Hall Effect

Onderzoeken 5

Brian de Keijzer
Julia Norbart

Vak	Onderzoeken 5
Klas	NH2B
Docent	dr. ir. J. B. Oostinga

June 4, 2018

THE HAGUE
UNIVERSITY OF
APPLIED SCIENCES

Hall Effect

Onderzoeken 5

by

Brian de Keijzer
Julia Norbart

Names:	Brian de Keijzer	Julia Norbart
Studentnumbers:	16011015	16083946
Emails:	16011015@student.hhs.nl	16083946@student.hhs.nl

THE HAGUE UNIVERSITY OF APPLIED SCIENCES

Summary

Brian de Keijzer
Julia Norbart
Delft, June 4, 2018

The research question to be answered is as follows. What is the charge carrier density of silver? The experimental results are as follows. The Hall coefficient of silver is determined to be: $R_H = (8.3 \pm 2) \cdot 10^{-11} \mathrm{m}^3\mathrm{C}^{-1}$. The literature value for the Hall coefficient of silver is [1] $\mid R_{Hliterature} \mid = (8,9 \pm 2) \cdot 10^{-11} \mathrm{m}^3\mathrm{C}^{-1}$. The charge carrier density of silver is determined to be $n = (7.4 \pm 2) \cdot 10^{28} \mathrm{m}^{-3}$. Of which the literature value is equal to [1] $n_{literature} = (6.6 \pm 2) \cdot 10^{28} \quad \mathrm{m}^{-3}$. Out of these results it is concluded that the experimental results are in agreement with the literature values.

Contents

1 Introduction

The Hall voltage is a voltage due to the Hall effect. This effect is often use in modern equipment. In this report the Hall effect will be explained and used to measure the hall voltage. The Hall coefficient is defined as the ratio of the induced electric field to the product of the current density and the applied magnetic field. This coefficient depends on the material from which the conductor is made. In this experiment, the material that will be used to measure the Hall voltage is silver.

The research question is as follows:

- What is the charge carrier density of silver?

2
Theory

In this chapter the fundamental physics behind the Hall effect will be discussed. The Hall coefficient and charge carrier density will also be discussed. These both are unique material properties, which are related to each other. How so will become clear at the end of this chapter.

2.1. The Hall effect

When an electric current I flows through a conductor perpendicular to a magnetic field B, it results in a transverse force F_m on the moving charge carriers due to the magnetic field. Those charge carriers are pushed to one side of the conductor due to the Hall effect. All the chargers are building up at one side of the conductor. Because of this, there is a measurable voltage difference between the two sides of the conductor. This measurable voltage difference is called the Hall voltage. This Hall voltage is due is a potential difference due to the Hall effect. This effect is called after E.H. Hall, who discovered the Hall effect in 1897 [bron?]. The change in the direction of the current I is caused by the magnetic force. This force is given by [bron?]:

$$\vec{F} = q \cdot (\vec{E} + \vec{v} \times \vec{B}) \tag{2.1}$$

The quantities belonging to Equation 2.1 are defined in Table 2.1. Because of this force, the positive and

Table 2.1: The quantities belonging to Equation 2.1.

Quantity	Description	Unit
q	Electrical charge	[C]
$\vec{E}$	Electric field strength	[V/m]
$\vec{v}$	Drift speed	[m/s]
$\vec{B}$	Magnetic field	[T]

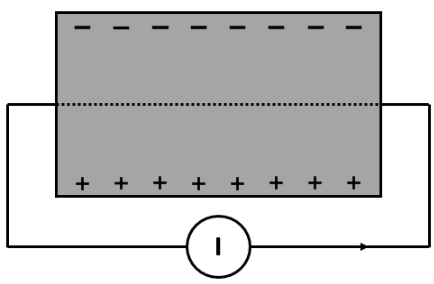

Figure 2.1: A schematic of the coil configuration.

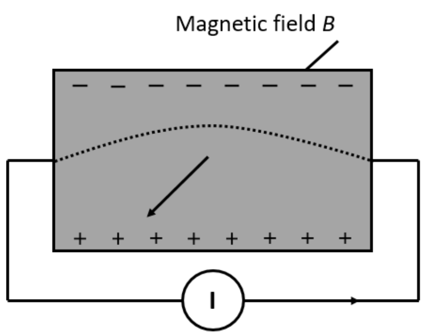

Figure 2.2: The schematic setup for the experimental setup of the Hall effect.

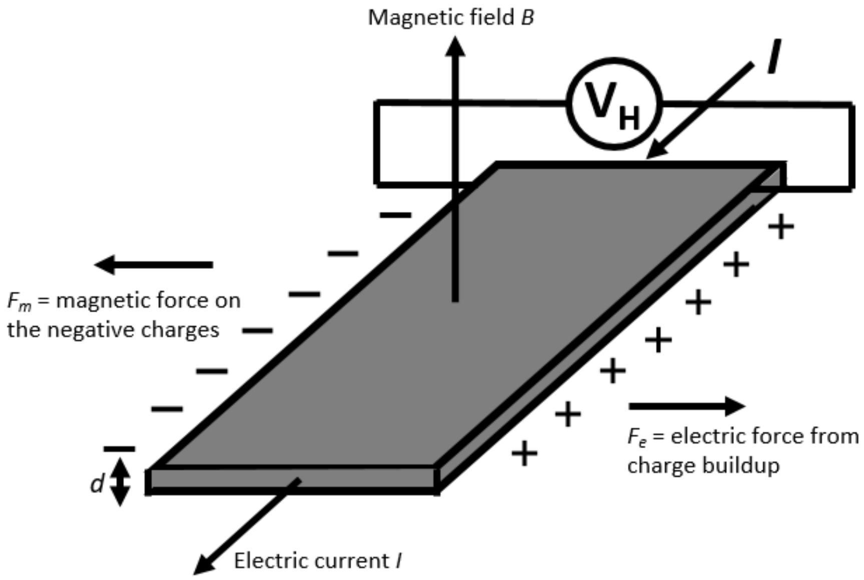

Figure 2.3: A schematic representation of the force on a current due to the Hall effect.

negative charges will have an acceleration in the direction of the force. This results in a change of the path of the charges. Which will lead to a potential difference.
Without magnetic field and thus without the force, the charges will go straight from one side of the material to the other, see Figure 3.1. When there is a magnetic field, the path changes in a curve, see Figure 3.2. The potential different due to this effect is called the Hall Voltage. The Hall voltage is given by:

$$U_H = v_d \cdot B \cdot d \tag{2.2}$$

With the distance d between the positive and negative side of the plate. There also is current of the electrical charge in the negative direction with respect to the electon current, this is the conventional 'hole' current. This current can be written as:

$$I_x = n \cdot tw \cdot (-v_d) \cdot (-e) \tag{2.3}$$

The quantities belonging to Equation 2.3 are defined in Table 2.2. In which e is the elementary charge, being

Table 2.2: The quantities belonging to Equation 2.3.

