HALL EFFECT IN THIN FILMS

REFERENCES

1. Halliday, D. and Resnick, A., Physics, 4th edition: Ney York, Wiley and Sons, Inc, 1992, Volume II, Chapter 34-4, pp.745-746.
2. S. Tolansky, Multiple Beam Interferometrv of Surfaces and Films.

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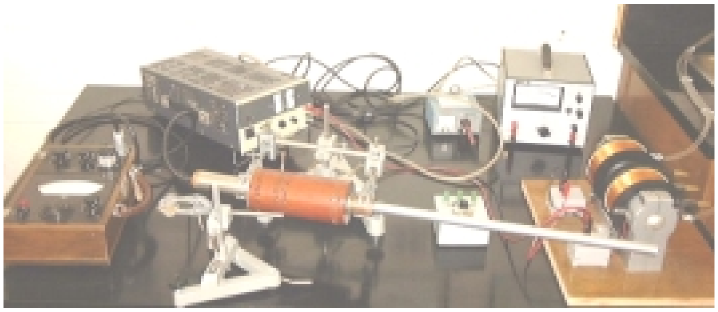
INTRODUCTION



When a current-carrying conductor is placed in a transverse magnetic field, the Lorentz force on the moving charges pushes them toward one side of the conductor producing a charge separation and, as a result, a voltage in the direction perpendicular to both the field and the current. This is known as the **Hall Effect**. The Hall voltage is the voltage transverse to both magnetic field and current.

Measurements of the Hall voltage are used to determine the density and sign of charge carriers in a conductor. When this is known, the effect is used as a probe for magnetic field measurements. In this experiment, samples of chromium and silver in the form of thin films of various thickness are available.

THEORY

The force $\boldsymbol{F}_L$ on a charge q moving with speed $\boldsymbol{v}_d$ in a magnetic field $\boldsymbol{B}$ (the Lorentz force) is given by

$$\boldsymbol{F}_L = q\,[\boldsymbol{v}_d \mathrm{x} \boldsymbol{B}]. \qquad (1)$$

The direction of the force acting on a positive charges can by determined by the Right Hand Rule No.1 (see Fig.3, APPENDIXES).

Consider the slab of conductor shown in Fig. 1. With current I flowing in the x-direction (the current density is $J_x=I/A$, where $A= wt$ is the cross-section area of the slab, w is the width and t is the thickness of the slab.)

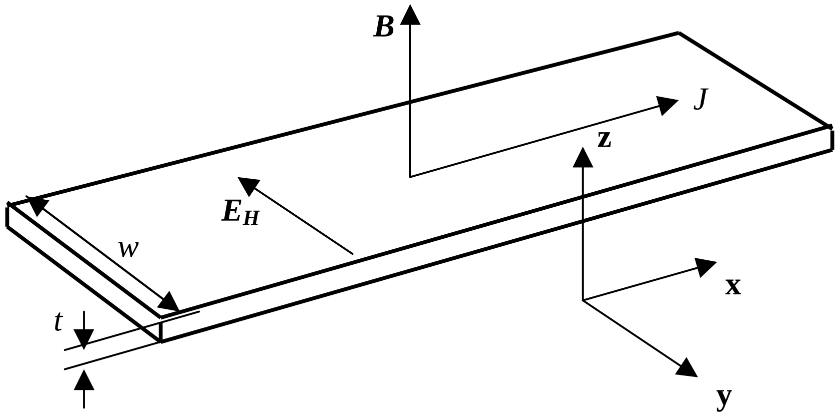


Figure 1. Geometry of the Hall Effect

In the presence of a magnetic field B_z along the z-direction, the charge carriers will experience a force driving them in the direction perpendicular to both the direction of the magnetic field and the current.

