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.

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.

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, 30×30×48 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
3	Connecting cord, l = 500 mm, red	07361-01
2	Connecting cord, l = 500 mm, blue	07361-04
2	Connecting cord, l = 750 mm, black	07362-05
1	Teslameter, digital	13610-93
1	Digital multimeter	07134-00

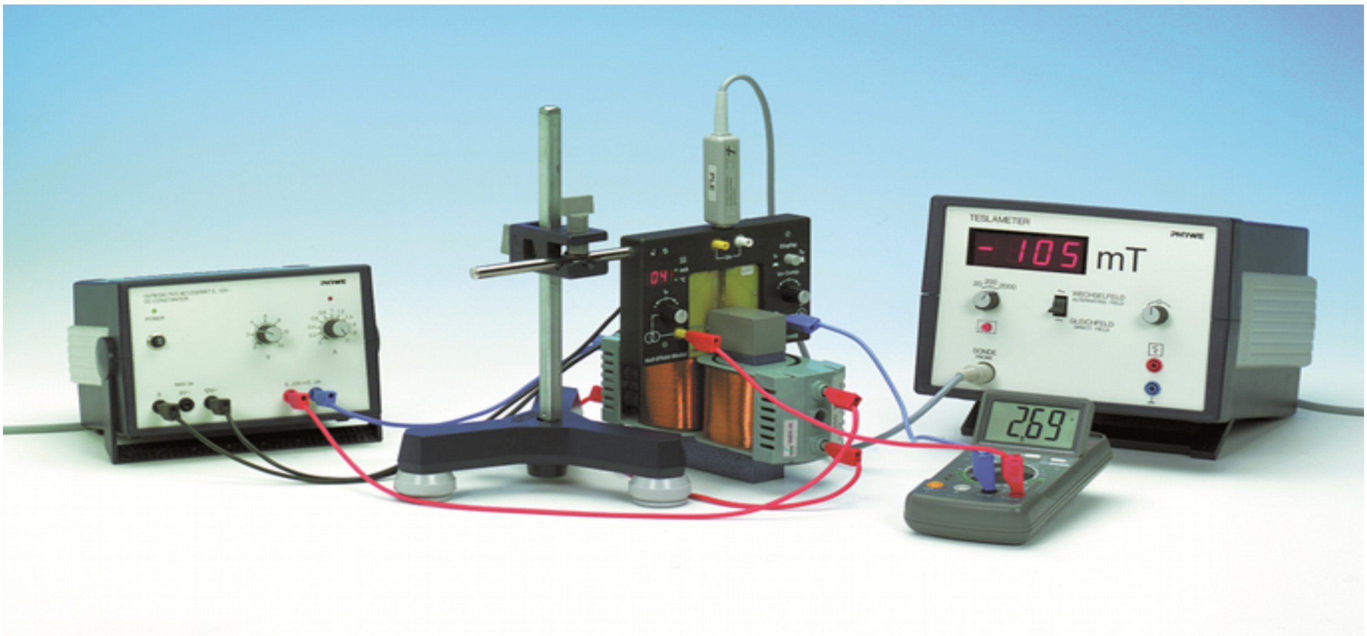

Figure 1: Experimental set-up

Task

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 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.

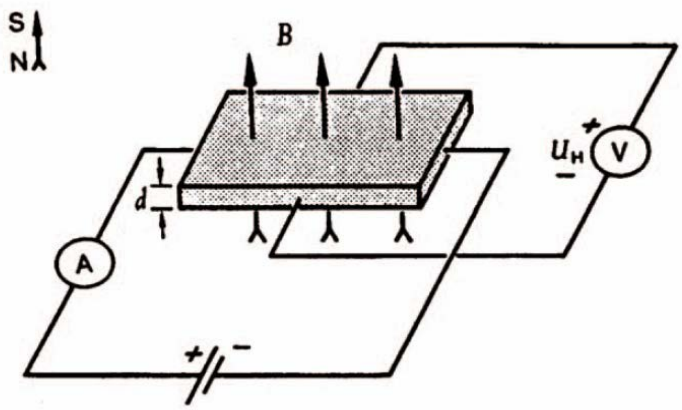

Fig. 2: Hall effect in sample of rectangular section. The polarity sign of the Hall voltage shown applies when the carriers are negatively charged.

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-module via the guide-groove. The module is directly connected with the 12 V~ output of the power unit over the ac-input on the backside of the module.

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.

The Hall voltage and the voltage across the sample are measured with a multimeter. Therefore, use the sockets on the front-side of the module. The current and temperature can be easily read on the integrated display of the module.

The magnetic field has to be measured with the teslameter via 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.

Task 1

Set the magnetic field to a value of 250 mT by changing the voltage and current on the power supply. Connect the multimeter to the sockets of the hall voltage (U_H) on the front-side of the module. Set the display on the module into the "current-mode". 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. 3.

