 – 40% different to the actual value for the band gap of germanium which is 0.66 eV [1]. Due to imperfect data however, this compromise is necessary.

There was a single outlier in the measured data (see Figure 5) which can be attributed to a displacement of the instrumentation causing imperfect contact with the sample. It also could have been cause random event in the hardware.

The four-probe method, though imperfect, is still superior to other method of measuring the resistivity of a material. Because the millivoltmeter is applied in parallel with the sample (see Figure 6) and it has a high impedance (10MΩ) it does not draw any current out of the circuit and affect the calculation of the resistance of the material. This calculation is based on Ohm’s law.

If the method of soldering wires onto the sample, the associated resistivity of the soldering and wires would contribute to the series resistance calculated by the probe that is mean to represent that of the sample. This in turn would generate inaccurate data, more so than data generated by the four-probe method. Comparatively the series resistance contributed by the four-probe method is very small.

The experimental data’s qualities could be improved by an increased number of trials and greater care to implement the four-probe method’s setup.

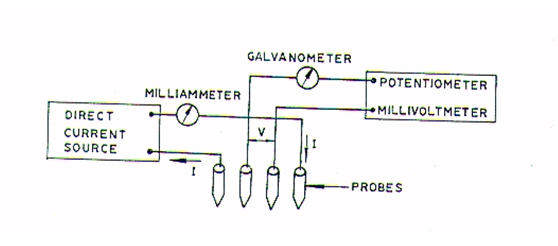


Figure 6: Four-probe method’s individual contacts diagram.

## Data Analysis

The near-linear sections of the plot in Figure 5 which are positively sloped indicate that as the sample cooled the resistance of the sample rose. This implies that the materials conductivity increased with temperature.

The reason that the germanium’s conductivity rose as the sample was heated is that the thermal energy is transferred to the electrons and agitates them. If the agitation is sufficiently large the electrons may be pushed across the band gap and into the conduction band. This generates a hole in the valence band (p-type) which is a positive charge carrier. It also creates an extra electron in the conduction band (n-type) which is a negative charge carrier. This is called *intrinsic* conduction.

Figure 7: Ideal plot of change in conductivity due to temperature

In Figure 7 above, which is an ideally linear shaped dummy plot, the flat areas of the plot indicate regions of *extrinsic* conductivity, as temperature has no affect on this region. Therefore, for sufficiently small temperatures insufficient energy is supplied to electrons to cross the band gap. This is the conductive behaviour of the material without extra energy and it can be improved via doping.

By accounting for errors of ±5% in the linear fit of the plots, the uncertainty in the band gap was found to be ±0.026 eV.

# Conclusion

By using the relatively accurate four-probe method to measure the resistivity of a germanium wafer and observing the wafer’s changing resistivity as a function of temperature the band gap of germanium could be found. The measure value was 0.516 ± 0.026 eV and the calculated value was 0.4429 ± 0.026 eV. Disparity between the calculation and the measured value is likely due inaccuracies in measurements also the nature of the linear fit method used in excel. Likewise, this is the justification for the difference in found values and the actual value for germanium’s band gap of 0.66 eV [1].

# Appendix

## Calculations

1. *Calculation of the bandgap from the gradient of the linear fit plot Figure 5. ln(ⲣ) vs 1/T .*

*Therefore,*

*Hence,*

# Bibliography

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