Suppose that the carriers are positive charges (i.e. holes in the p-type doped semiconductor). According to (1), the positive charges will move towards the right side of the slab in the **+y** direction, leaving the left side of the slab (in the **–y** direction) with an excess of the negative charge. This charge separation causes an electrostatic field in the slab which opposes the magnetic force on the carriers. When the electrostatic and magnetic forces cancel, the charge carriers will no longer move in the perpendicular direction.

If the current consists of negatively charged particles (i.e. electrons in a conducting wire), such carriers must be moving in the **–x** direction for the current flowing in the x direction. The magnetic force will again be in the same direction (**+y**) since we have changed the sign of both q and $\boldsymbol{v}_d$. The carriers again will be drawn to the part of the slab in **+y** direction (to the right), but this part of the slab now carries a negative charge (leaving the excess of a positive charge on the opposite side). A measurement of the sign of the potential difference between two sides of the slab in the direction perpendicular to both $\boldsymbol{B}$ and I tells us the sign of the charge carriers.

Quantitatively, the electric field $\boldsymbol{E_y}$ adjusts itself so that its force on the holes exactly cancels the Lorentz force or

$$qE_y = qv_x B_z \qquad (2)$$

where $\boldsymbol{v_x}$ is the carriers drift velocity.

The current density can be represented as

$$J_x = qnv_x \qquad (3)$$

(where n is the **density** of charge carriers)
so that, from (2) and (3),

$$E_y = \frac{J_x B_z}{qn} = R_H J_x B_z \qquad (4)$$

(where R_H is the called the Hall coefficient)

or

$$R_H \equiv \frac{E_y}{J_x B_z} = \frac{1}{qn} \qquad (5)$$

Note especially that **the Hall coefficient has opposite signs for positive and negative carriers** for the reasons described above.

Finally, remembering that the cross-sectional area of the sample $A=wt$, $J_x=I/A$ and $E_x=V_H/w$, (where V_H is the Hall voltage across the slab) for the slab passing a current I at right angles to an applied magnetic field B, the Hall coefficient is

$$R_H=E_\perp/(JB)=tV_H/(IB) \qquad (6)$$

where t is the thickness of the sample, I is the current, and V_H is the Hall voltage.

The **density** of charge carriers, n, and the drift velocity**,** v_d follow from the measured values of R_H, assuming the free-electron model of metals. For electrons in metals $q=e$, the electronic charge, so that (5) becomes

$$R_H=1/(ne) \qquad (7)$$

and the drift velocity is given by

$$J = I/A = nev_d \qquad (8)$$

where A is the cross-sectional area of the conductor and J the current density. Write down a similar equation for the positive charge carriers such as holes in semiconductors.

The Hall effect, in the limit of very high magnetic fields, has been used for a new determination of e^2/h (See Physics Today June 1981 p.17(optional)).

THE APPARATUS

In this experiment the current-carrying coil serves as a source of the magnetic field. You can change the magnetic field by changing the current through the coil. A regulated power supply allows us to change the current through the Hall probe.

MAGNETIC FIELD MEASUREMENTS

The magnetic field is measured using a Rawson-Lush rotating coil gaussmeter type 820B based on the phenomenon of electromagnetic induction (see Reference 1, Chapter 36-1, 36-2). It operates with 0.1% accuracy. The rotating coil is located near the tip of the long probe, at the end opposite to the motor. It is spun on one of its diameters so that it cuts the lines of the magnetic field twice during each revolution, generating a relatively pure sine-wave at a frequency of 30 Hz. The dimensions of the coil are carefully chosen to drive the maximum output for a given volume of field occupied by the coil, and also to give the best average reading in highly non-uniform field.

The position of the coil is shown by the lines scribed on the probe near its end. The entire coil lies within the limits of the three lines. The probe itself is covered by a protective tube while **not** in use.

It is recommended that **the field is measured at every magnet current for which Hall measurements are made**. Use the null facility on the gaussmeter for most accurate results.

