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Hall Effect

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Contents

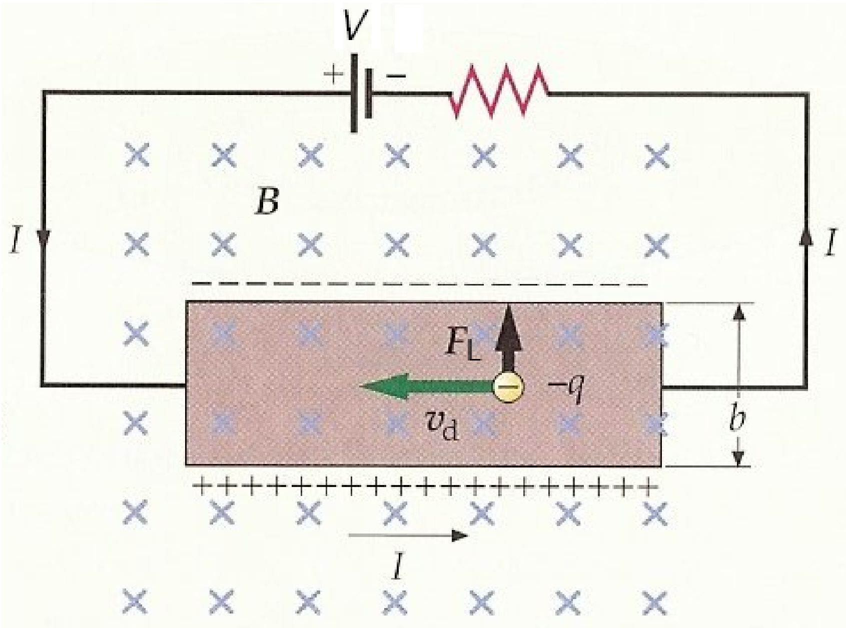

Figure 1: The Hall effect in a metal. Electrons, drifting with speed v_d, are deflected due to the Lorentz force F_L arising from them moving in a perpendicular external magnetic field B.[1]

1 The Hall effect

History. The Hall effect was discovered in 1879 by Edwin Herbert Hall who was only 24 years old and working on his doctoral thesis. In 1856, William Thomson had already measured an increase in resistance when a conductor is put into a magnetic field but it was Hall who first measured the tiny voltage perpendicular to the applied magnetic field and the current direction produced by this effect. This was a tremendous achievement with the equipment at that time.

Simple explanation of the effect. Whenever a current carrying conductor is brought into a magnetic field, a potential difference is induced normal to the direction of current flow and to the direction of the magnetic field. This potential difference is called the Hall voltage.

Figure 1 depicts a thin stripe of conducting material connected to a power source. Electrons flow from right to left with the drift velocity $\vec{v}_d$. A homogeneous magnetic field $\vec{B}$ is applied perpendicular to the plane. Moving charges with charge q in a magnetic field are subject to the Lorentz force $\vec{F}_L = q\vec{v}_d \times \vec{B}$ which in this case points upwards as shown in the figure. This results in the electrons being deflected to one side of the conductor charging it slightly negative and leaving the other side with a deficit of free electrons charging it slightly positive. From this nonuniform distribution of charge, the Hall voltage V_H arises across the conductor. This potential difference induces an electric field E_H across the conductor which acts on a drifting electron with the electrostatic force $\vec{F}_E = -q\vec{E}_H$. In equilibrium, the Lorentz force and the electrostatic force are equal in size, thus: ($|\vec{E}_H| =$) $E_H = v_d B$ ($= |\vec{v}_d||\vec{B}|$). If the conductor's width is b, and if we assume a homogeneous electric field distribution accross the width of the conductor, the Hall voltage is given by

$$V_H = E_H b = v_d B b. \tag{1}$$

With n being the carrier density, d the conductor's thickness, $A = bd$ the conductor's cross sectional area, and I_s the sample current we get

$$I_S = nqv_d A = nqv_d bd \quad \Rightarrow \quad v_d = \frac{I_S}{nqbd}. \tag{2}$$

With Eqs.(1) and (2), the Hall voltage V_H is

$$V_H = \frac{I_S}{nqbd} Bb = \frac{1}{nq}\frac{I_S B}{d}. \tag{3}$$

Finally, in the case of a conductor with electrons as charge carriers ($q = -e$) we define the Hall coefficient $R_H = 1/nq$ and Eq. (3) becomes

$$\boxed{V_H = R_H \frac{I_S B}{d}, \qquad \text{where } R_H = -\frac{1}{ne}.} \tag{4}$$

The Hall voltage is proportional to the current I_S and to the magnetic field B. It is inversely proportional to the thickness of the conductor measured in the direction of the magnetic field, and to the density n of electrons.

