Related topics

Semiconductor, band theory, forbidden zone, intrinsic conductivity, extrinsic conductivity, valence band, conduction band, Lorentz force, magnetic resistance, mobility, conductivity, band spacing, Hall coefficient.

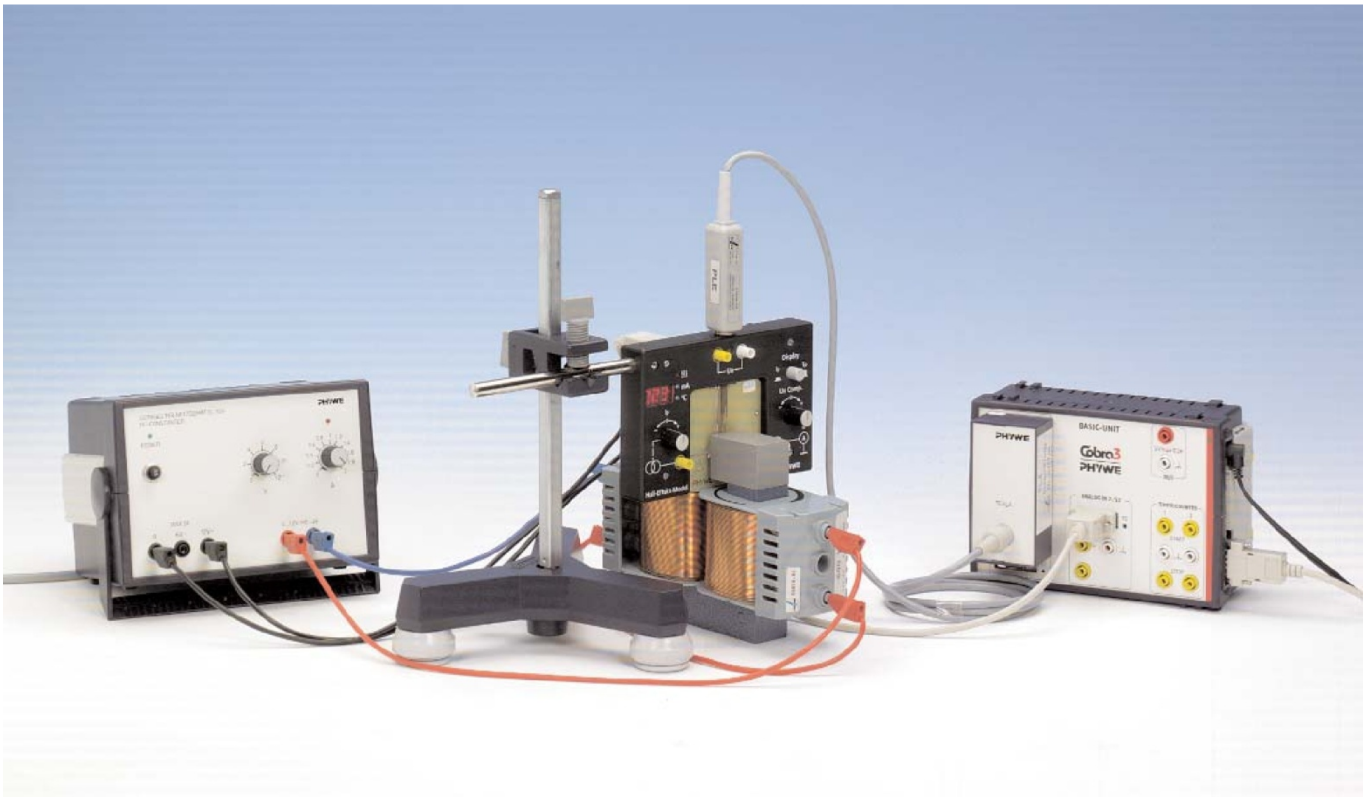
Principle

The resistivity and Hall voltage of a rectangular germanium sample are measured as a function of temperature and magnetic field. The band spacing, the specific conductivity, the type of charge carrier and the mobility of the charge carriers are determined from the measurements.

