The Hall Effect in Silver and Tungsten

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Silver and tungsten samples were used to examine the Hall effect and determine their Hall constants. While the data from tungsten was less than satisfactory, silver provided excellent results. The questionable results from tungsten are most likely attributable to thermal effects due to tungsten's higher resistance. Based on the results, it would appear that the primary charge carriers in silver and tungsten are of opposite sign.

In 1879, E.H. Hall discovered the effect that bears his name at the Johns Hopkins University while studying under Rowland.[1] His investigation of the mechanism of conduction was an important step forward in solid state physics and gave direct evidence of the sign of charge carriers. He found that when a current traveling in a metal bar was subjected to a perpendicular magnetic field, a potential difference developed along the direction perpendicular to both the current and magnetic field. This potential increased with a larger current and magnetic field and was given by

$$V_H = R_H \cdot \frac{B \cdot I}{d} \tag{1}$$

where R_H is the Hall constant, B and I are the magnitudes of the magnetic field and current respectively, and d is the thickness of the metal bar. This experiment seeks to find the Hall constant R_H for silver and tungsten.

EQUIPMENT

The apparatus used is from Leybold-Heraeus and includes:

- U-core electromagnet
- $50\mu m$ thick Silver and Tungsten samples (mounted)
- B-field probe
- Teslameter
- Microvoltmeter
- High current power supply
- Variable extra low voltage transformer
- Ammeter

The B-field probe and teslameter were used to calibrate the magnetic field, the extra low voltage transformer and ammeter were used to generate and measure the current through the electromagnet, the high current power supply provided the current through the metal samples, and the microvoltmeter measured the Hall potential.

The microvoltmeter was connected to a PC via an A/D converter card and was used with LabVIEW to acquire data over an extended period of time.

PROCEDURES

This experiment roughly consisted of two parts: calibration of the magnetic field and the measurement of the Hall effect. The procedures used are outlined as follows.

Calibration of the Magnetic Field

For obvious reasons, the magnetic field passing through the metal sample needs to be known in order to calculate the Hall constant. However, when the sample is placed in the electromagnet, there is not enough space for the B-field probe. So, the magnetic field must be determined from the current through the electromagnet (and hence requires calibration).

Without anything between the two magnetic pole pieces besides the B-field probe, currents from 0-9 Amps were tested at 0.5 Amp increments. At each current value, the magnetic field was recorded. Since the measurements for tungsten and silver were completed on separate days (10/5/2006 and 10/6/2006 respectively), calibration curves were created on each day and can be seen in Figure (1).

Measurement of the Hall Potential

After calibrating the magnetic field, the metal sample was positioned midway between the magnetic poles (and centered). With the current held constant, nine different magnetic fields (within the range of the calibration curve) were applied and then repeated for a different current or sample. The acquisition time for each measurement was varied in order to minimize uncertainties and was roughly inversely proportional to the current. The times used can be seen in Table (I).

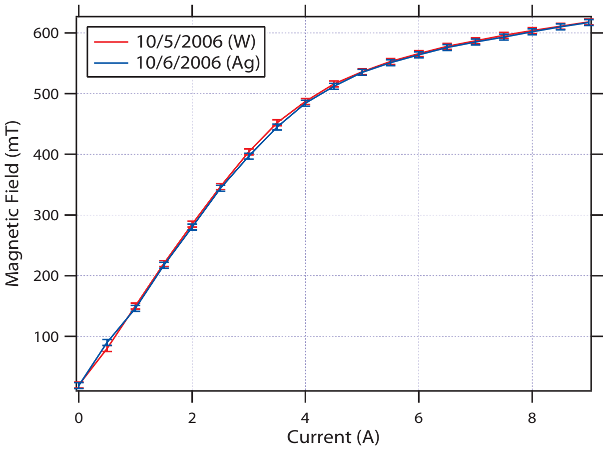

FIG. 1: The calibration curves used for determining the magnetic field through the tungsten and silver samples when measuring the Hall potential.

Sample	Current (A)	Time (s)
Tungsten	5.0	45.0
	10.0	30.0
Silver	10.0	20.0
	15.0	15.0
	20.0	10.0

TABLE I: The acquisition times for each current/sample combination.

ANALYSIS

The data collected is presented in Figure (2) along with linear fits of each curve. As one can see, the linear relation between the Hall voltage and magnetic field is better illustrated by silver. Tungsten, on the other hand, had several anomalous points, especially at higher magnetic fields. For each curve, a linear fit was applied to the points which best represented a line.

The slopes of these lines should be equivalent to $R_H \cdot \frac{I}{d}$ as Equation (1) would suggest. Thus, R_H can be determined by

$$R_H = \frac{d}{I} \cdot (slope) \tag{2}$$

The values for R_H obtained with this method appear in Table (II) along with their uncertainties.

