Hall effect in p-germanium

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 and task

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.

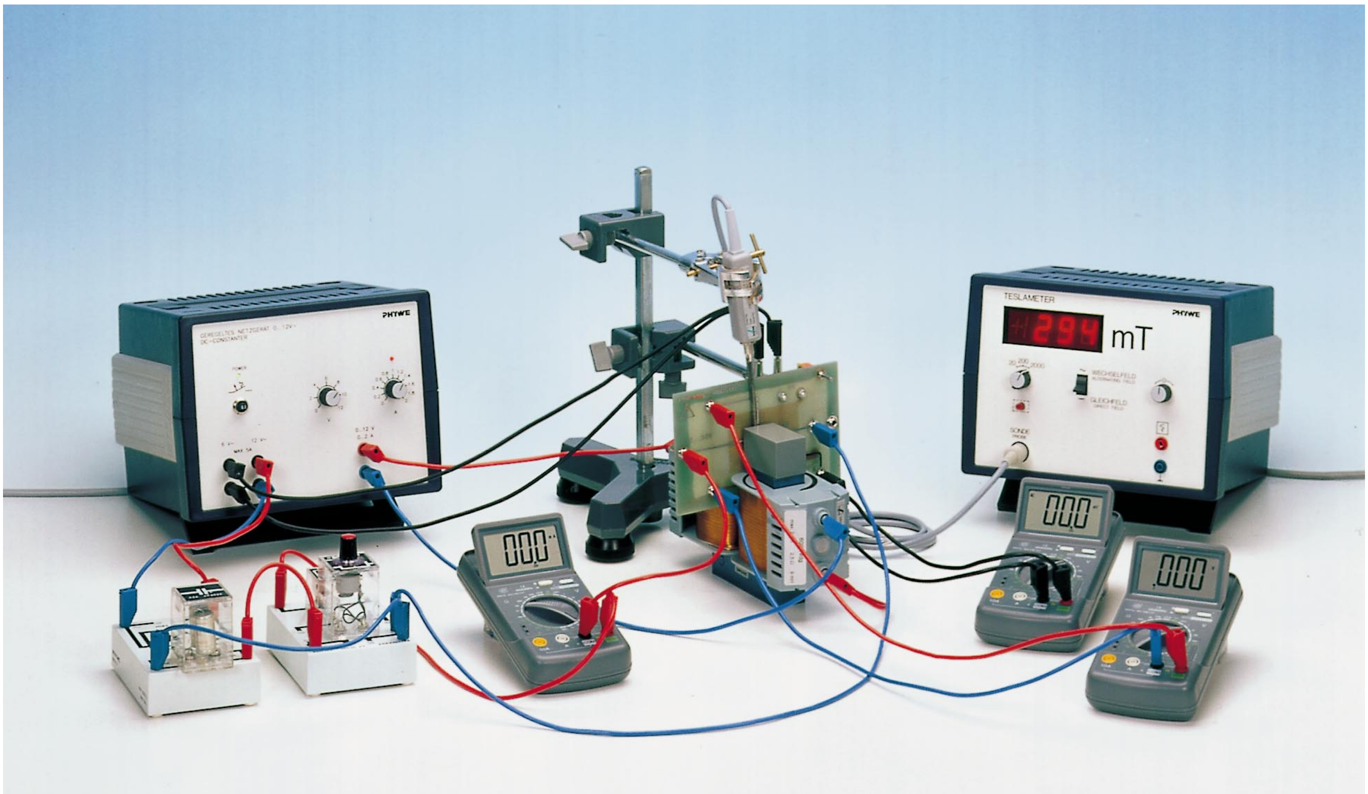
Equipment

Hall effect, p-Ge, carrier board	11805.00	1
Coil, 600 turns	06514.01	2
Iron core, U-shaped, laminated	06501.00	1
PEK carbon resistor 1 W 5 % 330 Ohm	39104.13	1
Pole pieces, plane, 30×30×48 mm, 2	06489.00	1
Connection box	06030.23	1
Distributor	06024.00	1
Bridge rectifier 250 VAC/5 A	06031.11	1
PEK electro.capacitor 2000 mmF/25 V	39113.08	1
PEK potentiometer 560 Ohm lin 4 W	39103.18	1
Teslameter, digital	13610.93	1
Hall probe, tangent., prot. cap	13610.02	1
Power supply 0-12 V DC/6 V, 12 V AC	13505.93	1
Digital multimeter	07134.00	3
Tripod base -PASS-	02002.55	1
Support rod -PASS-, square, l 250 mm	02025.55	1
Right angle clamp -PASS-	02040.55	2
Universal clamp	37715.00	1
Connecting cord, 100 mm, red	07359.01	1
Connecting cord, 100 mm, blue	07359.04	1
Connecting cord, 500 mm, red	07361.01	6
Connecting cord, 500 mm, blue	07361.04	4
Connecting cord, 750 mm, black	07362.05	4

Problems

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.1: Experimental set-up for measurements of Hall effect.



Set-up and Procedure

The experimental set-up is shown in Fig. 1.

The plate must be brought up to the magnet very carefully, so as not to damage the crystal In particular, avoid bending the plate.

1. The control current is derived from the alternating voltage output of the power unit, using a bridge rectifier.

To do this, the rectifier is connected on the one hand to the lower socket of the power supply unit and on the other to the socket marked “15 V” on the selector ring above it (see Fig. 2).

An electrolytic condenser is connected to the rectifier output for smoothing. (Note the polarity). The control current is set with the aid of a potentiometer. A 330 Ω resistor is connected in series to limit the current and so prevent accidental overstepping of the maximum permissible current (50 mA).