Equipment

1	Hall effect module,	11801.00
1	Hall effect, p-Ge, carrier board	11805.01
2	Coil, 600 turns	06514.01
1	Iron core, U-shaped, laminated	06501.00
1	Pole pieces, plane, 30x30x48 mm, 2	06489.00
1	Hall probe, tangent., prot. cap	13610.02
1	Power supply 0-12 V DC/6 V, 12 V AC	13505.93
1	Tripod base -PASS-	02002.55
1	Support rod -PASS-, square, l = 250 mm	02025.55
1	Right angle clamp -PASS-	02040.55
2	Connecting cord, l = 500 mm, red	07361.01
1	Connecting cord, l = 500 mm, blue	07361.04
2	Connecting cord, l = 750 mm, black	07362.05
1	Cobra3 Basic-Unit	12150.00
1	Power supply, 12 V	12151.99
1	Tesla measuring module	12109.00
1	Cobra3 Software Hall	14521.61
2	RS 232 data cable	14602.00
1	TESS Expert CD-ROM Laboratory	16502-42
	PC, Windows® 95 or higher	

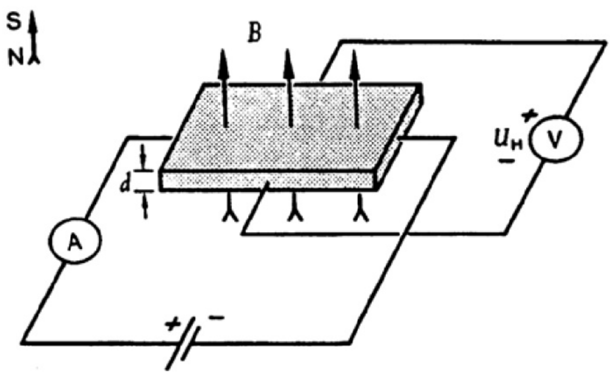
Fig. 1: Experimental set-up.



Tasks

1. The Hall voltage is measured at room temperature and constant magnetic field as a function of the control current and plotted on a graph (measurement without compensation for defect voltage).
2. The voltage across the sample is measured at room temperature and constant control current as a function of the magnetic induction B.
3. The voltage across the sample is measured at constant control current as a function of the temperature. The band spacing of germanium is calculated from the measurements.
4. The Hall voltage U_H is measured as a function of the magnetic induction B, at room temperature. The sign of the charge carriers and the Hall constant R_H together with the Hall mobility μ_H and the carrier concentration p are calculated from the measurements.
5. The Hall voltage U_H is measured as a function of temperature at constant magnetic induction B and the values are plotted on a graph.

Fig. 2: Hall effect in sample of rectangular section. The polarity sign of the Hall voltage shown applies when the carriers are negatively charged.



Set-up and procedure

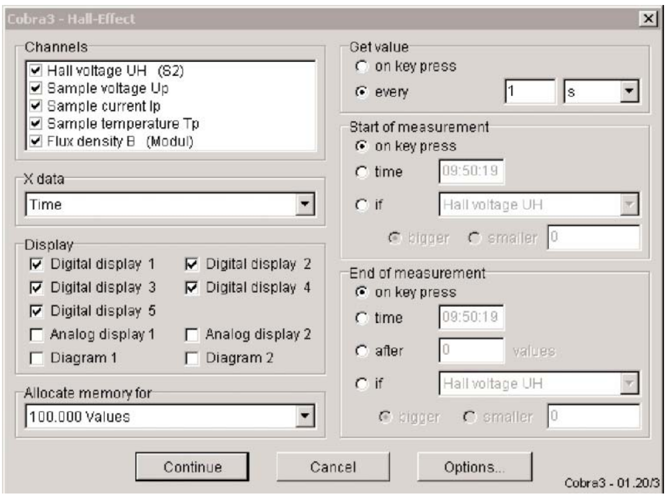
The experimental set-up is shown in Fig.1. The test piece on the board has to be put into the Hall-Effect-modul via the guide-groove. The module is directly connected with the 12 V~ output of the power unit over the ac-input on the back-side of the module.

The connection to the Analog In 2 – port of the Cobra3 Basic-Unit is realized via a RS232 cable from the RS232-port of the module.

The Tesla-module is connected to the module-port of the Interface.

The plate has to be brought up to the magnet very carefully, so as not to damage the crystal in particular, avoid bending the plate. It has to be in the centre between the pole pieces. The different measurements are controlled by the software. The magnetic field has to be measured with a hall probe, which can be directly put into the groove in the module as shown in Fig.1. So you can be sure that the magnetic flux is measured directly on the Ge-sample.