The measurement of Hall coefficients is one of the most important methods to measure the sign of the carrier charge and carrier density in solid materials.

Validity of the simple model in different materials. The model in Eq. (3) is only valid for conductors with only one type of charge carrier contributing to the conductance. In normal metals only electrons carry the electrical current as (negative) charge carriers. In p-doped semiconductor materials, conduction arises in the valence band, where positively charged holes carry the current. In some materials (e.g., in semimetals such as graphite), electrons and holes contribute to the electrical current. In such cases the Hall effect becomes more complicated to describe. The same complications arise in materials, where the same type of charge carriers (e.g. electrons) exist with different masses. This can be the case in certain semiconductors, in which several conduction band minima are occupied with electrons.

Drude model. The expression for the Hall voltage has been derived above within an intuitive model exposing the essence of the effect. We will now introduce a more general view on the effect. The dynamics of the gas of charge carriers follows Newton's law of motion. The Lorentz force and a frictional force influence the change of drift velocity $\vec{v}$ in the gas. If a steady flow pattern establishes, we have

$$m\dot{\vec{v}} = q(\vec{E} + \vec{v} \times \vec{B}) - \frac{m}{\tau}\vec{v} = 0, \tag{5}$$

where $\vec{E}$, $\vec{B}$ and $\vec{v}$ are vector fields. The quantity τ^{-1} is an average scattering rate, τ may be interpreted as the mean time between two scattering events of a charge carrier. The drift velocity $\vec{v}$ and the current density $\vec{j}$ are related by

$$\vec{j} = nq\vec{v}.$$

If we replace the drift velocity in eq. (5) by the current density, we obtain a linear relation between electric field and current density, namely

$$\vec{E} = \frac{m}{nq^2\tau}\vec{j} + \frac{1}{nq}\vec{B} \times \vec{j}, \tag{6}$$

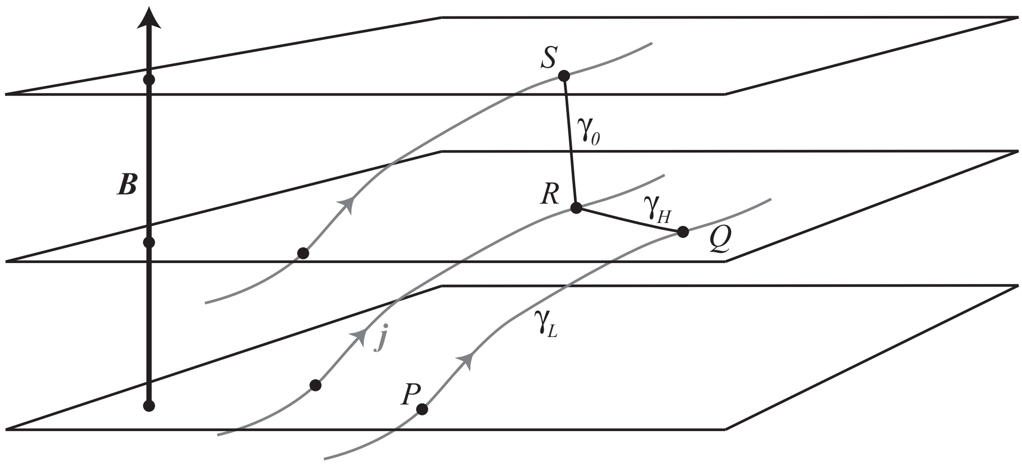

Figure 2: Integration path between two points P and S in the sample. The path is split in three parts, one from P to Q, giving a longitudinal voltage contribution related to ρ_0, one from Q to R giving a Hall voltage contribution related to R_H, and one from R to S, giving no contribution to the voltage.

