X: The Hall Effect in Metals

I. References

C. Kittel: *Introduction to Solid State Physics*, pp. 148-151.

Ashcroft and Mermin: *Solid state Physics*, pp. 6-15.

Dekker: *Solid State Physics,* pp. 301-302.

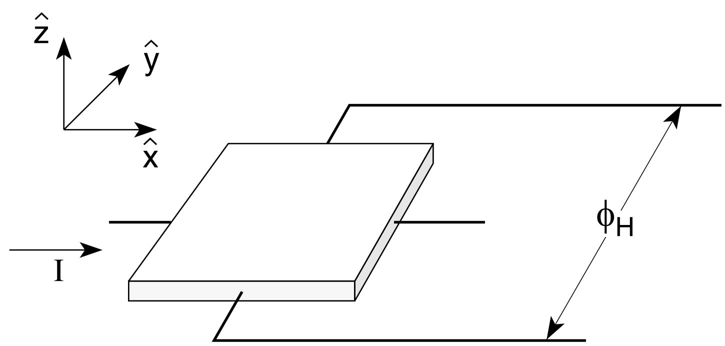
Yarwood: *High Vacuum Technique*, pp. 1-38, 77-78; 81-83; 96-100; 150-158.

II. Preparatory Questions

(must be answered in lab book before experiment is started and signed by instructor or TA)

A. Answer Question A in section VII. (In the first part of the question, express the answer as an algebraic relation between the quantity to be determined and the measured quantities.) Be sure that all numerical answers are labelled with the appropriate units.

B. Assuming in the figure below that $I = I_x$ and $B = B_z$, show how a measurement of the "sign" of the Hall voltage, ϕ_H, gives the sign of the charge carriers.



C. Show how you could extract a value of R_H (or n) from plots of ϕ_H vs. B_z and ϕ_H vs. I_x; compare the accuracy of this method of obtaining R_H with that resulting from simply substituting values into the equation obtained in answer to Question A.

Figure X-1

III. Purpose

To use the Hall effect to show that an electric current passing through metallic silver is carried by electrons, and to determine the number density and mean drift velocity of these electrons.

IV. Introduction

The conductivity of a metal such as copper can be explained on the basis of a free electron gas within the metal if these electrons are allowed to have collision with the atoms of the metal lattice. In this experiment we determine that electrons are the charge carriers in metals. By measuring the sign of the charge carriers, their mean drift velocity and their number density can be determined based on the assumption that each carries a single electron charge. From the negative sign of the charge carrier and their number density, it is difficult to conceive of anything other than electrons as the charge carriers. This is consistent with other known experimental results.

V. Principles

A. The Hall Effect

When an electric charge q moves with velocity v in a magnetic field B the charge experiences a force perpendicular to its direction of motion such that

$$\vec{F} = q\vec{v} \times \vec{B} \qquad \text{X-1}$$

Thus, in a slab of metal carrying an electric current I_x (Fig. X-1) the current density is j_x and if the current carriers have charge q

$$j_x = nq\langle v_x \rangle \qquad \text{X-2}$$

where n is the number density of charge carriers and $<v_x>$ is their mean drift velocity in the x-direction. If a magnetic field B_z is applied in the z-direction some of the charge carriers will be deviated towards the shaded side of the slab (Fig. X-2)

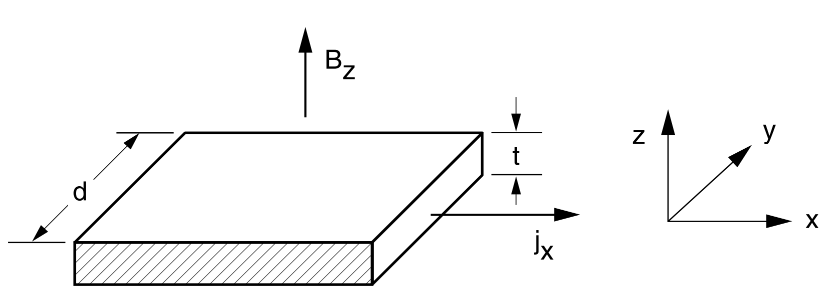


Figure X-2

where the surface charge density will build up until the electric field repelling further charges from that surface is sufficient to counteract the force of the magnetic field, then

$$qE_H = q\langle v_x \rangle B_Z \qquad \text{X-3}$$

The electric field developed by the surface charge density is known as the Hall field E_H, and the potential ϕ_H across the slab is the Hall voltage