Fig. 3: Start menu of the software Cobra3 Hall effect.



To perform the measurements, start the software and choose as gauge the Cobra3 Hall-Effect.

You will receive the following window (Fig.3):

This is the start-screen which appears before every measurement. Here, you can choose, which parameters have to be measured, displayed, etc., e.g. Hall voltage as a function of Sample current (Fig.4)

You can also calibrate the Tesla-module via "options" (Fig.5). Start the measurement-screen by pressing the "continue"-button.

1. Choose The Hall voltage as the measurement-channel and the Sample current as x-axis.

   Choose the measurement on "key press".

   Continue. Set the magnetic field to a value of 250 mT by changing the voltage and current on the power supply. Determine the hall voltage as a function of the current from -30 mA up to 30 mA in steps of nearly 5 mA.

   You will receive a typical measurement like in Fig.6.

2. Choose The Sample voltage as the measurement-channel and the Flux density as x-axis. Choose the measurement on "key press". Continue.

   Set the control current to 30 mA. Determine the sample voltage as a function of the magnetic induction B. Start with -300 mT by changing the polarity of the coil-current and increase the magnetic induction in steps of nearly 20 mT. At zero point, you have to change the polarity to receive a positive magnetic induction, as the current and voltage are only positive. You will get a typical graph as shown in Fig.7.

3. Choose The Sample voltage as the measurement-channel and the sample temperature as x-axis. Choose the measurement "every 1 s". Continue.

   Set the current to a value of 30 mA. The magnetic field is off. The current remains nearly constant during the measurement, but the voltage changes according to a change in temperature. Start the measurement by activating the heating coil with the "on/off"-knob on the backside of the module and start the measurement in the software.

   Determine the change in voltage dependent on the change in temperature for a

Fig. 4: Example of measurement parameters.

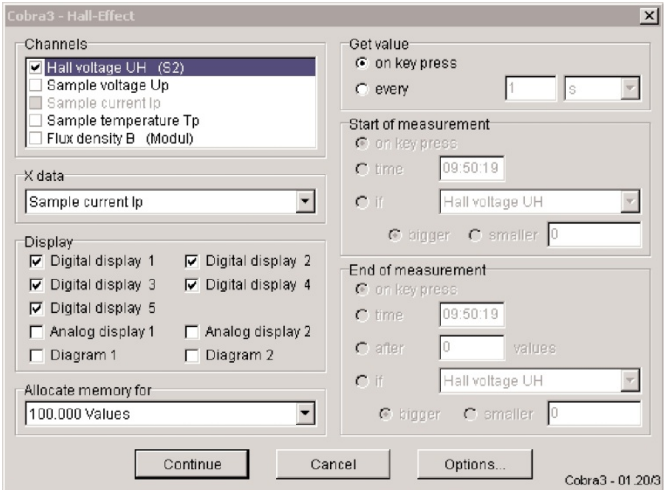


Fig. 5: Calibration menu.

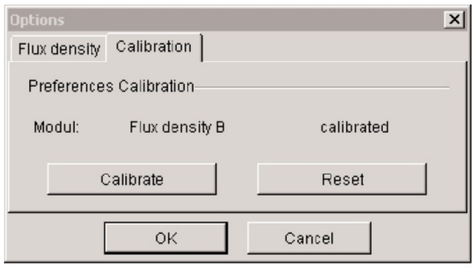


Fig. 6: Hall voltage as a function of current.