Quantity	**Description**	**Unit**
n	Charge carrier density	[Electrons/m^3]
tw	The cross-sectional area	[m^2]
$-v_d$	Drift speed	[m/s]
$-e$	Charge of each electron	[C]

equal to [2]:

$$e = (1.602... \cdot 10^{-19} \pm 6.1 \cdot 10^{-9}) \quad [\mathrm{C}] \tag{2.4}$$

This equation can be solved for w and plugged into Equation 2.2 resulting in the Hall voltage:

$$U_H = \frac{1}{n \cdot e} \frac{B \cdot I}{d}. \tag{2.5}$$

2.2. Hall coefficient & charge carrier density

The Hall effect can be used to determine the Hall coefficient, which is an unique material property. this can be done by writing equation 2.5 in the form of

$$U_H = R_H \frac{BI}{d} \tag{2.6}$$

Where $R_H = \frac{1}{n \cdot e}$ is called the Hall coefficient. For silver R_H is equal to [1]:

$$\mid R_H \mid = (8,9 \pm 2) \cdot 10^{-11} \quad [\mathrm{m^3C^{-1}}] \tag{2.7}$$

When the electric charge of the charge carriers in a material is known, Equation 2.6 can be used to determine the charge carrier density. The charge carrier density n is the number of charge carriers per volume. The charge carrier density denotes the number of charge carriers per volume. It is measured in m^{-3}. As any density it can depend on position. It should not be confused with the charge density, which is the number of charges per volume at a given energy [bron?]. The charge carrier density is received by rewriting Equation 2.5 to:

$$n = \frac{1}{e} \cdot \frac{1}{R_H} \tag{2.8}$$

In which R_H is the Hall coefficient and e the elementary charge. The charge carrier density cannot be directly measured. Therefor it has to be experimentally determined. This can be done by using the Hall effect. Silver for example has a charge carrier density of [1]:

$$n = (6.6 \pm 2) \cdot 10^{28} \quad [\mathrm{m^{-3}}] \tag{2.9}$$

It is important to note that the uncertainties of Equation 2.7 and Equation 2.9 are not given by their source. However, their experimental results in comparison with the literature value are given. The difference between these two have been chosen as the uncertainties for Equation 2.7 and Equation 2.9.

3

Experimental procedure

This chapter consists of the experimental setup and measurement procedure. Firstly the required apparatus is specified. After the apparatus is known, the calibration of the magnetic field is explained. At last the measurement procedure for the Hall voltage is discussed.

3.1. Experimental setup

The experimental setup can be divided into two sections. The first section is used to create a magnetic field. A schematic of this part of the experimental setup is shown in Figure 3.1. The maximum continues current supported by the coils is 5 A, this current is supplied by the power supply unit (PSU). It is possible to supply the coils with a higher current, for example 15 A. However, this has to be in a relatively short time frame. This is so the coils do not get damaged. A list of the required apparatus is shown in Figure A.1, which can be found in Appendix-A. The power supply used to power the coils has to be able to deliver a current up to 5 A. This current is measured with a TTi 1604 digital multimeter. This multimeter is used for all current and voltage measurements. The necessary magnetic field strength to be created is between 0.1 and 0.6 T [1].

The second section of the experimental setup consists of the material on which the Hall voltage is measured.

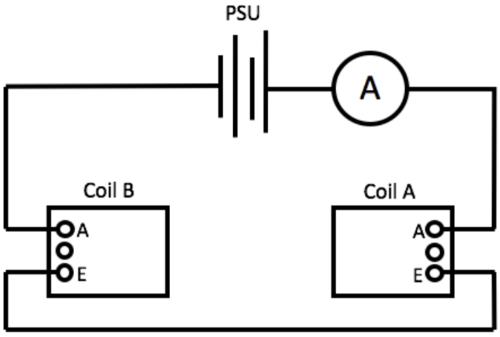

Figure 3.1: A schematic of the coil configuration.

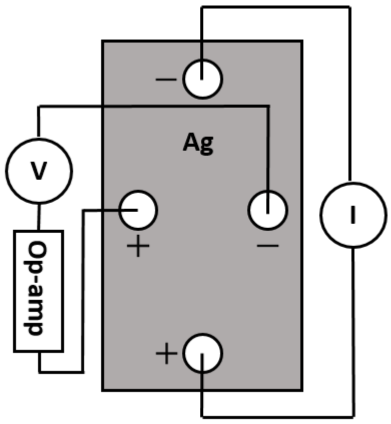

Figure 3.2: The schematic setup for the experimental setup of the Hall effect.

A schematic of this part of the experimental setup can be seen in Figure 3.2. The PSU which supplies the current through the material must be able to supply up to 20 A. The Hall voltage is measured by a multimeter. An operational amplifier (Op-amp) might be needed to amplify the Hall voltage. The need for an Op-amp depends on the material used. Silver for example, has a Hall voltage of 5 μV when a current of 15 A flows through the material, in a 0,2 T magnetic field perpendicular to the flow of current [3]. 5 μV cannot be measured by the TTi 1604 multimeter, therefor an Op-amp circuit is required to amplify the voltage to an order of magnitude which can be measured by the TTi 1604 [4]. The chosen Op-amp is an AD521, which can amplify the signal up to one thousand times. With a maximum output voltage of 30 V [5]. Note that the exact amplification of the Op-amp has to be determined before it is used in a measurement. This can be done by using two multimeters and a signal generator to apply a known signal and measure the Op-amps output. At last a computer with CASSY Lab is required for the data-acquisition of the Combi B-Sensor S. The Combi B-Sensor S measures the strength of the magnetic field at the Hall apparatus center with respect to earth's magnetic field.

3.2. Magnetic field calibration

The magnetic field strength created by the coils as a function of the current through them has to be known. This is due to the fact the magnetic field strength sensor does not fit in between the coils while the Hall apparatus is present. By experimenting it can be seen that the magnetic field in between the coils is homogeneous. For this reason a model for the magnetic field as function of current through the coils can respectively simply be made. This part of the experimental setup can be seen in Figure 3.3.

The magnetic field as a function of the amount of current through the coils is calibrated as follows. The

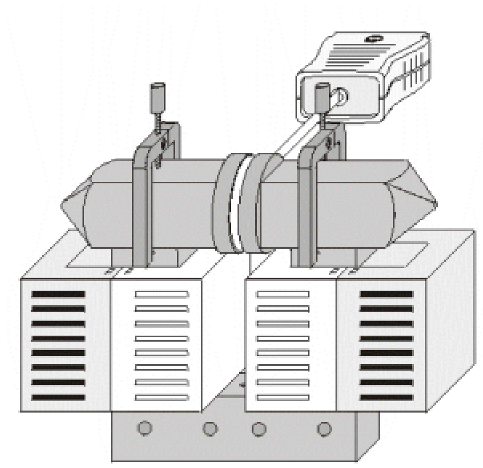

Figure 3.3: Calibration of the magnetic field schematically [3].