Task 2

Set the control current to 30 mA. Connect the multimeter to the sockets of the sample voltage on the front-side of the module. Determine the sample voltage as a function of the positive magnetic induction B up to 300 mT. You will get a typical graph as shown in Fig. 4.

Task 3

Be sure, that the display works in the temperature mode during the measurement. At the beginning, 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. Set the display in the temperature mode, now. Start the measurement by activating the heating coil with the "on/off"-knob on the backside of the module. Determine the change in voltage dependent on the change in temperature for a temperature range of room temperature to a maximum of 140 °C. You will receive a typical curve as shown in Fig. 5.

Task 4

Set the current to a value of 30 mA. Connect the multimeter to the sockets of the hall voltage (U_H) on the front-side of the module. 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. 6.

Task 5:

Set the current to 30 mA and the magnetic induction to 300 mT. Determine the Hall voltage as a function of the temperature. Set the display in the temperature mode. Start the measurement by activating the heating coil with the "on/off"- knob on the backside of the module. You will receive a curve like Fig. 7.

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:

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

(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.

Task 1

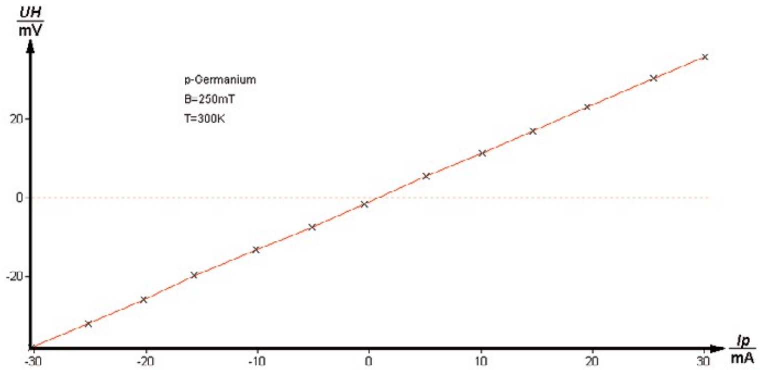

Fig. 3: Hall voltage as a function of current.

Fig. 3 shows that there is a linear relationship between the current I and the Hall voltage U_H:

$$U_H = \alpha \cdot I$$

where α = proportionality factor.

Task 2

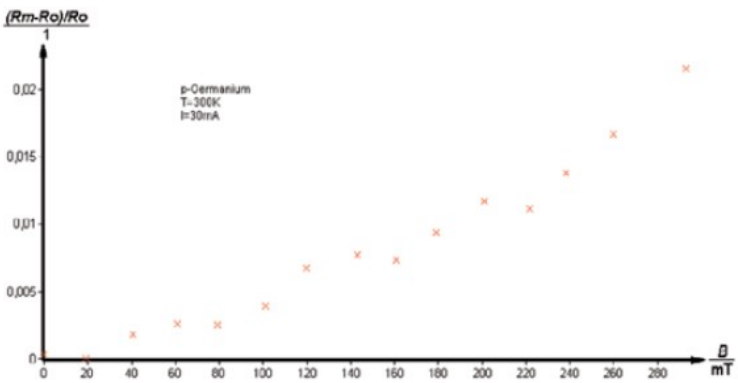

Fig 4: Change of resistance as a function of magnetic induction.

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. 4 shows the non-linear, clearly quadratic, change in resistance as the field strength increases.