$$\phi_H = E_H d \qquad \text{X-4}$$

Since for negative charge carriers, i.e., q negative, $\langle v_x \rangle$ is negative and therefore the shaded surface of the slab becomes negative while for positive charge carriers $\langle v_x \rangle$ is positive and the shaded surface becomes positive, the sign of the charge carriers can readily be determined. Further the magnitude of $\langle v_x \rangle$ can be determined from

$$v_x = \frac{E_H}{B_Z} \qquad \text{X-5}$$

Then if the charge q is taken as one electron charge e, the density of charge carriers can be determined from Eq. X-2.

For a given material, i.e., fixed n and q, the Hall voltage ϕ_H depends only on the magnetic field B_z and the current density j_x. Therefore to make ϕ_H a measurable voltage the current density must be made large. To achieve this high current density without the need for large sample currents ($I_x = j_x\, d\, t$), the thickness t of the slab of metal is made very small (~1000 Å) by using a thin film of the metal.

B. The Production of Thin Films

Thin films of thickness approximately 1000 Å are extremely fragile and although they can be made free of a substrate, usually in the form of a skin stretched on a supporting frame, they are very difficult to handle in that form. For this experiment it is advantageous to have the metal film closely attached to a substantial non-conducting substrate, partly because this allows several independent electrical connections to be made to the film and partly as a means of removing any heat developed in the metal film by ohmic heating. At the same time a very pure, clean and uniform metal film can be made by evaporating the metal under vacuum onto a clean glass substrate (microscope slide). See the Laboratory Staff for explicit instructions on how to evaporate the metal film, and how to measure the thickness of the sample.

VI. Experimental Procedure

The preparation and production of the thin silver film used in this experiment, the setting-up of the measuring system, the recording of data, and the measurement of the film thickness can all be completed in a four-hour laboratory period providing one is adequately prepared. There is no convenient point to divide the experiment to spread it out over two laboratory periods due to the rapid oxidation of the silver films.