Set-up

The field to be measured must always be perpendicular to the axis of rotation (i.e. the axis of the probe tube). Any component of the field along the axis of the tube will not produce a deflection of the meter. The instrument always reads the component of the field in the direction of the arrow on the back of the motor housing (and perpendicular to the tube). The letters N & S on the arrow indicate the north and south poles of the magnet producing the magnetic field. The north pole of a magnet is defined as that pole which points north when the magnet is suspended as a compass. It is interesting to note that the earth actually has a south pole up at the “North Geomagnetic Pole” location. Otherwise, it would attract south poles instead.

Meter

The indicating meter is a regular Rawson type 501 high sensitivity millivoltmeter, approximately 50 000 ohms per volt. The button marked “CLAMP” removes the weight of the moving system from the pivots and jewels for transit and storage. The button is operated by turning it in either direction. Do not submit the instrument to undue vibration when the moving system is unclamped. A ‘ZERO’ button is also provided.

For best results the meter should be placed on a firm support, fairly level, where there are no strong magnetic fields.

It is good practice to keep the meter switch on the highest range when making changes in the set-up to prevent accidental over1oad.

Measurements

With the instrument set up in a magnetic field and indicating its value on the meter, the switches and ten-turn potentiometer can he used to introduce a voltage from the reference generator into the circuit. The pointer on the meter will drop towards zero. Continue the adjustment until a reading around zero is reached.

Then the range switch on the meter can be turned to a more sensitive range and the potentiometer readjusted for a close balance. Final adjustment is made with the meter on the most sensitive range. It will be necessary to check the angular adjustment of the probe on its axis as the increased sensitivity makes this adjustment more critical. The correct adjustment of the angle is the one which give the highest reading of the pointer on the scale. When this is adjusted to zero, the switches and ten-turn potentiometer indicate the correct value of the field.

The meter range switch should be returned to a higher range as soon as the readings are completed, to save the meter from severe overloads if the probe is moved to a weaker or stronger field, putting the voltages out of balance.

HALL VOLTAGE MEASUREMENTS

Inspect the Hall probe and its wires. The set up for measuring R_H is sketched in Fig. 2. Note that the Hall probe and the magnet pole face are drawn not to scale.