Task 3

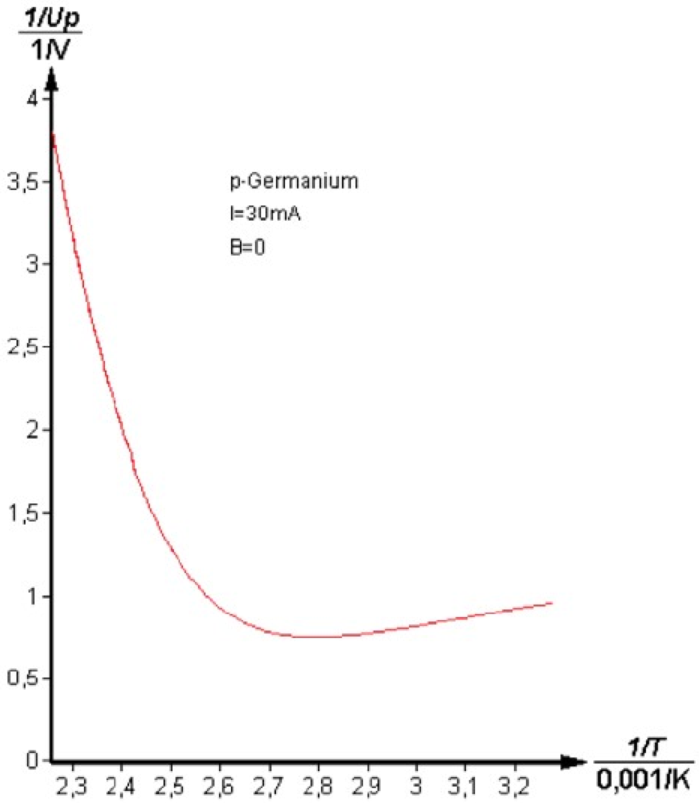

Fig 5: Reciprocal sample voltage plotted as a function of reciprocal absolute temperature. (Since I was constant during the measurement, $U^{-1} \sim \sigma$ and the graph is therefore equivalent to a plot of conductivity against reciprocal temperature).

In the region of intrinsic conductivity, we have

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

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 from which E_g can be determined. From the measured values used in Fig. 5, the slope of the regression line

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

is

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

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

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

Task 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 σ_0, the chargecarrier mobility μ, and the charge-carrier concentration p are related through the Hall constant R_H:

$$R_H = \frac{U_H}{B} \cdot \frac{d}{I}, \quad \mu = R_H \cdot \sigma_0; \quad p = \frac{1}{e \cdot R_H}$$

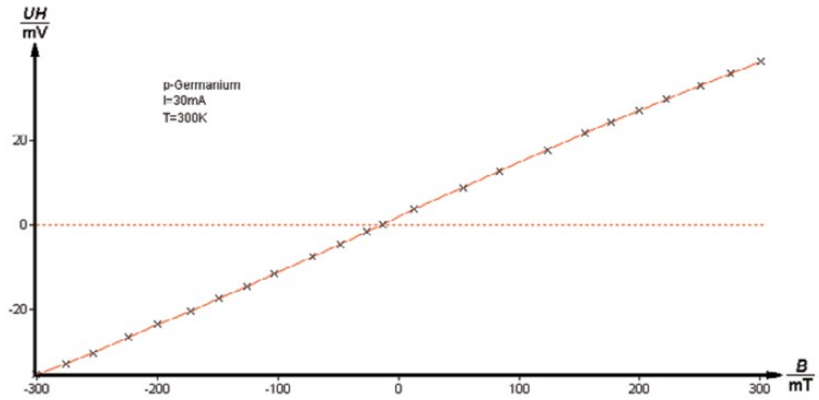

Fig 6: Hall voltage as a function of magnetic induction.

Fig. 6 shows a linear connection between Hall voltage and B field. With the values used in Fig. 6, the regression line with the formula

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

has a slope b = 0.125 $\mathrm{VT^{-1}}$, with a standard deviation s_b = ± 0.003 $\mathrm{VT^{-1}}$.
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 $d = 1 \cdot 10^{-3}$m and I = 0.030 A,

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

With the standard deviation

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

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

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

we have

$$\sigma_0 = 57.14\ \frac{1}{\Omega\ \mathrm{m}}$$

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

$$\mu = R_{\mathrm{H}} \cdot \sigma_0$$

Using the measurements given above, we get:

$$\mu = (0.238 \pm 0.005)\ \frac{\mathrm{m}^2}{\mathrm{Vs}}$$

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

$$p = \frac{1}{e \cdot R_{\mathrm{H}}}$$

Using the value of the elementary charge

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

we obtain

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

Task 5

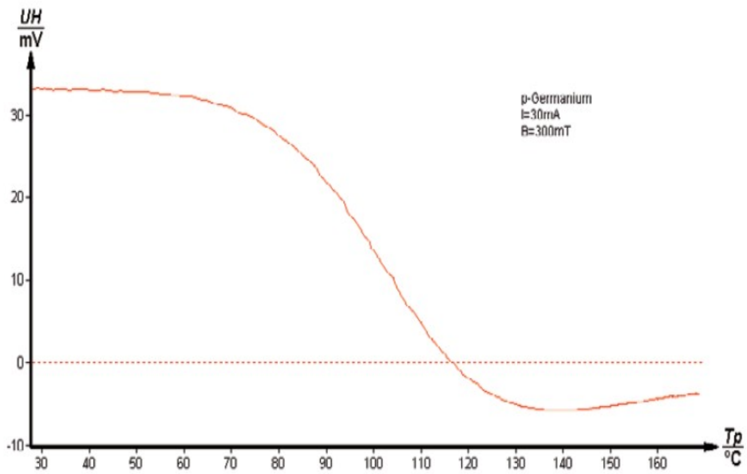

Fig 7: Hall voltage as a function of temperature.

Fig. 7 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

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

Since in the intrinsic conductivity 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 $v = \mu + E$) the greater mobility.
Fig. 7 shows accordingly the reversal of sign of the Hall voltage, typical of p-type materials, above a particular temperature.