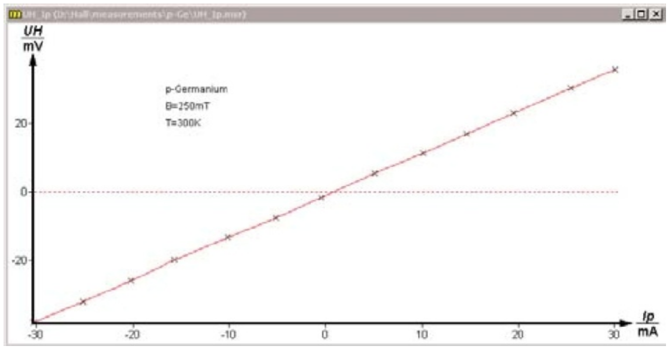
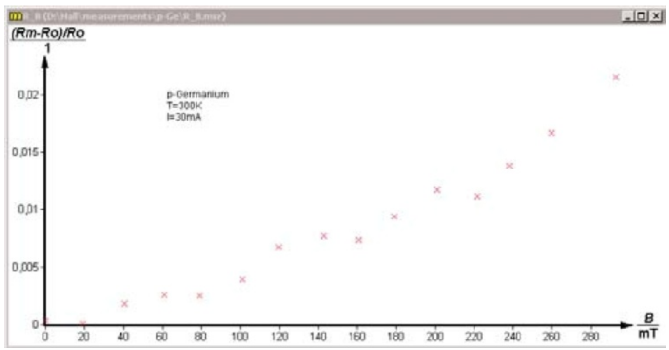


Fig. 7: Change of resistance as a function of magnetic induction.



temperature range of room temperature to a maximum of 170°C. The module automatically controls and stops the heating. You will receive a typical curve as shown in Fig.8.

4. Choose The Hall voltage as the measurement-channel and the Flux density as x-axis.

   Choose the measurement on “key press”. Continue.

   Set the current to a value of 30 mA. Determine the Hall voltage as a function of the magnetic induction. Start with -300 mT by changing the polarity of the coil-current and increase the magnetic induction in steps of nearly 20 mT. At zero point, you have to change the polarity. A typical measurement is shown in Fig.9.

5. Choose The Hall voltage as the measurement-channel and the sample temperature as x-axis. Choose the measurement “every 1 s”. Continue.

   Set the current to 30 mA and the magnetic induction to 300 mT.

   Determine the Hall voltage as a function of the temperature.

   Start the measurement by activating the heating coil with the “on/off”-knob on the backside of the module and starting the software.

   After a channel modification (compare evaluation) you will receive a curve like Fig.10.

Fig. 8: Reciprocal sample voltage plotted as a function of reciprocal absolute temperature. (Since I was constant during the measurement, $U^{-1} \sim s$ and the graph is therefore equivalent to a plot of conductivity against reciprocal temperature).

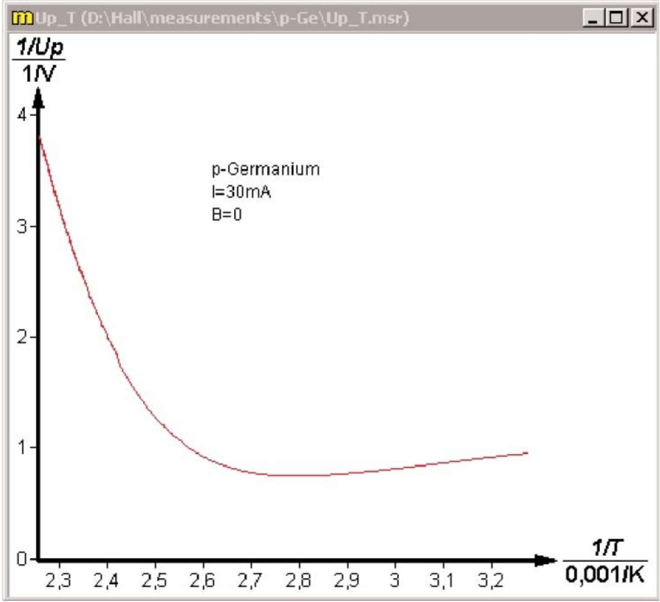
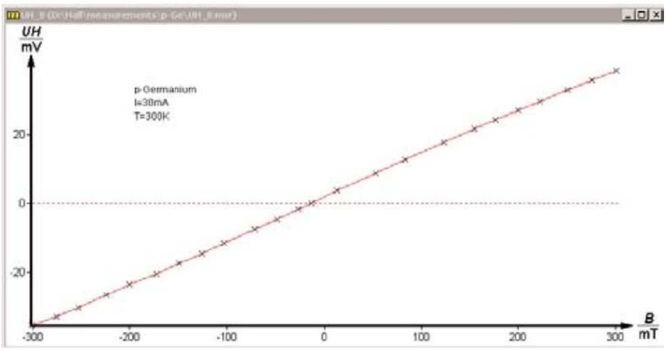


Fig. 9: Hall voltage as a function of magnetic induction.