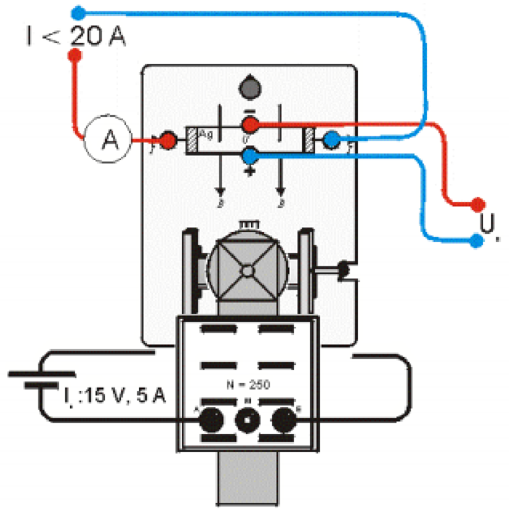

Figure 3.4: The wiring diagram for the experimental setup of the Hall effect [3].

current through the coils is increased by steps of 0,1 A from 0 to 5 A. At each step the strength of the magnetic field is measured. This data can be used to create a mathematical model, which later on can be used to calculate the magnetic field strength when the current through the coils is known. This is done in Chapter 4.1. It is important to emphasize that the hysteresis characteristics of the soft metal surrounded by the coils is ignored due to simplicity.

3.3. Hall voltage measurement

The experimental setup should look like Figure 3.4 when the coils and Hall apparatus are setup according to respectively Figure 3.1 and Figure 3.2. A Hall voltage can be create by two physical situations. When the current flow in the material is constant, the strength of the magnetic field perpendicular to this current flow has to increase. Or when the strength of the magnetic field is constant, the current has to increase. Either one will create a Hall voltage, as long as Equation 2.5 is not equal to zero. Which means that B and I have to be larger then 0.

In case of the current through the coils being a constant, the magnetic field strength perpendicular to the material has to be increased. This is done by starting with 0 A through the coils, going up all the way to 5 A in steps of 0,5 A. This way the magnetic field B can be calculated because the current through the coils is known, the Hall voltage at this specific magnetic field strength can also be measured. This should result in a linear model, since Equation 2.5 is linear.

The same thing goes for a constant magnetic field strength of for example 0,2 T. The current through the material is varied from 0 to 20 A in steps of 1 A. This should also result in a linear model because of the reason

stated above.
In this experiment a Hall apparatus with silver has been used in a 0,3 T magnetic field. It it important to note that two different silver apparatuses have been used with part number ’58681 B2’ & ’58681’. Why this is important will become clear in Chapter 6. When measuring the hall voltage, the offset voltage has to be determined first. This is done by turning off the magnetic field and measuring the offset voltage across the Hall apparatus. Once this is done the magnetic field can be turned on, which will result in a voltage increase due to the Hall effect. The actual difference between the measured voltage with magnetic field and the offset voltage is the voltage due to the Hall effect. One can also reverse the magnetic field to remove any longitudinal impurities in the force vector on the charge carriers.

3.4. Python simulation

Equation 2.5 can be used to simulate experimental results. These simulations can be used to verify the actual experimental results while measuring.

$$U_H = \frac{1}{n \cdot e} \frac{B \cdot I}{d} \tag{2.5}$$

Multiple physical situations have been modelled. In each situation all variables except for one, have been kept constant. These situations give insight in how the Hall voltage changes for different materials in different situations. In each situation Equation 2.4 has been used as the value for the elementary charge e.

4 Results

In this chapter the experimental results will be presented. This will include the data analysis of both the magnetic field strength calibration, the hall coefficient and charge carrier density. The uncertainty calculations are also given.

4.1. Magnetic field strength calibration

The calibration result of the coils are visible in Figure 4.2. It can be seen that the magnetic field strength created by the coils as a function of the current through them is

$$B(I) = 40,4 \cdot I + 0,7678 \tag{4.1}$$

with a correlation coefficient R^2 of 0,9995 and root-mean-square error (RMSE) of 1,35.

4.2. Data analysis

All data analysis has been done in Python. The code can be found in Appendix B. The correlation coefficient R^2 and standard error of the estimated gradient (stderr) are values given by the fit which is created with SciPy. The magnetic field strength calibration has been fitted by using MATLAB.

4.3. Results

The results of sample 1-6 of the Hall voltage measurement of silver are visible in Figure 4.1. In which

$$\frac{U_H}{I} = \frac{1}{n \cdot e} \frac{B}{d} \tag{2.5}$$

is determined to be equal to

$$\frac{U_H}{I} = (0.558 \pm 0.005) \quad [\mathrm{VA}^{-1}]. \tag{4.2}$$

This gives a Hall coefficient of

$$R_H = \frac{U_H}{I} \frac{d}{B} \tag{4.3}$$

$$R_H = 0.558 \cdot 10^{-6} \cdot \frac{5 \cdot 10^{-5}}{0.333} \quad [\mathrm{m^3C^{-1}}] \tag{4.4}$$

$$R_H = (8.3 \pm 2) \cdot 10^{-11} \quad [\mathrm{m^3C^{-1}}] \tag{4.5}$$

and a charge carrier density of

$$n = (7.4 \pm 2) \cdot 10^{28} \quad [\mathrm{m^{-3}}]. \tag{4.6}$$

In which both the uncertainties are equal to the standard deviation of individual results from sample 1-6. These results can be found in Appendix A.

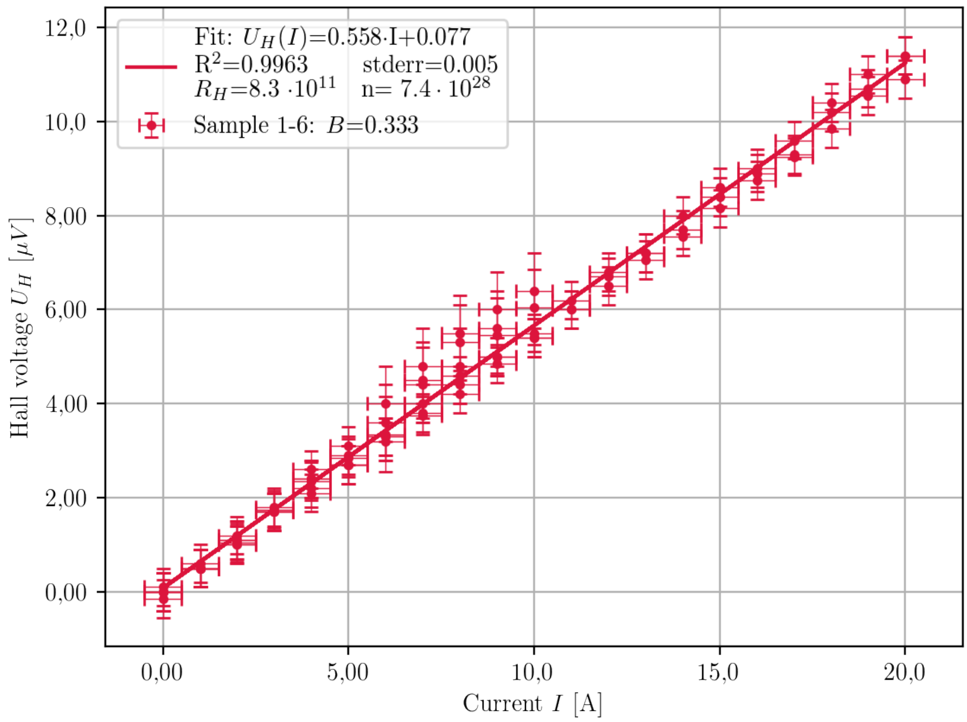

Figure 4.1: Results of sample 1-6 of the Hall voltage measurement with the Hall apparatus (silver).