At zero magnetic field, the first term on the right hand side describes the electric field that develops in a sample in response to a current density pattern $\vec{j}$, the longitudinal electric field. The proportionality constant

$$\rho_0 = \frac{m}{nq^2\tau}$$

is the zero magnetic field electrical resistivity. The second term in eq. (6) describes the additional electric field that builds up as a result of the presence of the magnetic field, i.e., the Hall field. The prefactor is the Hall coefficient R_H introduced above. We can now rewrite eq. (6) as

$$\boxed{\vec{E} = \rho_0 \vec{j} + R_H \vec{B} \times \vec{j}.} \tag{7}$$

Equation (7) is Ohm's law in a magnetic field, establishing a linear relationship between the electric field $\vec{E}$ and the current denstiy $\vec{j}$. This model of electrical conduction is called the Drude model.[1] We now introduce the notion of the longitudinal voltage and the Hall voltage. Suppose we wish to know the voltage difference between any to points P and S in the sample, as shown in Fig. 2. We can always find a path connecting the two points, which is a sequence of three particular segments $\gamma_L \equiv PQ$, $\gamma_H \equiv QR$, and $\gamma_0 \equiv RS$. The segment γ_L follows a flux line of the current density $\vec{j}$, i.e. it follows the longitudinal electric field $\rho_0 \vec{j}$. The longitudinal voltage is the voltage measured between the two points P and Q. Integrating the electric field along γ_L gives the longitudinal voltage

$$V_L(\gamma_L) = \int_{\gamma_L} \vec{E}\frac{\vec{j}}{|\vec{j}|}ds = \rho_0 \int_{\gamma_L} |\vec{j}|ds. \tag{8}$$

The segment γ_H follows a flux line of the vector field $\vec{B} \times \vec{j}$, which is perpendicular to both $\vec{B}$ and $\vec{j}$. As a consequence, γ_H runs in a plane perpendicular to $\vec{B}$, and along the Hall field $R_H \vec{B} \times \vec{j}$. The Hall voltage is the voltage measured between Q and R. Integrating the electric field along

[1] P. Drude, Ann. Physik **1**, 566 (1900); *ibid.* **3**, 369 (1900).

this path gives the Hall voltage

$$V_H(\gamma_H) = \int_{\gamma_H} \vec{E}\frac{\vec{B}\times\vec{j}}{|\vec{B}\times\vec{j}|}ds = R_H B \int_{\gamma_H} j_\perp ds, \tag{9}$$

where $j_\perp$ is the projection of $\vec{j}$ into the plane along γ_H. The third segment γ_0 is chosen perpendicular to the direction of the electric field $\vec{E}$, such that the integral along this path gives no contribution to the voltage. As a result, the voltage between P and S is the sum of the longitudinal and the Hall voltage contribution, i.e.,

$$V_{PS} = V_L(\gamma_L) + V_H(\gamma_H).$$

Sample geometry. Ohm's law establishes a (material specific) relation between $\vec{E}$ and $\vec{j}$. In order to understand, which equations describe the vector fields $\vec{E}$ and $\vec{j}$ alone, we use Maxwell's equations. Assuming that we have a static magnetic field, and zero total charge density in the sample (the charge of free carriers nq is exactly compensated by the positive ionic background charge), we have

$$\nabla\vec{E} = 0, \quad \nabla\times\vec{E} = 0, \tag{10}$$

which determines the vector field $\vec{E}$ uniquely, if appropriate boundary conditions are given. Similarly one finds for the current density

$$\nabla\vec{j} = 0, \quad \nabla\times\vec{j} = 0, \tag{11}$$

which determines the vector field of the current density in a sample uniquely, if appropriate boundary conditions are given. The first of these relations follows directly from the continuity equation for the charge density (charge conservation). The second relation is derived from $\nabla\times\vec{E} = 0$, using eq. (7).

The trick used for measuring the Hall effect is the use of a suitable geometry, which imposes boundary conditions on $\vec{j}$ leading with eq. (11) to a homogeneous vector field $\vec{j}$, which is independent of the magnetic field. This is achieved with the so-called Hall-bar geometry shown in Fig. 3. The boundary conditions are that the current density normal to the Hall bar surfaces vanish on the surfaces. As a consequence, the applied current flows along a well defined bar-shaped piece of material and both the transverse voltage drop ($V_y = V_H$) and the longitudional voltage drop (V_x) can be directly measured, as we will see below. The benefit of this structure is, that sufficiently far away from the current contacts, the vector field $\vec{j}$ is homogeneous, pointing along the Hall bar axis in x-direction. Therefore, $j_y = j_z = 0$, and $j_x = I_S/bd$. The magnetic field is applied along the z-direction, i.e., perpendicular to $\vec{j}$.