Silver

For the silver sample, we find that the the lower currents are closer to the true value of $8.9 \times 10^{-11} \frac{m^3}{C}$ with about 14% error. The fact that the higher current is farther from the accepted value is understandable; heating effects become greater with higher current while there is more noise for lower currents (requiring longer acquisition times). Since the measurements with 10 and 15 Amps have a satisfactory amount of uncertainty (equivalent to that of the 20 Amp measurements), their values can be accepted as more trustworthy.

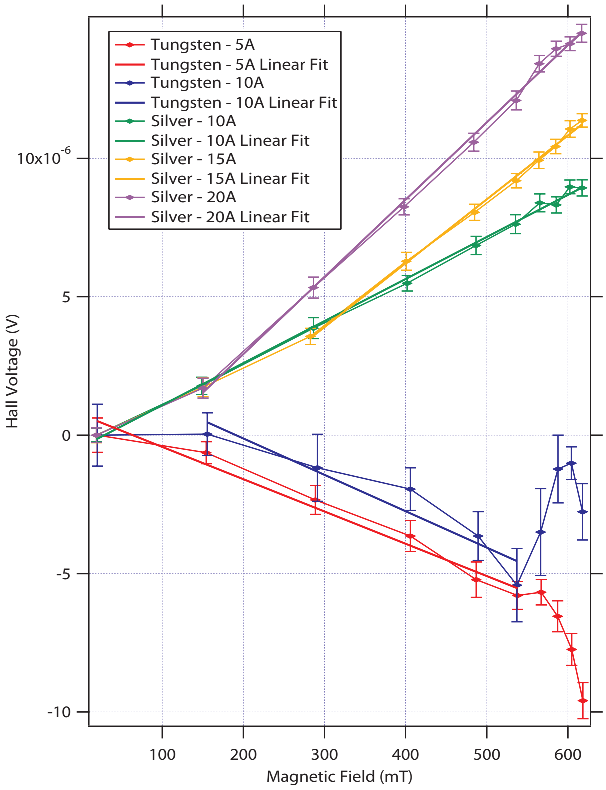

FIG. 2: The Hall potentials measured for varying magnetic fields in tungsten and silver with different currents.

Sample	Current (A)	R_H $(\times 10^{-11} \frac{m^3}{C})$
Tungsten	5.0	-11.7 ± 1.0
	10.0	-6.6 ± 1.3
Silver	10.0	7.6 ± 0.13
	15.0	7.7 ± 0.15
	20.0	7.0 ± 0.13

TABLE II: The Hall constants, R_H, obtained for each data set.

Tungsten

Unfortunately, the data taken with tungsten did not turn out very well. Even though the acquisition times were much longer, the uncertainty was still an order of magnitude greater. Additionally, there was quite peculiar behavior above 550 mT, especially for the 10 Amp measurements which actually started to decrease in magnitude.

The shape of the curves below 550 mT almost seem parabolic, making a linear fit inaccurate and casting doubt on any obtained results. One possible explanation is heating due to the high current. This would have affected tungsten more than silver due to its higher resistivity and lower heat capacity. Since the measurements were completed from low to high magnetic fields, there would have been a positive correlation between temperature and magnetic field.

Based on Equation (2) and the fact that $R_H = \frac{1}{n \cdot e}$ where n is the charge carrier concentration and e is the charge, we obtain

$$slope = \frac{I}{d \cdot n \cdot e} \tag{3}$$

In an attempt to explain the increase in magnitude of the slope, consider the thermal expansion of materials. While an increase in d would imply a decrease in slope, it would also suggest a decrease in charge carrier concentration, n. Since n would go as $\frac{1}{d^3}$, we should expect the slope to go as d^2. While this would explain the parabolic behavior, considering the magnitude of this effect would suggest otherwise. Tungsten's coefficient of linear expansion is approximately $4.5 \times 10^{-6} K^{-1}$ at room temperature and would only allow for an increase in slope of less than 0.1% for a generous $80°C$ increase in temperature.

CONCLUSION

The Hall constant of silver was determined fairly well while the value for tungsten was only accurate enough to measure its sign. While it has been shown that the inaccurate results from tungsten are not due to thermal expansion, it is likely that there is some other thermal effect taking place.

The fact that silver and tungsten have Hall constants of opposite sign is of particular interest. This would seem to indicate a difference in the sign of the charge carriers. However, this is contrary to our knowledge that electrons, which are negative, are the charge carriers in metal conductors. This can be explained with "holes", which are locations where an electron is absent. These act just like positive charge carriers and would explain the difference in signs. If this hypothesis is correct, it would mean that silver and tungsten conduct electricity by different carriers (on average): one with electrons and the other with holes.

To reduce some of the errors, it could have been helpful to have taken data with a reversed magnetic field. This would have provided more data points over a larger range, allowing for more accurate linear fits.

[1] Purcell, Edward M. Electricity and Magnetism. Vol. 2. 2nd ed. Boston: McGraw-Hill, 1985.