NOT TO SCALE

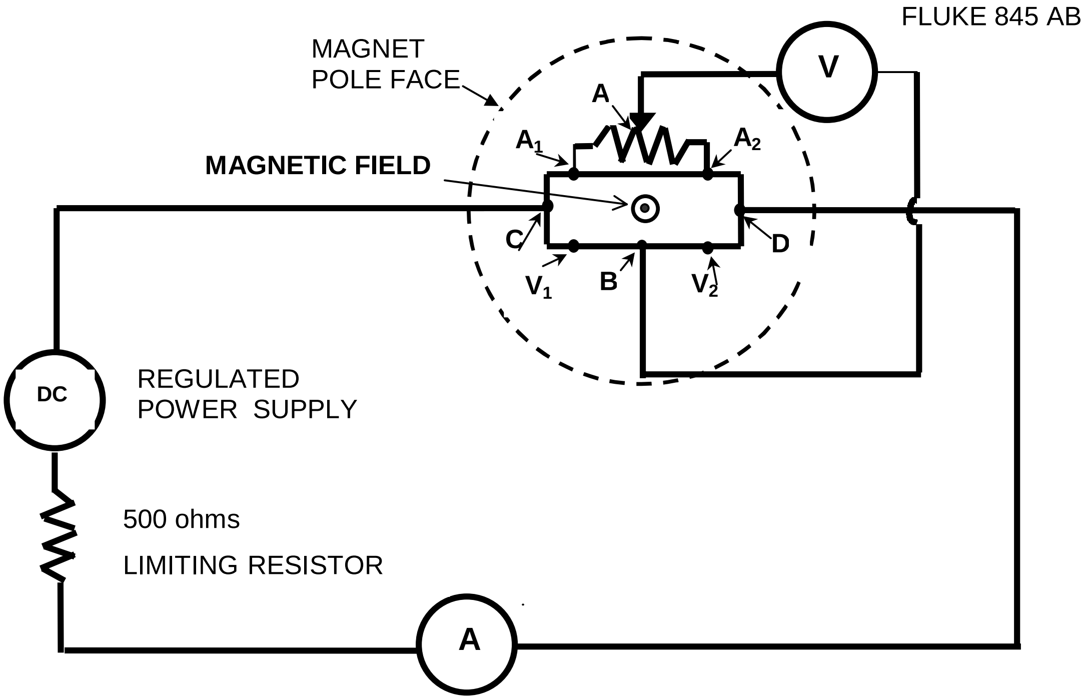


Figure 2. Hall Chip and Circuit

It is suggested that you begin measurements on one of the Ag samples. **Use the potentiometer at A_1A_2 (see Fig. 2) to zero out the voltage across AB at zero field.** Why does this voltage arise at all? Make sure the potentiometer gives a zero even when high currents (~30 mA) are applied at CD. **Always use the limiting resistor (500 Ω) on the power supply and never exceed 40 mA current through the sample.** Otherwise the sample will be destroyed. Check the potentiometer setting throughout the experiment.

Place the sample in the centre of the magnet gap with its broad side perpendicular to the field as shown in Fig.2. Determine R_H and its sign by using Eq. (6) and making the appropriate plots (i.e. Hall voltage versus current through the Hall probe at constant magnetic field **or** Hall voltage versus magnetic field at constant current through the Hall probe).

The thickness of the Hall samples can be determined from the interferometric photographs provided by the manufacturers. In our case,
t (A) = (fringe step/ fringe separation) x 2945 Å. Note: 1 Å = 0.1 nm. Having obtained R_H, the quantity n can be found. Comment on the magnitude of n and the type of carriers.

Now take measurements on a Cr sample using the same procedure. How does the Hall effect in Cr differ from that in Ag?

One of your samples can now be used to investigate the homogeneity of the magnet. The strength of the magnetic induction B of the unknown field can be measured by placing the slab in the unknown field, sending a current through the slab and measuring the Hall voltage. As a final exercise, run a profile across the central diameter. How does the homogeneity change with the magnet current?

BRIEF NOTE ON THE HALL SAMPLE THICKNESS MEASUREMENTS

The sample thickness was obtained by interference measurements before the electrodes were attached. A thin semi-reflective layer was deposited on them and another semi-reflective flat was placed over, and parallel to, the substrate and sample to form a thin parallel air gap. Interference fringes were observed in light of wavelength 5890 A, as in Fig. 4 (Appendixes). The fringes are displaced at the edge of the sample due to the change in the spacing in the air gap. It can be shown that this fringe displacement or ‘fringe step” is given by the relation:

FRINGE DISPLACEMENT= FRINGE SEPARATION x SAMPLE THICKNESS/(λ/2)) provided that the fringes are observed nearly normal to the plane of the sample and where λ = the wavelength of the light used = 5890 Å. Thus the interferograms may be used to find the sample thickness.

(GMG Nov. -1984, ta-Aug. 2000)

APPENDIXES

Appendix I. Right-hand rule No. 1

When the right hand is oriented so the fingers point along the magnetic field B and the thumb points along the velocity v of the **positively** charged particle, the palm faces in the direction of the magnetic force F applied to the particle (Fig. 3). If the moving charge is negative instead of positive, the direction of the magnetic force is opposite to that predicted by RHR-1.