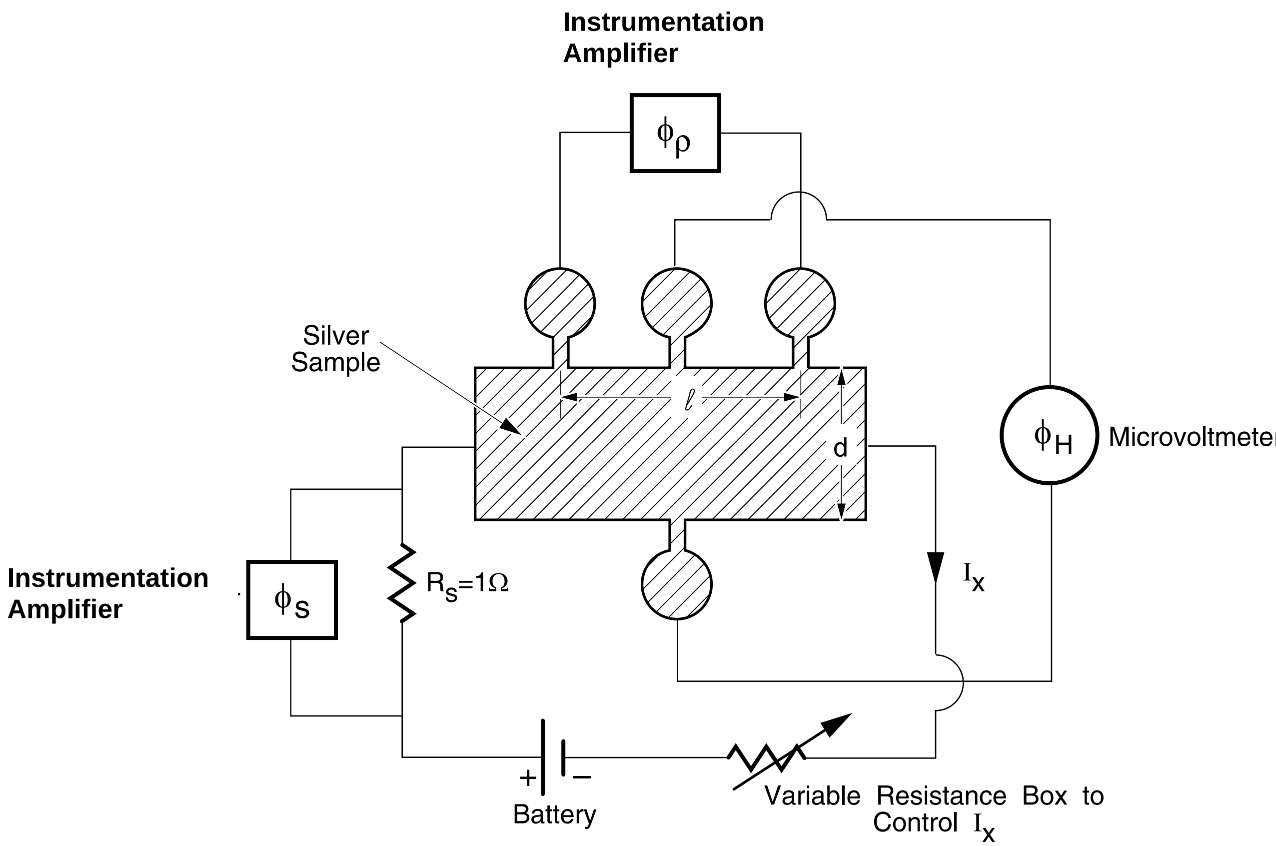


Figure X-3

In the first lab period, be sure that you have completed the prelab questions so that you have an estimate of the quantities you'll be determining in this experiment. You should also take some time to familiarize yourself with the vacuum system and the procedure for making a thin film. The meters used in this experiment (particularly the micro voltmeter) are very sensitive and subject both to small drifts and to noise pickup and you should consider ways to minimize these effects as you collect data. In the second lab period make a second evaporation of the silver and proceed with the full set of measurements.

A. Making the Measurements

A small electromagnet (E.S.I. Model #4 HF) provides the B_z field. It has 4-inch pole pieces with a 0.69 inch gap and produces 4000 gauss with the maximum permissible current of 15 amps. A Hall-probe gauss meter is used to measure its output. Be careful not to wear a wristwatch or to place steel objects near the magnet: 4000 gauss is a surprisingly strong magnetic field.

B. Connections to record the Hall Effect voltage output:

The following connections will permit you to simultaneously record the output of the Gauss meter, the micro voltmeter and the voltages ϕ_ρ and ϕs. Connect the circuit shown in Fig. X-3 and insert the Hall-effect sample holder between the magnet pole pieces. Note that a Lab Pro, data acquisition system, has been added to this experiment to ease the data taking in this experiment. The gaussmeter and micro-voltmeter used in this experiment have analog outputs. Connect channels one and two of the Lab Pro to these outputs. Two Instrumentation Amplifiers connected to channels three and four of the Lab Pro will be used to measure ϕ_ρ and ϕs.

Note: the analog output from any device may be different from the actual value displayed on the instrument. The relationship between these should be noted and recorded for later data analysis.

Also be sure to carefully adjust the zeros of the meters and the LabPro inputs prior to collecting data.

C. Computer acquisition of the data using the program Logger Pro:

You are now ready to run the computer program "Logger Pro" which will permit you to record the data collected by the Lab Pro.

1. Select the folder on the computer desktop labeled Lab_Pro_Templates. This folder contains Logger Pro templates designed for the Phys 405 lab experiments. Selecting one of these templates starts the program Logger Pro and loads the setup information for the experiment selected.

   ### The following information is stored in the Logger Pro template.

   - The Lab Pro will collect data from 4 analog channels.
   - Channel 1 Voltage Probe. Channel 1 is set to collect data from the analog output of the Gauss Meter and display this data in a table and as a graph.
   - Channel 2 Voltage Probe. Channel 2 is set to collect data from the analog output of the Micro voltmeter and display this data in a table and as a graph.
   - Channel 3 (Instrumentation Amplifier with Gain setting +/- 20millivolt) is set to collect data and display this data in the table and on the graph.
   - Channel 4 (Instrumentation Amplifier with Gain setting +/- 20millivolt) is set to collect data and display this data in the table and on the graph.
   - The Data Collection sampling rate is set to 10 samples (measurements) per second.
   - The Data Collection Length has been set to 15 seconds.

2. Zero the instruments. Make sure battery is disconnected so no current is flowing in the circuit. Place the gauss meter probe is in the "Zero Gauss Chamber" and press the zero button on the gauss meter. Adjust the zero controls on the micro voltmeter until its display is at zero. From the tool bar in Logger Pro, press the "Zero" button and select

"OK" to zero all sensors. This zeros, or aligns, Logger Pro and the Lab Pro with the sensors.