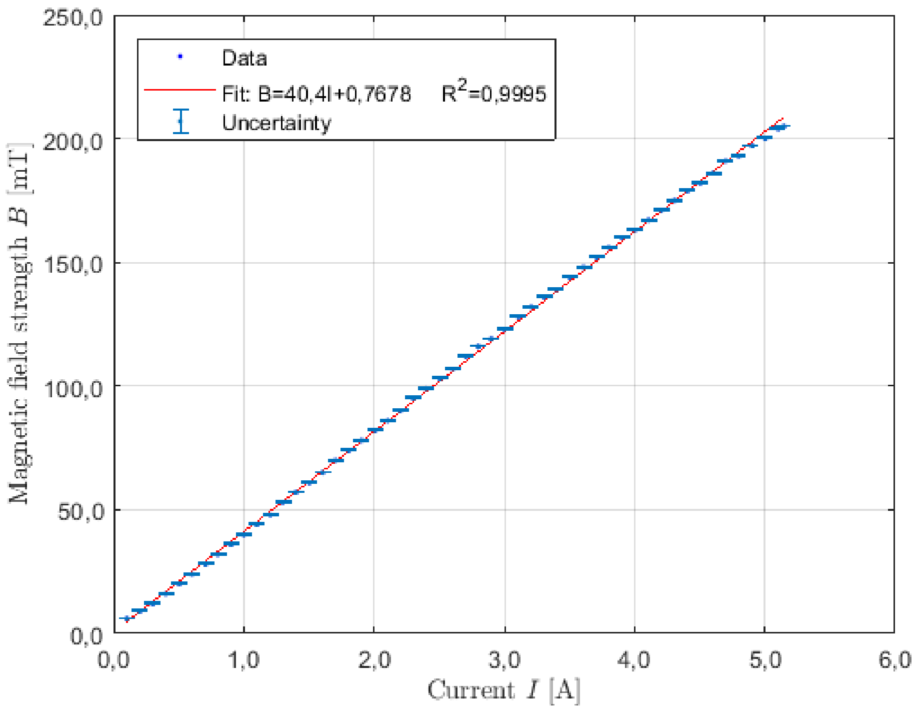

Figure 4.2: Calibration of the magnetic field strength produced by the coils as a function of the current through the coils. This fit has a RMSE of 1,35.

4.4. Uncertainty calculations

The hall coefficient R_H is calculated as follows.

$$R_H = \frac{U_H}{I}\frac{d}{B} \tag{4.7}$$

Of which its uncertainty has to be determined. The uncertainty of d is not known. Therefor it is estimated to be in the same order of magnitude as its given value. Silver for example with a plate thickness $d = 5 \cdot 10^{-5}$ m [1], will have an estimated uncertainty of:

$$\Delta d = 1 \cdot 10^{-5} \quad [\mathrm{m}] \tag{4.8}$$

For ΔB the RMSE of the linear regression fit will be used. For $\Delta \frac{U_H}{I}$ the standard error of the estimated gradient (STDERR) will be used. These are calculated respectively by MATLAB and SciPy, see Appendix B for more information. Finally ΔR_H has to be determined. This is done by using propagation of uncertainty [6]:

$$s_f = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 s_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 s_y^2 + \left(\frac{\partial f}{\partial z}\right)^2 s_z^2 + \ldots} \tag{4.9}$$

where s_f represents the standard deviation of the function f. The standard deviation of x, y, z is represented by respectively s_x, s_y, s_z. Writing Equation 4.7 in the form of Equation 4.9 results in:

$$\Delta R_H = \sqrt{\left(\frac{d}{B}\right)^2 \cdot \left(\Delta \frac{U_H}{I}\right)^2 + \left(\frac{U_H}{I}\frac{1}{B}\right)^2 \cdot \left(\Delta d\right)^2 + \left(-\frac{U_H}{I}\frac{d}{B^2}\right)^2 \cdot \left(\Delta B\right)^2} \tag{4.10}$$

In which $\frac{U_H}{I}$ is assumed to be one variable, since its uncertainty is equal to the STDERR given by the fit of $\frac{U_H}{I}$ done in Python. The error Δx in the final result of the Hall coefficient R_H and charge carrier density n is calculated by using the standard error of the mean which is given by [7]:

$$\Delta x \approx \frac{s}{\sqrt{N}} \tag{4.11}$$

In which s equals the standard deviation in the data set and N equals the number of samples.

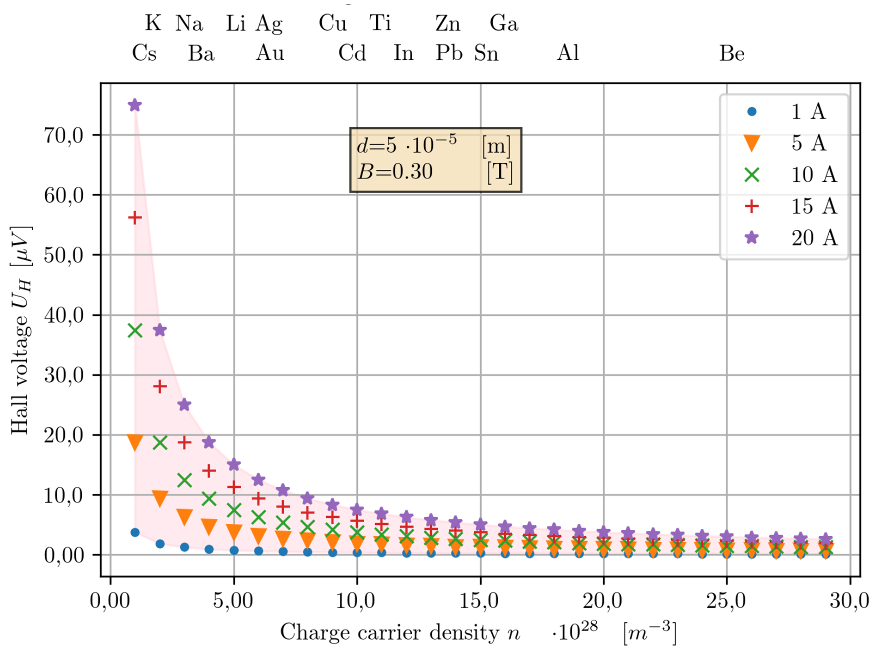

Figure 4.3: Simulation result of Equation 2.5, with above of the figure the charge carrier densities ofdifferent materials [8].

4.5. Python simulation

Figure 4.3 shows the Hall voltage for different materials with a different charge carrier density. It can be seen that silver (Ag) for example, with a charge carrier density of $n \approx 6,5 \cdot 10^{28}$ m^{-3}, has a Hall voltage of $U_H \approx 11\mu$V in a magnetic field of 0,3 T with a plate width of $5 \cdot 10^{-5}$ m. It is also visible that cesium (Cs) and kalium (K) have a higher Hall voltage than silver (Ag). In others words, their Hall coefficient is higher.

