Characterising the Semiconductor Properties of Germanium via the Hall Effect

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Abstract

This experiment aims to characterize the semiconductor properties of germanium using the Hall effect and a four-point probe measurement technique. We investigated the temperature-dependent resistivity of a doped germanium crystal under varying current strengths, heating levels, and magnetic field intensities. The experimental setup involved recording voltage readings across seven points on the crystal, enabling us to plot the natural logarithm of the inverse voltage against inverse temperature. A linear fit in the high-temperature regime allowed for extracting the band gap energy E_g of germanium, calculated as 0.41 ± 0.01 eV, in agreement with theoretical expectations. While initial results are promising, further refinements—such as correcting the alignment of Hall voltage probes and conducting low-temperature measurements with liquid nitrogen—are necessary. These additional measurements will help in the accurate determination of the Hall coefficient, electron mobilities, and other fundamental properties of germanium, ultimately providing a comprehensive understanding of its behavior as a semiconductor.

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1 Components completed thus far

Note: for all measurements mentioned below, we've been recording the readings for all 7 voltage probe points wired into the germanium crystal, and the thermocouple reading.

- Experimenting with current source strength: 1mA, 3mA, 10mA and 30mA without any heating or magnetic field. The same kind of behaviour was found for different current strengths, so 10mA was used for the rest of the experiment.
- Experimenting with the heating element: 6V, 12V and 18V applied to the resistor to see how it affected the heating of the sample. It was found that the sample simply heated up faster and to a higher temperature, so we used 18V for the rest of the experiment when heating the sample (which brought it up to 80 degrees Celsius).
- Experimenting with the magnet strength: we adjusted the power source until the magnetic field sensor had readings of 50, 100, 200, 300, 350 mV, with and without heating the sample. The sample was heated and then placed inside the magnet, and we let the run go until the sample cooled back down to room temperature

2 Measurements planned

- While making the analysis for the plots above, we realized that we might've misaligned the V1 and V2 connections with the magnetic field, meaning they did not measure the Hall voltage correctly. We will therefore retake our measurements in order to have accurate Hall voltage readings.
- Liquid nitrogen will be used to cool the sample to colder temperatures and allow it to warm to room temperature while in the magnet, to observe the behaviour of the germanium in colder temperature regimes.

3 Hypothesis and theory

The overall goal of this experiment is to investigate various properties of germanium as a semiconductor. One of these properties we can understand is the band gap energy, E_g, that we can investigate with our four-point-probe setup. To do this, we can consider the resistivity of our sample, which we can get from the applied current and our measured voltages along with measurements taken of the germanium sample.

Electrical conductivity is given by $\sigma = \rho^{-1} = \frac{Il}{VA}$, where l is the length of the sample and A is the cross-sectional area. We can compute this from the measured voltages during our runs, as well as measurements taken of the sample itself. However, this conductivity will also be temperature dependent via an exponential relationship for the semiconductor: $\sigma(T) = \sigma_0 \exp(-\frac{E_g}{2kT})$ [1]. This expression describes the conductivity of the material at high temperature since the intrinsic effect dominates over the effects of the dopants. This means we can get a value for the band gap energy by plotting $\ln(\sigma)$ vs T^{-1} and fitting for the slope in the high temperature region where the logarithmic relationship is linear [2].

With the data we have acquired so far, we have taken the voltage readings from channel V5 and made the following plot of $\ln(V^{-1})$ vs T^{-1}. We fit a degree one polynomial only in the high temperature range since this is where we expect the relationship to be linear.

From the linear relationship, we have slope $= \frac{-E_g}{2k_B}$ and intercept $= \ln(\frac{\sigma_o A}{IL})$. Fitting for these and solving for E_g and σ_o, we found values for the band gap energy, $E_g = 0.41 \pm 0.01$ eV, and for the intrinsic conductivity of the material, $\sigma_o = (6 \pm 1) \times 10^4$ S/m. The theoretical value for the band gap energy of pure Germanium at 300K is 0.66 eV [3]. Since our sample is doped, we don't expect to obtain exactly this value as we are only approximating that the material acts as an intrinsic semiconductor at high temperatures. However, we currently get the right order of magnitude which is a good indication that with further measurements and by taking into account other effects, we can get a good estimate of our sample's band gap energy.