Theory and evaluation

If a current I flows through a conducting strip of rectangular section and if the strip is traversed by a magnetic field at right angles to the direction of the current, a voltage – the so-called Hall voltage – is produced between two superposed points on opposite sides of the strip.

This phenomenon arises from the Lorentz force: the charge carriers giving rise to the current flowing through the sample are deflected in the magnetic field B as a function of their sign and their velocity v:

$$\vec{F} = e(\vec{v} \times B)$$

(F = force acting on charge carriers, e = elementary charge).

Since negative and positive charge carriers in semiconductors move in opposite directions, they are deflected in the same direction.

The type of charge carrier causing the flow of current can therefore be determined from the polarity of the Hall voltage, knowing the direction of the current and that of the magnetic field.

1. Fig. 6 shows that there is a linear relationship between the current I and the Hall voltage U_B:

$$U_H = \alpha \cdot I$$

where α = proportionality factor.

2. The change in resistance of the sample due to the magnetic field is associated with a reduction in the mean free path of the charge carriers. Fig. 7 shows the non-linear, clearly quadratic, change in resistance as the field strength in-creases. Therefore use the channel modification in the analysis-menu.

3. In the region of intrinsic conductivity, we have

$$\sigma = \sigma_0 \cdot \exp\left(-\frac{E_g}{2\,kT}\right)$$

where σ = conductivity, E_g = energy of bandgap, k = Boltzmann constant, T = absolute temperature. If the logarithm of the conductivity is plotted against T^{-1} a straight line is obtained with a slope

$$b = -\frac{E_g}{2\,k}\ .$$

from which E_g can be determined.

From the measured values used in Fig. 8, the slope of the regression line

$$\ln \sigma = \ln \sigma_0 + \frac{E_g}{2\,k} \cdot T^{-1}$$

is

$$b = -\frac{E_g}{2\,k} = -4.18 \cdot 10^3\,\mathrm{K}$$

with a standard deviation $s_b = \pm 0.07 \cdot 10^3$ K.

3. To receive the necessary graph, do as follows:

Choose the channel modification in the analysis-menu. Set the parameters as shown in Fig.11. Continue. Remember the procedure with the parameters in Fig.12. Now, you have the desired graph. To determine the regression line, choose the “Regression”-icon.

(Since the measurements were made with a constant current, we can put $s \sim U^{-1}$, where U is the voltage across the sample.)

Since

$$k = 8.625 \cdot 10^{-5}\,\frac{\mathrm{eV}}{\mathrm{K}}$$

we get

$$E_g = b \cdot 2k = (0.72 \pm 0.03)\ \mathrm{eV}.$$

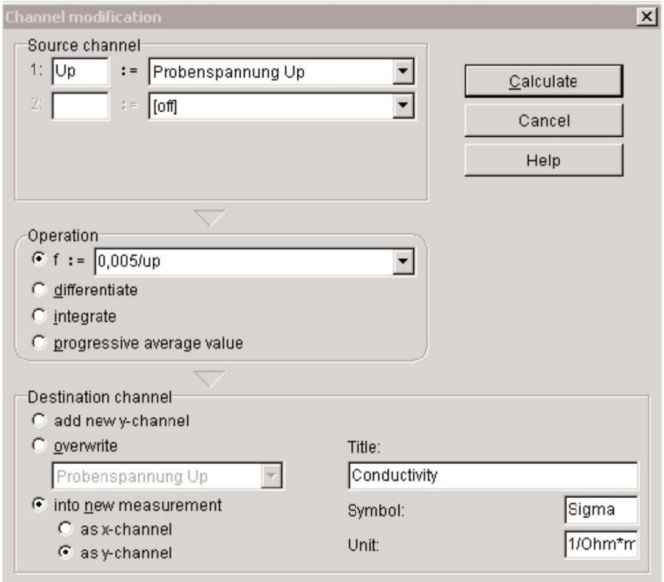


Fig. 11: Parameters for the first channel modification.