More simulations results can be found in Appendix A. In Figure A.2 all variables except the magnetic field strength B have been kept constant. The same goes for Figure A.4, but in this case the current I is the changing variable. Both of these figures can be used to verify experimental results while measuring. Figure A.3 shows that a change in conductor thickness d in the magnitude of 10^{-5} does not have any significant impact on the Hall voltage. This is as excepted, since the conductor thickness is multiple orders of magnitude smaller than the generated Hall voltage in this physical situation. The Python code used to create these figures can be found in Appendix B.

5
Conclusion

The research question as given in Chapter 1 is:

- What is the charge carrier density of silver?

The Hall coefficient of silver is determined to be:

$$R_H = (8.3 \pm 2) \cdot 10^{-11} \quad [\mathrm{m}^3\mathrm{C}^{-1}] \tag{5.1}$$

The literature value for the Hall coefficient of silver is [1]:

$$\mid R_{H literature} \mid = (8,9 \pm 2) \cdot 10^{-11} \quad [\mathrm{m}^3\mathrm{C}^{-1}] \tag{5.2}$$

The charge carrier density of silver is determined to be:

$$n = (7.4 \pm 2) \cdot 10^{28} \quad [\mathrm{m}^{-3}]. \tag{5.3}$$

Of which the literature value is equal to [1]:

$$n_{literature} = (6.6 \pm 2) \cdot 10^{28} \quad [\mathrm{m}^{-3}] \tag{5.4}$$

It can be concluded that the measured Hall coefficient and charge carrier density of silver are in agreement with the literature values. The physical results for silver are also similar to the simulation results as presented in Chapter 4.5. Therefor it can be conclude that the used model is correct for silver. Moreover, there is no reason to believe that this model (Equation 2.5) is incorrect for other materials in different physical situations.

6
Discussion

In Figure 4.1 a bulge in the Hall voltage with respect to the fit between 6-10 A is visible. This is due to the fact that two different Hall apparatuses have been used. One of which (58681) had a rapidly increasing offset voltage, due to which its temperature increased a lot more than the other used apparatus (58681 B2). Any measurement with this apparatus after 10 A was unsuccessful. This is due to the fact that the voltage kept increasing for about 30 minutes per ampere. Due to this constant increase in the offset voltage, this bulge (6-10 A) has a greater uncertainty. As can be seen in Figure 4.1 the uncertainties in the negative direction of the Hall voltage of these points overlap the fit.
This experiment has not been without any trouble, as could be expected while measuring voltages in the order of 10^{-6} without any special equipment in an area with electromagnetic noise. At first there was no multimeter available which supported μV precision. Therefor an op-amp circuit was required which amplified the signal 500 times. The signal was decent, however noise was visibly present while touching or moving anything from the experimental setup by just a tiny bit. Therefor great care was required to get successful and precise measurements, nothing has to be touched or moved.
Another problem was that the first results did not agree with the literature values. After supplying the coils with 15 A instead of 5 A of current it was known why. Since the coils had to be turned off in-between individual measurements, it could be seen that the offset voltage increased with the increase in current through the Hall apparatus. With this knowledge the actual Hall voltage could be determined.

Bibliography

[1] LEYBOLD, “Hall effect apparatu (silver) 586 81.” [Online]. Available: https://www.leybold-shop.com/physics/physics-equipment/solid-state-physics/conduction-phenomena/hall-effect-silver-tungsten/hall-effect-apparatus-silver-58681.html(Bekekenop:23-05-2018)

[2] NIST, “The nist reference on constants, units, and uncertainty.” [Online]. Available: https://physics.nist.gov/cgi-bin/cuu/Value?e(bekekenop02-06-2018)

[3] L. D. GmbH, “Solid-state physics conduction phenomena hall effect: Investigating the hall effect in silver.”

[4] A.-T. . A. . T. T. INSTRUMENTS, “1604 4.75 digit bench multimeter.” [Online]. Available: https://www.aimtti.com/product-category/multimeters/aim-1604(Bekekenop:22-05-2018)

[5] A. W. DEVICE, “Integratedcircuit precisioninstrumentationamplifier ad521 i.” [Online]. Available: http://www.analog.com/media/en/technical-documentation/data-sheets/AD521.pdf(Bekekenop:22-05-2018)

[6] H. H. Ku, “Notes on the use of propagation of error formulas.” [Online]. Available: http://nistdigitalarchives.contentdm.oclc.org/cdm/compoundobject/collection/p16009coll6/id/99848/rec/1(Bekekenop:27-05-2018)

[7] M. P. Marder, “Research methods for science.”

[8] V. Palenskis, “Drift mobility, diffusion coefficient of randomly moving charge carriers in metals and other materials with degenerated electron gas.” [Online]. Available: http://file.scirp.org/Html/13-4800160_28333.htm(bekekenop03-06-2018)

[9] R. Nave, “Hall effect.” [Online]. Available: http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/Hall.html#c3(Bekekenop:23-05-2018)

A

Figures

Apparatus

1 Hall effect apparatus (silver)	586 81
1 Microvoltmeter	532 13
1 U-core with yoke	562 11
1 Pair of bored pole pieces	560 31
2 Coil with 250 turns	562 13
1 High current power supply	521 55
1 Variable extra low-voltage transformer	521 39
1 Multimeter LDanalog 30	531 130
4 Pair cables 100 cm, red/blue	501 46
2 Connecting lead 100 cm black	501 33
1 Leybold multiclamp	301 01
1 Stand rod, 25 cm	300 41
1 Stand base, V-shape, 20 cm	300 02

Option (a)

1 Universal Measuring Instrument Physics	531 835
1 Combi B-Sensor S	524 0381
1 Extension cable, 15-pole	501 11

Option (b)

1 Mobile-CASSY	524 009
1 Combi B-Sensor S	524 0381
1 Extension cable, 15-pole	501 11

Figure A.1: A screenshot of the required apparatus [3].

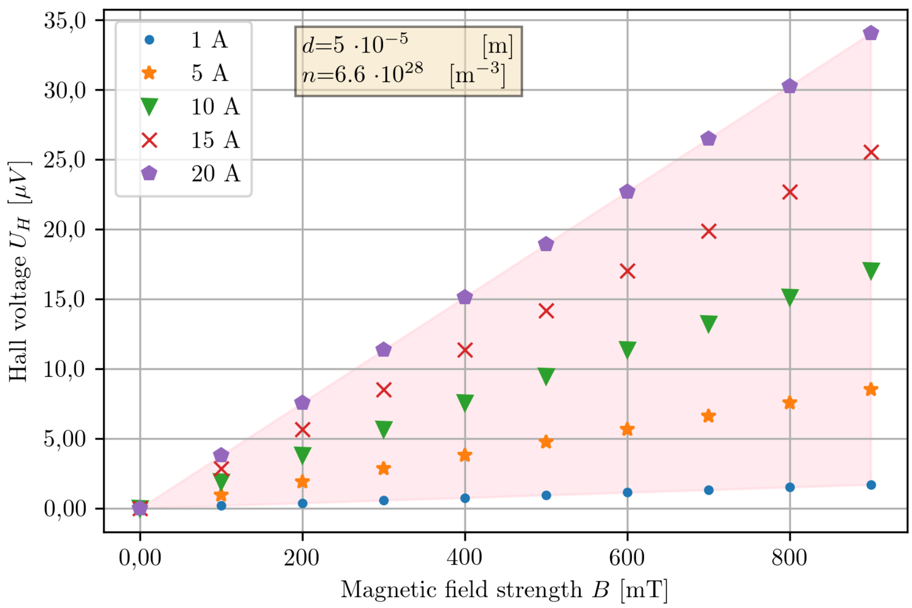

Figure A.2: Simulation result of Formula 2.5.