Equation (7) can be rewritten in cartesian coordinates as

$$\begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = \begin{pmatrix} \rho_0 & -R_H B_z & R_H B_y \\ R_H B_z & \rho_0 & -R_H B_x \\ -R_H B_y & R_H B_x & \rho_0 \end{pmatrix} \begin{pmatrix} j_x \\ j_y \\ j_z \end{pmatrix}, \tag{12}$$

where the matrix on the right hand side is called the *resistivity tensor*. Given our Hall bar geometry with $j_y = j_z = 0$, and $B_x = B_y = 0$, we obtain

$$E_x = \rho_0 j_x \tag{13}$$

$$E_y = R_H B j_x, \tag{14}$$

where $B = B_z = |\vec{B}|$. We see that the electric field is at an angle θ to the current density, with

$$\tan\theta = \frac{E_y}{E_x} = \frac{R_H B}{\rho_0} = \frac{q\tau}{m}B = \mu B.$$

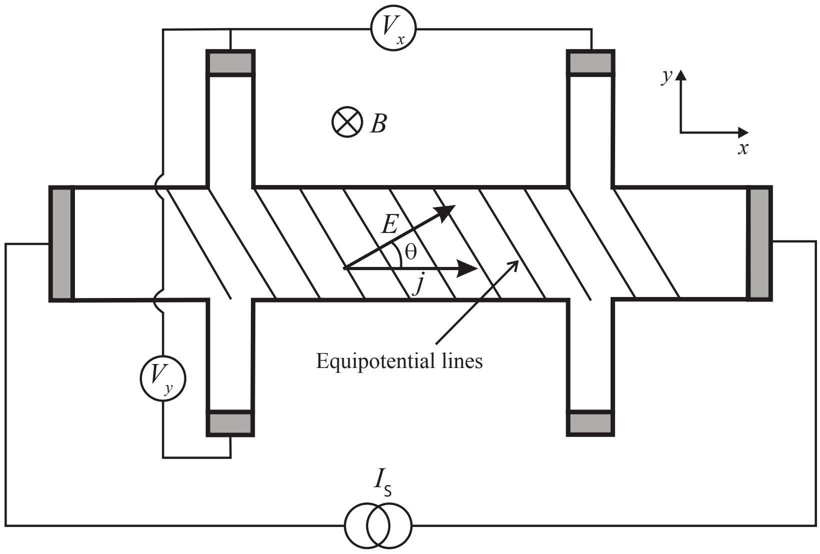

Figure 3: The Hall bar geometry. At finite magnetic field the electric field $\vec{E}$ and the current density $\vec{j}$ are no longer parallel, but enclose the so-called Hall angle θ. The equipotential lines drawn normal $\vec{E}$ show how the Hall voltage arises.

The angle θ is called *Hall angle*, the quantity $\mu = q\tau/m$ is the *mobility* of the charge carriers.

In the Hall bar geometry the longitudinal voltage in eq. (8) becomes

$$V_L(\gamma_L) = \rho_0 \int_{\gamma_L} |\vec{j}| ds = \frac{L}{bd} \rho_0 I_S = R_0 I_S = V_x,$$

where L is the distance between the voltage probes at the same edge of the Hall bar. The quantity $R_0 = L\rho_0/bd$ is called longitudinal resistance. It is independent of the magnetic field.

The Hall voltage in eq. (9) is

$$V_H(\gamma_H) = R_H B \int_{\gamma_H} j_\perp ds = \frac{1}{d} R_H B I_S = \frac{B}{qnd} I_S = V_y,$$

in agreement with eq. (4).

2 Samples

Goal of the experiment. The goal of this experiment is to determine the charge carrier density of gold and silver from Hall voltage measurements on two silver and two gold samples. The samples have different thicknesses d (values given on the sample board) and are numbered from one to four. The charge carrier density n will be calculated from the Hall coefficients R_H, which are determined by measuring the Hall voltage V_H as a function of the sample current I_S and the magnetic field B. The magnetic field is applied perpendicular to the plane of the samples. As one can see from Eq. (4), the Hall coefficient depends only on the charge carrier density of the material, not on the sample thickness.

Problem 1: What would the charge carrier density n and the Hall coefficient R_H of a sample of pure silver/gold be, assuming that every silver/gold atom provides one free conducting electron? Use the following values for the mass densities and the molar masses of silver and gold: $\rho_{\text{Ag}} = 10.49\ \frac{\text{g}}{\text{cm}^3}$, $M_{\text{Ag}} = 107.9\ \frac{\text{g}}{\text{mol}}$, $\rho_{\text{Au}} = 19.30\ \frac{\text{g}}{\text{cm}^3}$, $M_{\text{Au}} = 197.0\ \frac{\text{g}}{\text{mol}}$ [2, 3].