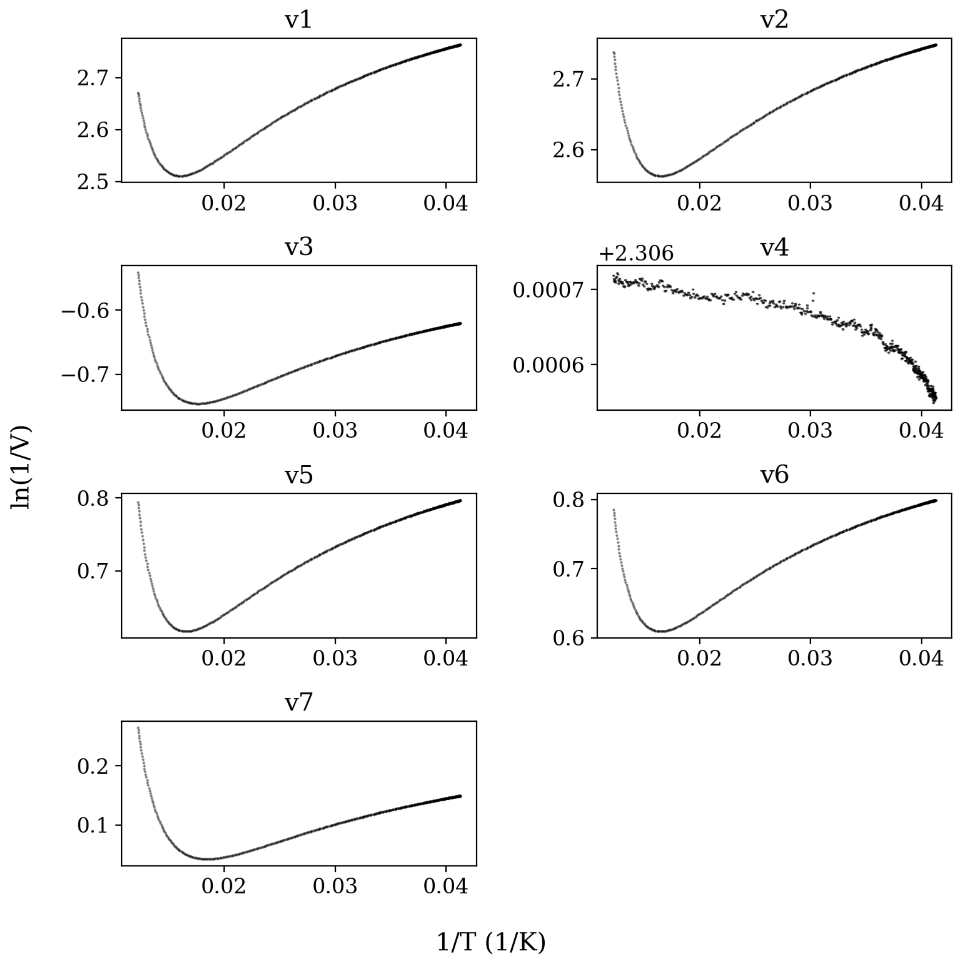

Figure 1: **Voltage readings across all seven voltage probes on the germanium crystal.** Natural log of the inverse voltage reading is plotted as a function of inverse temperature, across v1 and v2 (Hall voltages), v3 (transverse voltage), v4 (voltage across resistor inside current source), v5 and v6 (transverse voltages along the sample), and 7 (voltage between side and bottom of sample).

These values were found using only a single run of data at a specific magnetic field and current, so doing more runs and averaging the fit values will reduce errors. We will also be able to cross check the conductivity values using our Hall voltage measurements once we retake them. However, we may be limited by the maximum temperature our sample can reach, as this limits the temperature range over which we can fit a linear function to get the band gap energy.

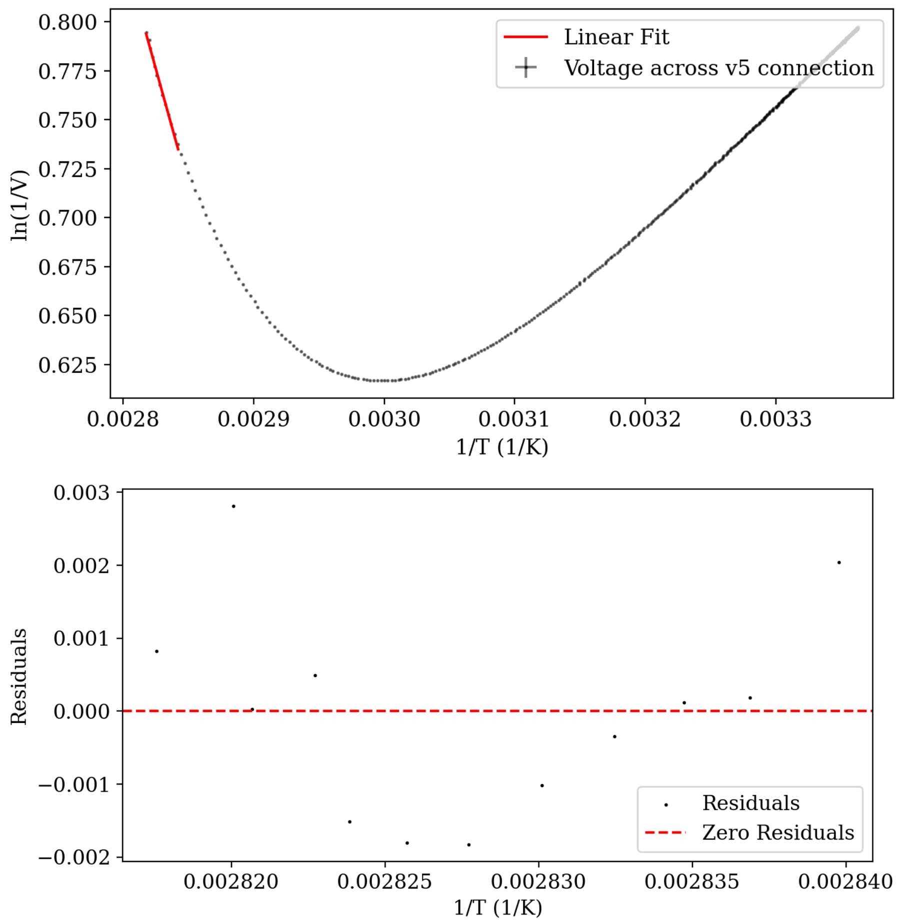

Figure 2: **Transverse voltage readings across the germanium crystal as a function of temperature.** Natural log of the inverse voltage reading is plotted as a function of inverse temperature, and a linear fit is applied at high temperature.

At low temperatures, we will be able to investigate more directly the semiconductor properties such as the Hall coefficient and electron mobilities [4]. We will also be able to analyze the Hall effect by looking at these mobilities, all of which will also be done by analysing the inverse temperature graphs [4].

References

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