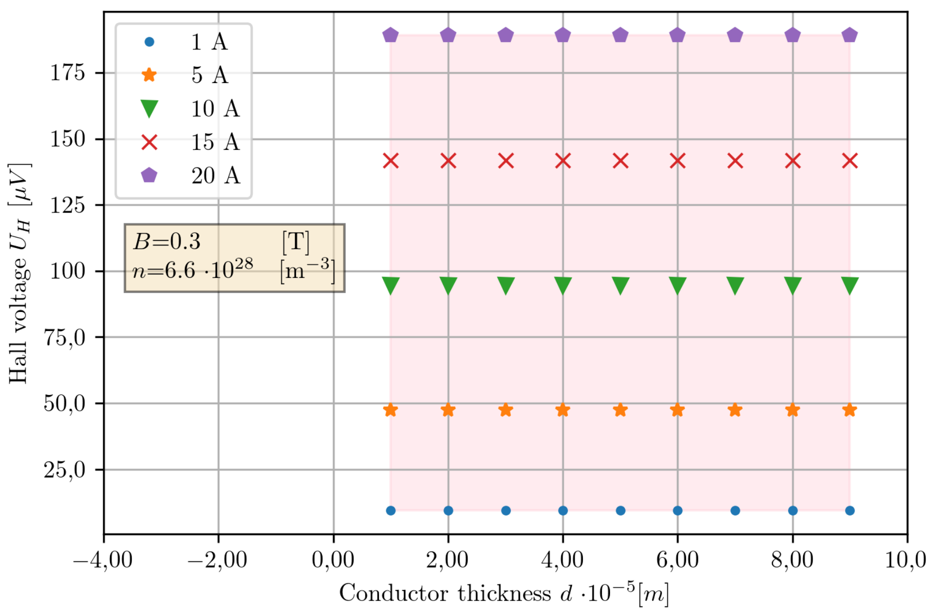

Figure A.3: Simulation result of Formula 2.5.

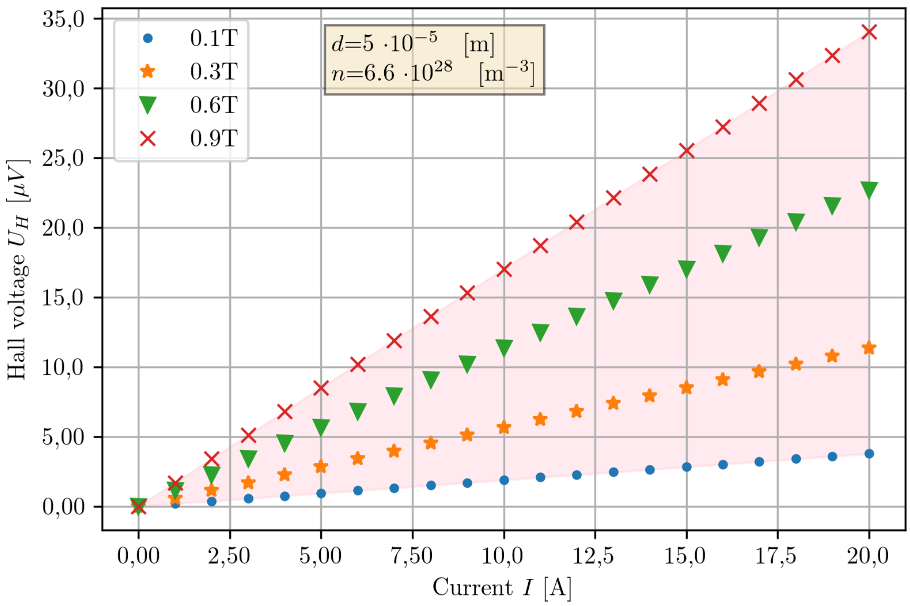

Figure A.4: Simulation result of Formula 2.5.

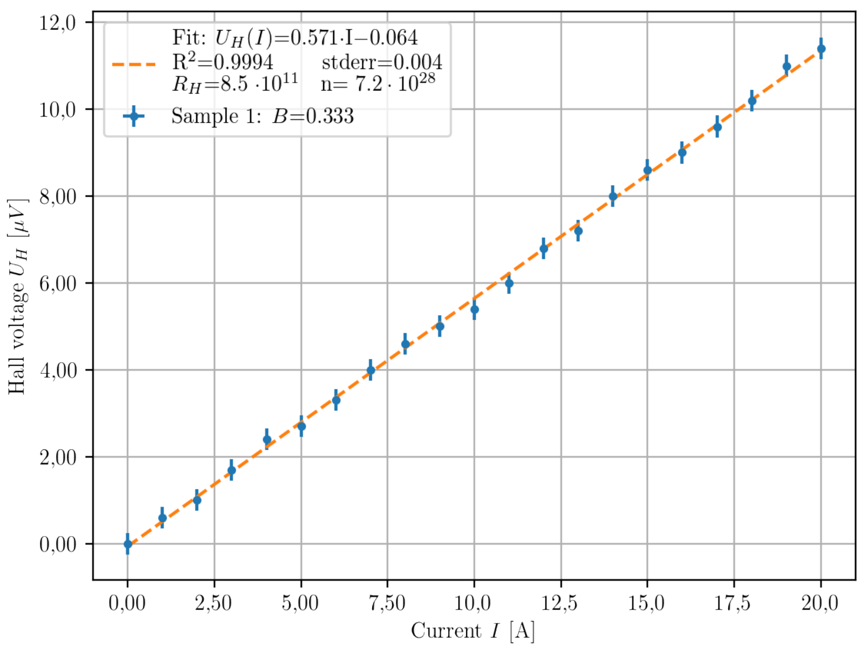

Figure A.5: Results sample 1 of the Hall voltage measurement with the Hall apparatus (silver).