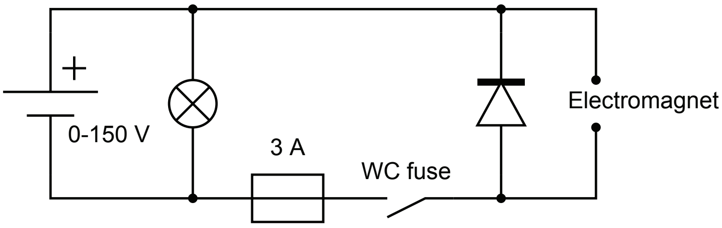

Figure 4: A circuit diagram of the electromagnet's circuit. The WC (water cooling) fuse is a fuse coupled to a thermometer at the electromagnet which stops the current if the electromagnet gets too hot (indicating that the water cooling is not working). The 3A fuse prevents too high currents to flow in the circuit.

3 Experimental Setup

The experimental setup consists of the following parts:

- A set of samples.
- A circuit board with the the electric circuit to provide the sample current, and a circuit to measure the Hall voltage.
- An electromagnet with power supply generating the required magnetic field.
- A sample holder allowing to place the sample in the magnetic field.
- Two (three) analog ammeters, one for measuring the current through the magnet, the other one for measuring the current through the sample. (In one setup also for measuring the compensation current).
- A digital multimeter by Keithley, which is to be used in the circuit to measure the Hall current.
- A hand multimeter (only on the setup with two analog ammeters).

3.1 The Electromagnet

In Fig. 4 the circuit providing current for the electromagnet is shown. A lamp will light up when the electromagnet is switched on (only for currents of 1 A and above through the magnet). In order to protect the thin wires of the electromagnet from overheating, it is water cooled. The water must be turned on before switching on the magnet. In case the water cooling is not working, a thermometer attached to the electromagnet will blow a fuse (labeled "WC fuse" in Fig. 4). A protection diode absorbs the switch-off pulse preventing a large voltage to build up in the electromagnet.

A calibration graph showing magnetic field against current through the electromagnet can be found in the lab. Note that the depicted curve was measured while decreasing the current. In order to minimize the error due to hysteresis the same technique should be employed in the experiment. Also, the magnetic field is given in gauss which is an old CGS unit. The conversion to the SI unit Tesla is: 1 T = 10′000 G.

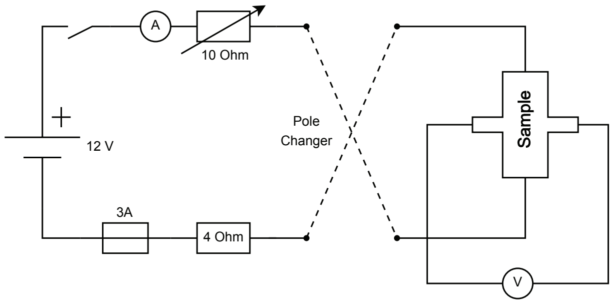

Figure 5: A circuit diagram of a theoretically possible experimental setup for metallic films. It has, however, major problems with detecting the Hall voltage correctly.

3.2 The Measurement Circuit

The experimental setup to measure the Hall voltage in the metal samples is not trivial. The rather complex circuit is explained in the following sections. Starting from a simple circuit, the final measurement circuit is developed step by step.

3.2.1 A first approach

In Fig. 5 one can see the circuit diagram with which, in principle, the Hall voltage can be measured. It consists of a main circuit to provide the sample current and a voltmeter to measure the Hall voltage across the sample.

Current supply. The circuit consists of a voltage supply (12 V), an ammeter, an adjustable resistor (10 Ω), the sample, a standard resistor (4 Ω) and a 3 A fuse all connected in series. Additionally, there is a pole changer to change the direction of the sample current quickly. This circuit provides a sample current which can be varied with the adjustable resistor. Note that the maximum current for the samples is 2 A.

Problem 2: The (internal) resistance R_i of a voltage or current source can be determined by measuring the open circuit voltage V_oc, and the short circuit current I_sc. It is given by

$$R_\mathrm{i} = \frac{V_\mathrm{oc}}{I_\mathrm{sc}}.$$

a. An *ideal* voltage source supplies the voltage V_oc, no matter what load resistance is connected to it. What is the internal resistance of such an ideal voltage source?

b. An *ideal* current source supplies the current I_sc, no matter what load resistance is connected to it. What is the internal resistance of such an ideal current source?

c. What is the internal resistance of the current supply used in this experiment?

d. Estimate the total resistance of your samples (at zero magnetic field). The specific electrical resistivities of silver and gold are: $\rho_{Ag} = 1.6 \cdot 10^{-8}\,\Omega m$, $\rho_{Au} = 2.2 \cdot 10^{-8}\,\Omega m$ [2, 3]. How do the estimated values of the total resistances compare to the internal resistance of the current supply? How strongly is the supplied current changed, if the sample is replace with a short?