In this measurement, the crystal is connected directly (terminals A and B in Fig. 2); hence the constant-current source and the defect voltage compensation are inactive.

The magnetic field is produced by the two series-connected coils fed from the DC outlet of the main supply unit. It is advisable for this purpose to set the voltage to the maximum value and to adjust the magnetic field to the desired value by use of the current control knob.

The power supply unit then acts as a constant-current source, so ensuring that temperature-induced resistance changes have no effect on the field strength.

The magnetic induction of the field is measured by the teslameter, the Hall probe of which is placed at the centre of the field (after the apparatus has been adjusted).

The Hall voltage is measured by the high-resistance digital multimeter.

2. The control-current supply is now connected to the outer terminals A and C (Fig. 2), so that the incorporated constant-current source becomes effective. The 560 Ω potentiometer is set to the maximum voltage. The control current should now be about 30 mA. (If it is not, the value can be readjusted using the trimmer on the supplementary board). The voltage across the sample is measured between the terminals A and B using the digital multimeter (see Fig. 2). The sample resistance in the absence of the magnetic field, R_0, is calculated and the change in resistance

$$\frac{R_B - R_0}{R_0}$$

is plotted as a function of the magnetic induction B (R_B sample resistance with the magnetic field).

3. The sample is heated to temperatures up to 175°C using the heating coil. The heating current required is taken from the 6 V AC output of the power supply unit. The sample temperature T can be determined by the built-in Cu/CuNi thermocouple, using the voltmeter :

$$T = \frac{U_T}{\alpha} + T_0$$

(U_T = voltage across the thermocouple;

α = 40 µV/K;

T_0 = room temperature).

CAUTION: The sample temperature must in no case rise above 190°C.