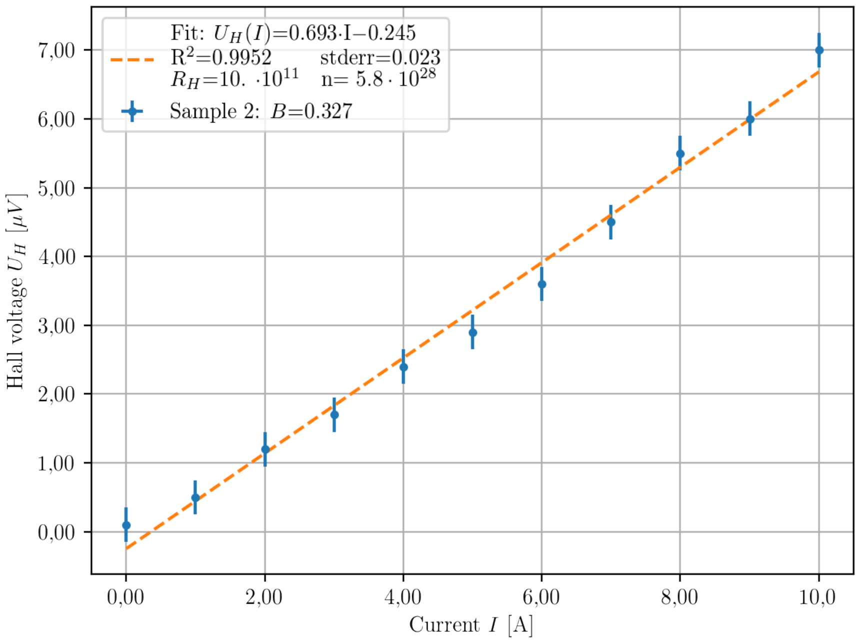

Figure A.6: Results sample 2 of the Hall voltage measurement with the Hall apparatus (silver).

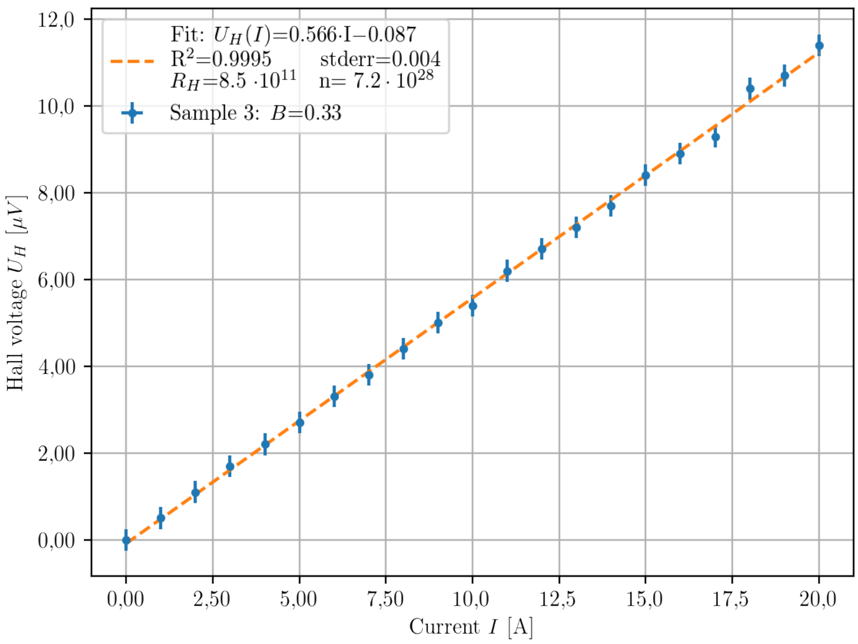

Figure A.7: Results sample 3 of the Hall voltage measurement with the Hall apparatus (silver).

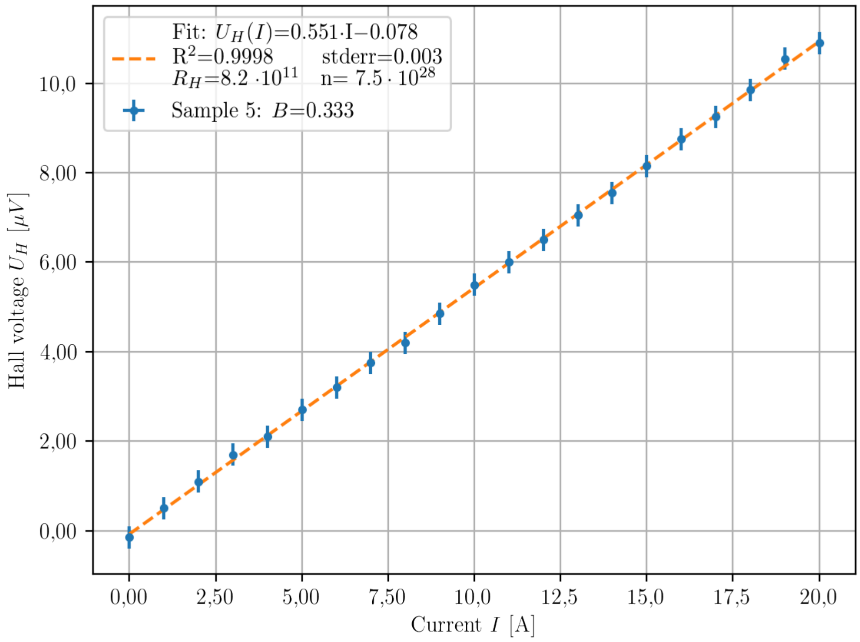

Figure A.8: Results sample 4 of the Hall voltage measurement with the Hall apparatus (silver).

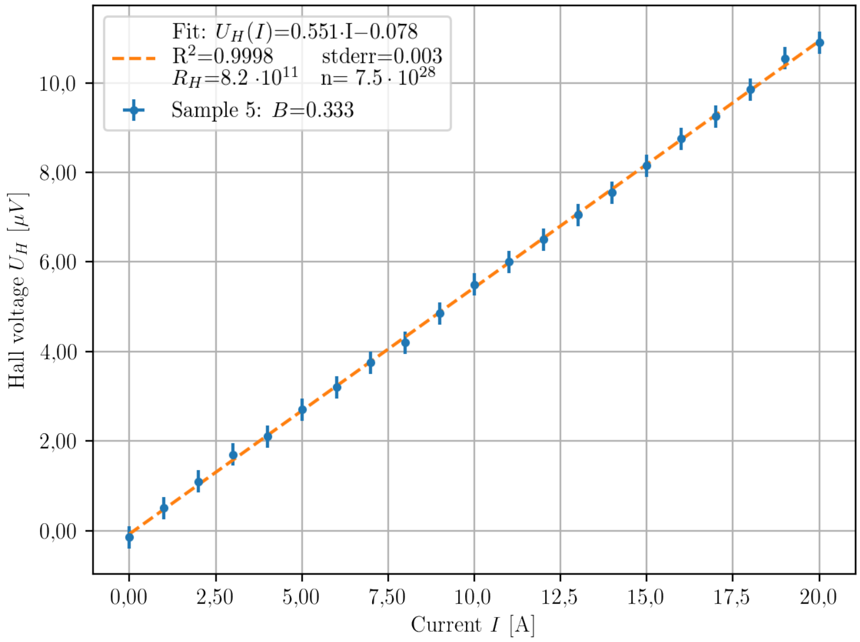

Figure A.9: Results sample 5 of the Hall voltage measurement with the Hall apparatus (silver).