3.2 The Measurement Circuit

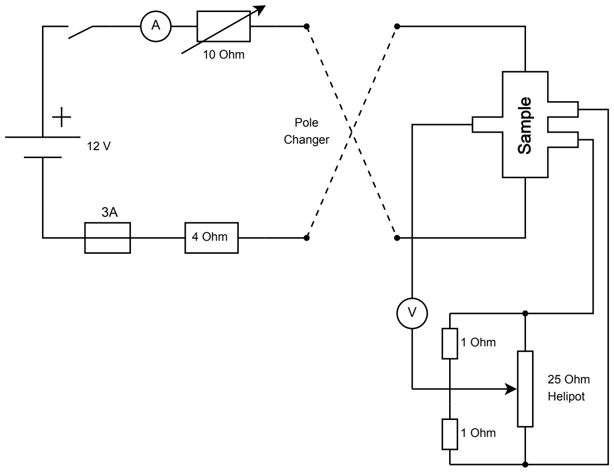

Figure 6: A circuit diagram of an enhanced experimental setup allowing to measure a voltage exactly perpendicular to the sample current. A second contact is placed on one side of the sample. It still has a problem with detecting the Hall voltage correctly.

Hall voltage measurement. In this setup, the Hall voltage is measured simply with a voltmeter connected across the sample via two contacts - one on each side. There are two major problems with this setup both of which have to do with the size of the Hall voltage.

Problem 3: Using the values for the Hall coefficients calculated before, compute what the Hall voltages would be for a sample current of $I = 2$ A, a magnetic field of $B = 1.2$ T and a sample thickness of $d = 3\,\mu$m (these are roughly the values in the experiment.) What would happen if the two measuring contacts were not located perpendicular to the sample current?

Problem 4: Any voltmeter or ammeter placed in a circuit can be regarded as a resistor called the internal resistance R_i of the meter.

a. An *ideal* ammeter measures the current without changing it. Is an ammeter connected in series or in parallel to the current source? What is the internal resistance of the ideal ammeter?

b. An *ideal* voltmeter measures the voltage without changing it. Is a voltmeter connected in series or in parallel to the voltage source? What is the internal resistance of the ideal voltmeter?

c. How would the current density pattern in the Hall bar sample change, if the Hall contacts were shorted? Make a schematic sketch of the flow pattern. If you consider the pair of Hall voltage probes as the output of a voltage source, can you estimate the order of magnitude of the internal resistance of this source?

d. How does the internal resistance of the voltmeter in Fig. 5 need to compare to this internal resistance of the Hall voltage source, if we wish to measure the Hall voltage accurately?

3.2.2 Measuring the Hall voltage perpendicular to the sample current

If you look at the samples provided, you find that the contacts on opposite sides of the Hall bar are not exactly perpendicular to the Hall bar axis. Instead, there is a pair of contacts on one

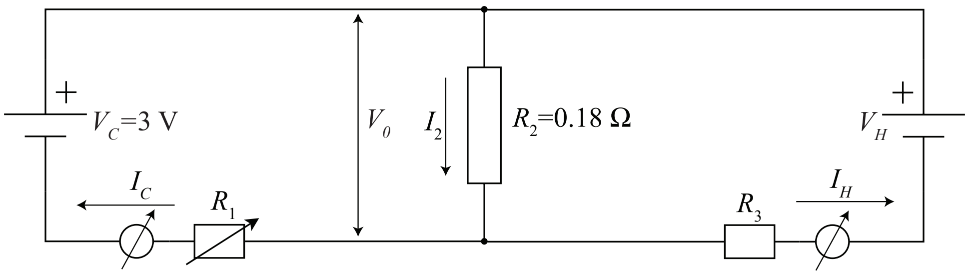

Figure 7: Schematic of the potentiometer technique. The Hall voltage generated by the sample is represented as an ideal voltage source at voltage V_H in series with a resistance R_3 (the internal resistance of the real source). The remaining circuit allows the measure the Hall voltage at zero current I_H.

side, with the contact on the opposite side in-between. The setup shown in Fig. 6 allows to measure the Hall voltage exactly perpendicular to the sample current. The two contacts on one side are connected to a voltage divider which can the be adjusted such that one is measuring the voltage effectively perpendicular to the sample current. The rest of the setup is the same as in Fig. 5.