3. Click on the Collect button and the data collection should start. A live display will appear on the computer screen.

Measuring small currents always calls for care. The micro voltmeter is delicate and should always be kept on scale. Keep it on its least sensitive scale when not using it. You must minimize movement near the circuit when measuring as you can induce currents and voltages even in shielded cable.

Note that the Instrumentation Amplifier has several range settings. It is important to note that if a different range setting is selected (default +/- 20 mVolt), the calibration for the amplifier must be changed to reflect this change. From the Logger Pro toolbar menu, select "Experiment". From the list displayed move the curser to "calibrate" and the three sensors used in this experiment will be displayed. Select the Instrumentation Amplifier, and in the "Current Calibration" box, select the range setting that you have chosen. Once the range of the amplifier has been changed and the calibration set, it is important to zero the Instrumentation Amplifier.

Using current of no more than 100 mA, take enough data to plot at least two curves for ϕ_H against I_x for two different magnetic field settings, and at least two curves for ϕ_H against B_z using different I_x. Sufficient data (typically around 10 points) should be taken to define each of the curves. Also, determine the resistivity ρ of your silver sample, and compare this with the accepted bulk value given for Ag in some of the references. Attempt to explain any discrepancies between your value and the accepted value. This may be done by measuring the potential drop ϕ_ρ along a measured length of the silver sample using the potentiometer. From your data, and the measured size of the sample, determine the sign of the charge carriers and their number density assuming each is slightly charged. Use Figures X-2 and X-3 to compute the Hall coefficient for silver, R_H, where R_H is defined from the relation

$$E_H = R_H\left(j_x \times B_z\right), \qquad \text{X-6}$$

and compare with the theoretically accepted value. Many spurious effects can cause signals which are large compared to the true Hall voltage. The contacts used to measure the Hall voltage may not be exactly opposite each other, so what is measured is actually the true Hall voltage plus part of the voltage drop along the film due to I_x. Also, the current I_x may not be uniform over the film, or exactly parallel to the length of the film. Be absolutely sure you are measuring the real effect, which is dependent on both I_x and B_z.

When you have successfully finished all the required measurements on your Hall Effect sample, proceed with the measurement of the film thickness t. You will need to make an appointment with the Laboratory staff to use the DEKTAK film thickness measurement apparatus. This measurement is necessary before R_H and ρ can be calculated, but it is best left until this time in case the Hall effect sample is damaged during the setting-up procedure, in which case a second Hall effect sample and a new monitor will have to be made.

VII. Discussion Questions (to be answered in lab report)

A. Measurements made in this experiment are

1. Hall voltage ϕ_H
2. Magnetic field B_z
3. Voltage drop across the standard resistor R_s, ϕ_S
4. Voltage drop along the silver sample ϕ_ρ
5. The dimensions of the sample, d, t, and ℓ.

How can these measurements be used to determine the number density of charge carriers, n, the mean drift velocity $\langle v_x \rangle$, and the resistivity of silver ρ?

If	B_z	=	2000 gauss
	R_s	=	1Ω and $\phi_S = 100$ mV
	ϕ_H	=	20×10^{-6} volts
	ϕ_ρ	=	0.1 volts
	d	=	1 cm; $\ell = 2$ cm; $t = 1000$ Å

what are ρ, n, $\langle v_x \rangle$ and R_H?

B. Briefly describe the methods of operation of an oil-sealed rotary vacuum pump and an oil diffusion pump.

C. Describe very briefly: 1) the ionization gauge, 2) the thermocouple gauge. Which is an absolute pressure gauge?

VIII. Possible Procedure Check List

1. Complete Prelab and get instructors permission to start experiment.
2. Learn about Vacuum systems; read Appendix A of lab manual.
3. Receive verbal instructions on proper operation of the vacuum system from Laboratory Staff.
4. Turn on vacuum system.
5. Remove Bell Jar and load Ag wire into filament. Install cleaned glass slide into holder.
6. Evaporate silver film on to glass slide.
7. Carefully load test sample (glass slide) in to holder.
8. Connect circuit, measuring instruments, and data collection system.
9. Take Hall measurements.
10. If (9) is successful, make film thickness measurement on the sample (glass slide).
11. Turn off vacuum system.