B

Python Data Analysis

All code can also be found at
https://github.com/deKeijzer/Onderzoeken-5---Charge-carrier-density-of-silver

B.1. Experimental results

```
# coding: utf-8

# In[48]:


import pandas as pd
import matplotlib.pyplot as plt
get_ipython().run_line_magic('matplotlib', 'notebook')
from scipy.stats import linregress
import TISTNplot as tn

# Nodig voor latex rendering
from matplotlib import rc
rc('font',**{'family':'sans-serif','sans-serif':['Helvetica']})
rc('text', usetex=True)
plt.rc('text', usetex=True)
plt.rc('font', family='serif')

sample = 6
B = 0.333

d = pd.read_excel('input/week 6 meting '+str(sample)+'.xlsx', columns=['I', 'I_spoel
    ', 'U_H', 'U_H_offset', 'U_H_verschil', 'B'])

a = pd.DataFrame()
a['I'] = d['I_plaat (A)']
a['U'] = d['U_H verschil'] #terug rekenen naar origineel in micro V

d = 5*10**-5
e = 1.602*10**-19
a['coefficient'] = a['U']*(d/B)


# In[49]:
```

```python


plt.close()
label_tekst = 'Sample %s: $B$=%s' % (sample, B)
plt.errorbar(a['I'], a['U'], 0.25, 0.05, '.', label=label_tekst)

#fit plotten
fit = linregress(a['I'], a['U'])

R_H = fit[0]*10**-6*(d/B)*10**11
n = 1/(R_H*e)*10**28
n = str(n)[:3]
fit_label='Fit: $U_H$($I$)=%.3f\cdot $I$ %.3f \quad \n R$^2$=%.4f \qquad $\mathrm{
    stderr}$=%.3f \n $R_H$=%.3s \cdot 10^{11} \quad $n$=' % (fit[0], fit[1], fit[2],
    fit[4], R_H)+n+'\cdot 10^{28}'
plt.plot(a['I'], fit[0]*a['I']+fit[1], '--', label=fit_label)

plt.legend()
plt.grid()
plt.xlabel('Current $I$ [A]')
plt.ylabel('Hall voltage $U_H$ \mathrm{[\mu V]}}')

#correcte opmaak
tn.PRECISION_X = 3
tn.PRECISION_Y = 3
tn.fix_axis(plt.gca())

fit
print(R_H)
print(n)
plt.savefig('output\sample'+str(sample)+'.png', dpi=200)


# In[50]:


linregress(a['I'], a['coefficient'])
```

B.2. Simulation results

```python

# coding: utf-8

# In[71]:


import matplotlib.pyplot as plt
import numpy as np
from scipy.stats import linregress
#%matplotlib notebook
import TISTNplot as tn

# Nodig voor latex rendering
from matplotlib import rc
rc('font',**{'family':'sans-serif','sans-serif':['Helvetica']})
rc('text', usetex=True)
plt.rc('text', usetex=True)
```

```
plt.rc('font', family='serif')

U_H = '-'
I = '-'
B = '-'
d = 5*10**-5
#n = 6.6*10**28
e = 1.60217662*10**-19

def f(I, n):
    B = 0.3
    d = 5*10**-5
    #n = 6.6*10**28
    e = 1.60217662*10**-19

    return (B*I)*10**6/(n*e*d*10**28)

n_list = [4.7, 2.65, 1.4, 1.15, 0.91, 8.47, 5.86]
B = []
U1 = []
U2 = []
U3 = []
U4 = []
U5 = []

for b in range(1, 30):
    B.append(b)
    U1.append(f(1, b)*10**0)
    U2.append(f(5, b)*10**0)
    U3.append(f(10, b)*10**0)
    U4.append(f(15, b)*10**0)
    U5.append(f(20, b)*10**0)


# In[109]:


plt.plot(B, U1, '.', label='1 A')
plt.plot(B, U2, 'v', label="5 A")
plt.plot(B, U3, 'x', label="10 A")
plt.plot(B, U4, '+', label="15 A")
plt.plot(B, U5, '*', label="20 A")


#fill plot
plt.fill_between(B, U1, U5, color='pink', alpha='0.3')

plt.xlabel('Charge carrier density $n$ \quad \cdot 10^{28} \quad [m^{-3}]')
plt.ylabel('Hall voltage $U_H$ \mathrm{[\mu V]}}')

#correcte opmaak
tn.PRECISION_X = 3
tn.PRECISION_Y = 3
tn.fix_axis(plt.gca())

plt.legend()
```

```
plt.grid()
#plt.xlim(1**26, 1**27)

props = dict(boxstyle='square', facecolor='wheat', alpha=0.75)
plt.text(10, 70, '$d$=5␣\cdot␣10^{-5}␣\quad␣\mathrm{[m]}␣\n␣$B$=0.30␣\quad␣\quad␣\mathrm{[T]}', verticalalignment='top', bbox=props)

plt.text(4.7, 90, 'Li', verticalalignment='top', bbox=None) #
plt.text(2.65, 90, 'Na', verticalalignment='top', bbox=None) #
plt.text(1.4, 90, 'K', verticalalignment='top', bbox=None) #
plt.text(1.15, 95, 'Rb', verticalalignment='top', bbox=None) #
plt.text(0.91, 85, 'Cs', verticalalignment='top', bbox=None) #
plt.text(8.47, 90, 'Cu', verticalalignment='top', bbox=None) #
plt.text(5.86, 90, 'Ag', verticalalignment='top', bbox=None) #
plt.text(5.9, 85, 'Au', verticalalignment='top', bbox=None) #
plt.text(24.7, 85, 'Be', verticalalignment='top', bbox=None) #
plt.text(8.61, 95, 'Mg', verticalalignment='top', bbox=None) #
plt.text(4.61, 95, 'Ca', verticalalignment='top', bbox=None) #
plt.text(3.55, 100, 'Sr', verticalalignment='top', bbox=None) #
plt.text(3.15, 85, 'Ba', verticalalignment='top', bbox=None) #
plt.text(13.2, 90, 'Zn', verticalalignment='top', bbox=None)
plt.text(9.27, 85, 'Cd', verticalalignment='top', bbox=None)
plt.text(18.1, 85, 'Al', verticalalignment='top', bbox=None) #
plt.text(15.4, 90, 'Ga', verticalalignment='top', bbox=None)
plt.text(11.5, 85, 'In', verticalalignment='top', bbox=None) #
plt.text(10.5, 90, 'Ti', verticalalignment='top', bbox=None)#
plt.text(14.8, 85, 'Sn', verticalalignment='top', bbox=None)
plt.text(13.2, 85, 'Pb', verticalalignment='top', bbox=None)

plt.savefig('output\\simulatie\\n.png', dpi=300)
```

C
Required appendix

Gezien dit de bijlage is en het twee onderdelen bevat welke als vereiste moeten worden toegevoegd aan de bijlage word dit onderdeel in het Nederlands geschreven.

C.1. Verantwoording

In deze sectie word omschreven wat de individuele bijdrages zijn geweest van beide duo-leden.

C.1.1. Brian de Keijzer

...

C.1.2. Julia Norbart

...

C.2. Zelfreflectie

Deze sectie bevat de zelfreflectie van beide duo-leden.

C.2.1. Brian de Keijzer

...

C.2.2. Julia Norbart

...