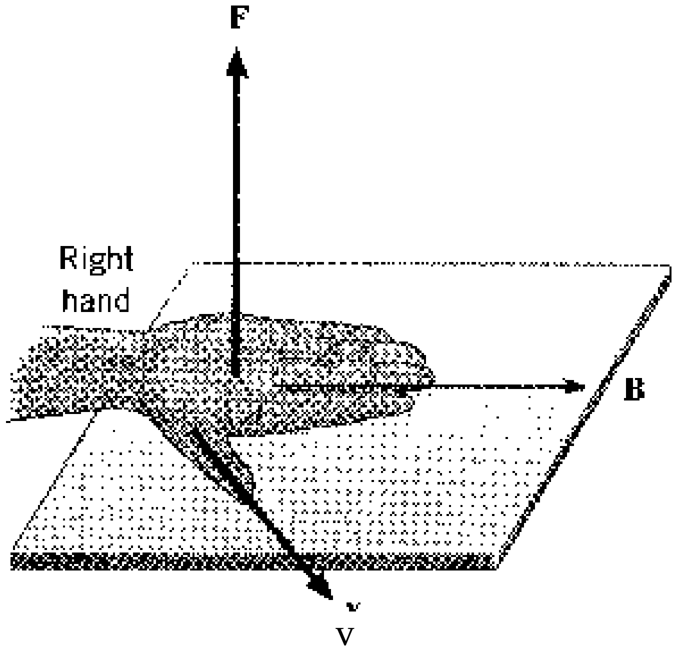


Figure 3. Right-hand Rule No.1

Appendix 2.

(Dimensions greatly exaggerated)

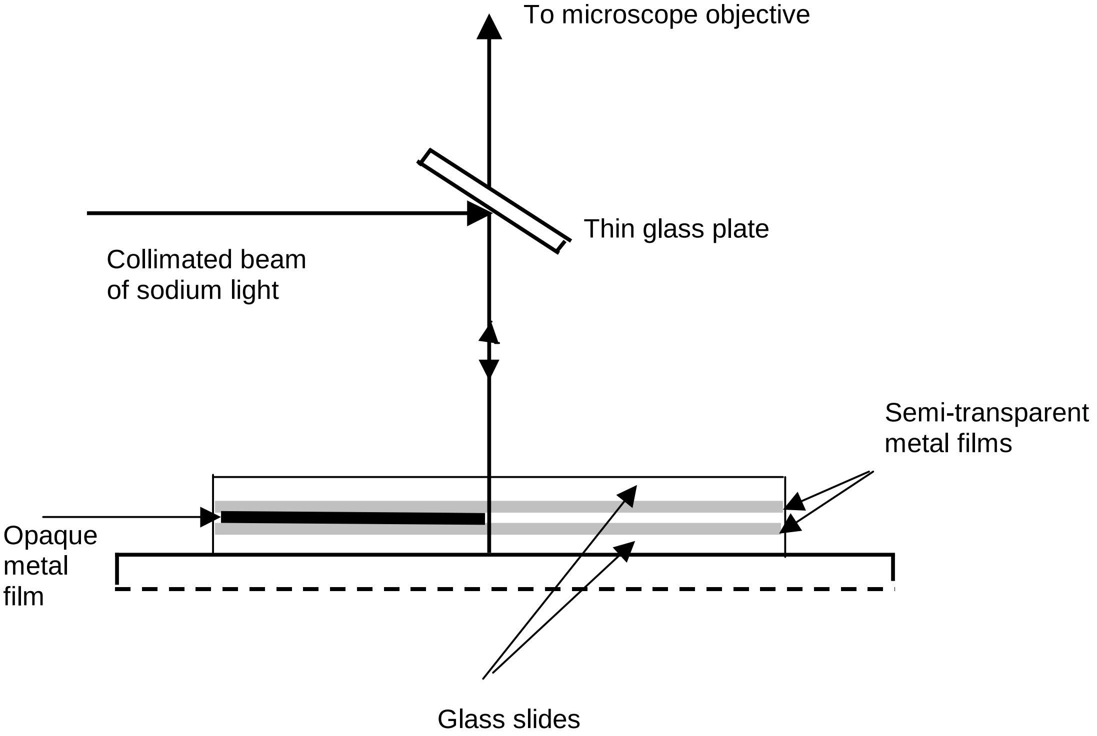


Figure 4. Arrangement of sandwiched films on a microscope stage to determine film thickness by an optical interference method.