Problem 5:

a. In Fig. 6 there are external resistances connected in parallel to a part of the Hall bar. Calculate the total external resistance. How does it compare to the resistance of the sample between the two voltage probes?

b. How would you experimentally adjust the Helipot to make sure that you measure the Hall voltage exactly perpendicular to the Hall bar axis?

c. Consider the two points at which the voltmeter in Fig. 6 is connected as a voltage source. What is the internal resistance of this voltage source? What is the resulting requirement for the internal impedance of the voltmeter?

3.2.3 The potentiometer technique

In this experiment, the small Hall voltage is measured with the potentiometer technique, which is illustrated in Fig. 7. The technique works as follows: the potentiometer R_1 is tuned such that the ammeter measuring I_H measures zero current. The Hall voltage V_H can then be calculated from the measured (nonzero) I_C and the known resistance R_2.

Problem 6: In this problem, you will learn, how the potentiometer technique works in detail.

a. Using Fig. 7 explain intuitively, why it is possible to null I_H by adjusting R_1. What is the voltage V_0 in this case? How can V_H then be determined from the measured current I_C?

b. Using Kirchhoff's current law express the current I_2 by the currents I_H and I_C. Using Ohm's law, express the three currents in terms of the voltages and resistances in the circuit.

c. Solve these four equations for I_C and I_S by eliminating the unknowns V_0 and I_2.

d. To which value do you have to set the potentiometer R_1, in order to null I_H?

e. Given the maximum Hall voltage worked out in Problem 3, what would be a reasonable value for the maximum resistance R_1 needed to achieve $I_H = 0$?

f. Once R_1 is set, such that $I_H = 0$, how can you determine V_H from the measured current I_C? Estimate the size of this current. Do you need to know the voltage V_C precisely? Is the internal resistance R_3 of the Hall voltage source of any relevance? What is the internal resistance of the voltmeter realized in this way?

Figure 8 shows the final circuit of our experiment, including the potentiometer technique discussed above. The voltage V_C is supplied by a battery (3 V). The resistance R_1 in Fig. 7 is replaced by a 2.2 kΩ resistor in series with a 50 kΩ potentiometer. The resistor labeled R (R_2 in Fig. 7) has a resistance of 0.18 Ω (setup 1) or 0.105 Ω (setup 2) in our experiment.