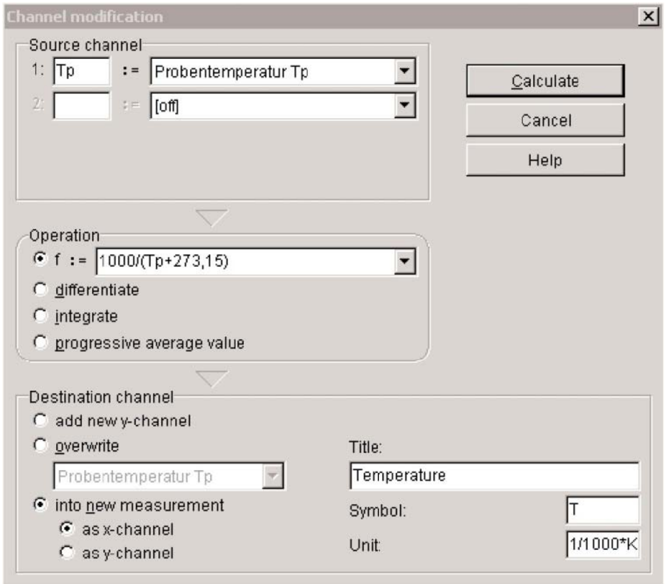


Fig. 12: Parameters for the second channel modification.

4. With the directions of control current and magnetic field shown in Fig. 2, the charge carriers giving rise to the current in the sample are deflected towards the front edge of the sample. Therefore, if (in an n-doped probe) electrons are the predominant charge carriers, the front edge will become negative, and, with hole conduction in a p-doped sample, positive.

   The conductivity s$_0$, the charge carrier mobility μ_H, and the charge-carrier concentration p are related through the Hall constant R_H:

$$R_H = \frac{U_H}{B} \cdot \frac{d}{I}, \quad \mu_H = R_H \cdot \sigma_0$$

$$p = \frac{1}{e \cdot R_H}$$

   Fig. 9 shows a linear connection between Hall voltage and B field. With the values used in Fig. 9, the regression line with the formula

$$U_H = U_0 + b \cdot B$$

   has a slope b = 0.125 VT^{-1}, with a standard deviation s_b ± 0.003 VT^{-1}.

   The Hall constant R_H thus becomes, according to

$$R_H = \frac{U_H}{B} \cdot \frac{d}{I} = b \cdot \frac{d}{I}$$

   where the sample thickness d = 1 · 10^{-3}m and I = 0.030 A,

$$R_H = 4.17 \cdot 10^{-3} \frac{m^3}{As}$$

   with the standard deviation

$$s_{RH} = 0.08 \cdot 10^{-3} \frac{m^3}{As} .$$

The conductivity at room temperature is calculated from the sample length l, the sample cross-section A and the sample resistance R_0 (cf. 2) as follows:

$$\sigma_0 = \frac{l}{R \cdot A} .$$

With the measured values

$$l = 0.02 \text{ m}, R_0 = 35.0 \ \Omega, A = 1 \cdot 10^{-5} \text{m}^2$$

we have

$\sigma_0 = 57.14 \ \Omega^{-1} \ \text{m}^{-1}$.

The Hall mobility μ_H of the charge carriers can now be determined from

$$\mu_H = R_H \cdot \sigma_0$$

Using the measurements given above, we get:

$$\mu_H = (0.238 \pm 0.005) \ \frac{m^2}{Vs} .$$

The hole concentration p of p-doped samples is calculated from

$$p = \frac{1}{e \cdot R_H}$$

Using the value of the elementary charge

$e = 1.602 \cdot 10^{-19}$ As

we obtain

$p = 14.9 \cdot 10^{20} \ \text{m}^{-3}$.

5. Fig. 10 shows first a decrease in Hall voltage with rising temperature. Since the measurements were made with constant current, it is to be assumed that this is attributable to an increase in the number of charge carriers (transition from extrinsic conduction to intrinsic conduction) and the associated reduction in drift velocity v.

(Equal currents with increased numbers of charge carriers imply reduced drift velocity). The drift velocity in its turn is connected with the Hall voltage through the Lorentz force.

The current in the crystal is made up of both electron currents and hole currents

$$I = A \cdot e \ (v_n \cdot n + v_p \cdot p).$$

Since in the intrinsic velocity range the concentrations of holes p and of electrons n are approximately equal, those charge carriers will in the end make the greater contribution to the Hall effect which have the greater velocity or (since $v = m+E$) the greater mobility.

Fig. 10 shows accordingly the reversal of sign of the Hall voltage, typical of p-type materials, above a particular temperature.