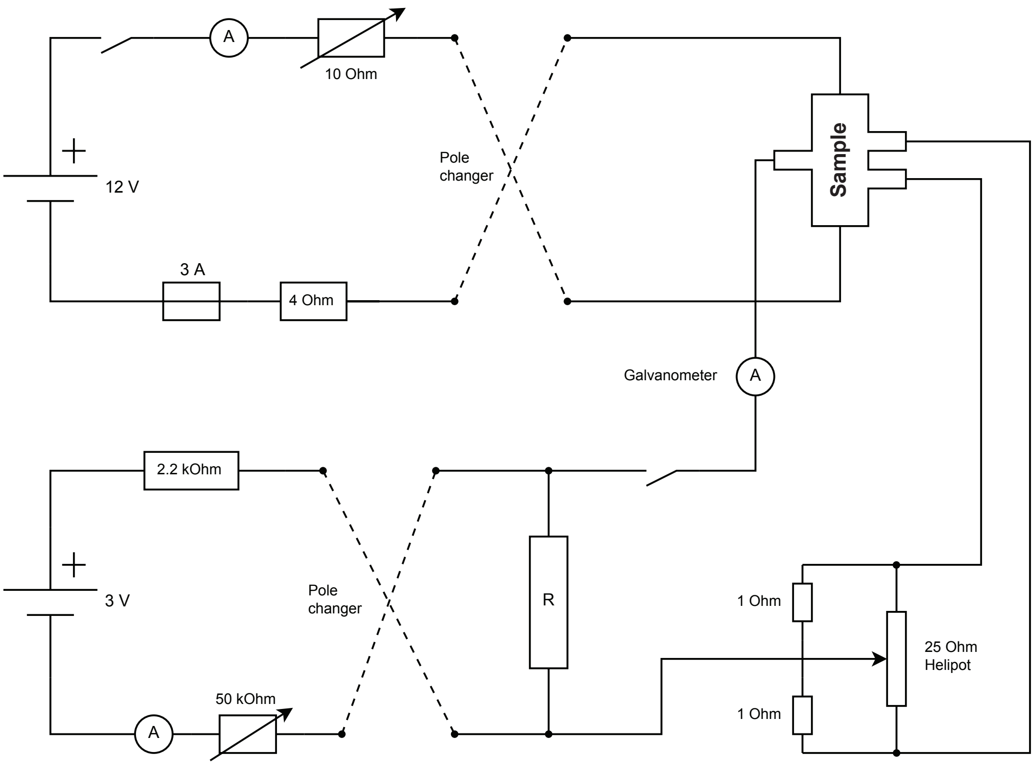

Figure 8: The actual experimental setup. Compared to Fig. 6, it is extended by the compensation circuit shown in Fig. 7 providing a compensation current (potentiometer technique).

4 Experimental procedure

When connecting the different parts of the experimental setup electrically, make sure that

- the 12V power supply for the sample current is connected exactly as shown in Fig. 8,
- the polarity of the diode in the electromagnet's circuit (cf. Fig. 4) is correct,
- the connection between electromagnet and diode **is not** disrupted, because otherwise the shut-off voltage pulse of the magnet will destroy the magnet,
- the cooling water is switched on before you use the electromagnet.

4.1 Measuring the Hall Voltage

When inserting the samples into the sample holder, one should make sure that the sample contacts are clean. If they are not, they should be cleaned with an eraser. This ensures good electrical contact between the sample and the rest of the circuit.

Before the Hall voltage can be measured, the 25 Ω helipot has to be adjusted in such a way that no Hall current is measured when there is a sample current flowing but no magnetic field is applied. The sample current is best set to maximum when adjusting the helipot and then continually reduced for taking the measurements. Also, the compensation circuit should be disabled by disconnecting the battery from the circuit. The helipot should *not* be adjusted while taking measurements, but it has to be readjusted whenever the sample current's direction or the sample itself is changed.

The samples to be measured can be seen in Table **??**. For each sample, the dependence of the Hall voltage V_H on the sample current I_S should be recorded (at constant B). In another set of measurements, the Hall voltage V_H is to be determined as a function of the magnetic field B (at constant I_S). For reasons explained below, each measurement should be done twice - once with the sample current in one direction and once in the other direction. The direction of the sample current can be easily changed with the pole changer.

From the measured data, the Hall coefficients and the corresponding charge carrier densities for silver and gold can be obtained by fitting the measurement points with straight lines (according to Eq. (4)). An estimation of the error in the Hall coefficients and the charge carrier densities can be obtained from the fits.

4.2 Galvanomagnetic and Thermomagnetic Effects

Table 1 shows all effects associated with a conductor in a magnetic field, through which either a current or heat is flowing. The Hall effect belongs to the same group of transport phenomena as electric and thermal conductance. Although the Hall effect has the largest effect on the measurement, a portion of the measured value will be due to other effects. Some of these effects can be eliminated when taking the mean of the measurement results with the sample current flowing in opposite directions.

Problem 7: What effects might affect the measurements besides the Hall effect? Which of these will be eliminated with taking the mean? Which are independent of the direction of sample current?

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[1] Paul A. Tipler and Gene Mosca. *Physik fuer Wissenschaftler und Ingenieure*, volume 2. Spektrum Akademischer Verlag, 2004.

[2] WolframAlpha. Gold. `http://www.wolframalpha.com/input/?i=gold`, 02 2010.

[3] WolframAlpha. Silver. `http://www.wolframalpha.com/input/?i=silver`, 02 2010.

		Galvan-Magnetic Effects		Thermo-Magnetic Effects	
		Conductor with Current I — In Magnetic Field B		Conductor with Heat Flow W — In Magnetic Field B	
		Potential Diff.	Temperature Diff.	Temperature Diff.	Potential Diff.
Transverse Field	Transverse Effects	Hall Effect	Ettingshausen Effect	1. Righi-Leduc Effect	1. Ettingshausen-Nernst Effect
Transverse Field	Longitudinal Effects	Effect Unnamed	Nernst Effect	2. Righi-Leduc Effect	2. Ettingshausen-Nernst Effect
Longitudinal Field	Longitudinal Effects	Effect Unnamed	Effect Unnamed	Effect Unnamed	Effect Unnamed

Table 1: An overview of the effects that occur when current or heat is flowing in a conductor which is placed in a magnetic field. Some of the effects (not only the Hall effect) influence the measurements.