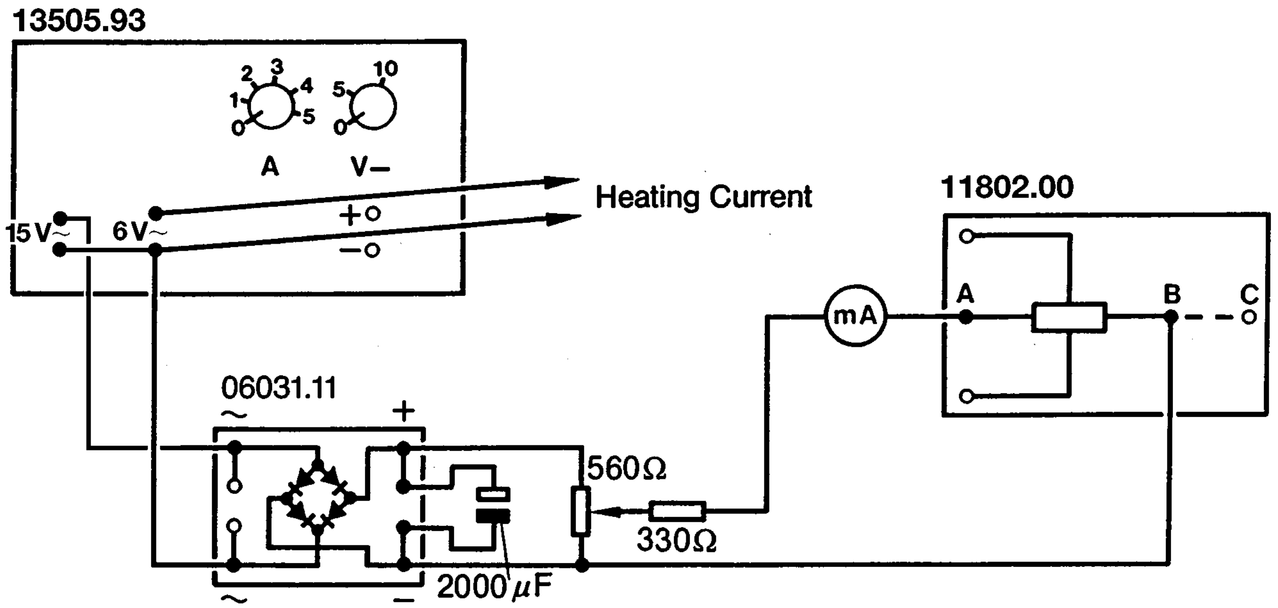
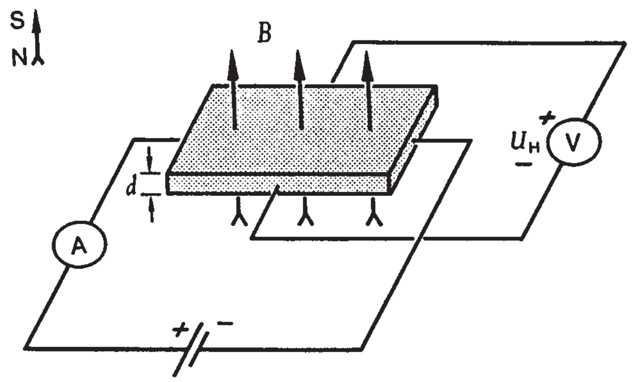


Fig. 2: Circuit diagram for control-current supply.

Fig. 3: Hall effect in sample of rectangular section. The polarity sign of the Hall voltage shown applies when the carriers are negatively charged.



4. With the magnetic field switched off and the pole pieces removed (remanence!), the control current is switched on (terminals A and C in Fig. 2) and the Hall voltage set to zero by the compensating potentiometer. The pole pieces are replaced and the Hall voltage is measured as a function of the magnetic induction for both field directions.

5. With the magnetic field constant, the sample temperature is slowly raised to the maximum temperature and the Hall voltage measured. The Hall probe of the Teslameter is removed from the heating zone during heating up.

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. 4 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.

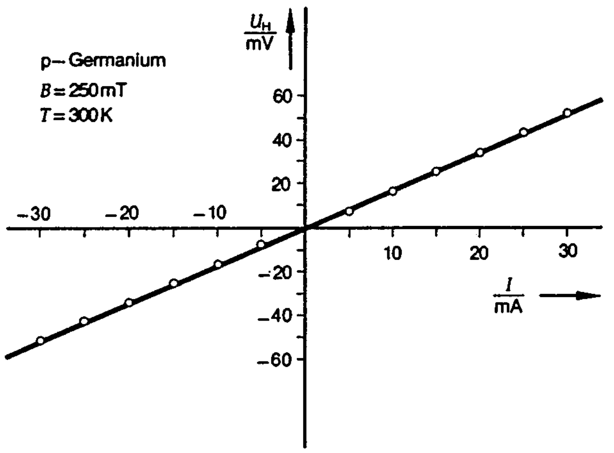


Fig. 4: Hall voltage as a function of current.

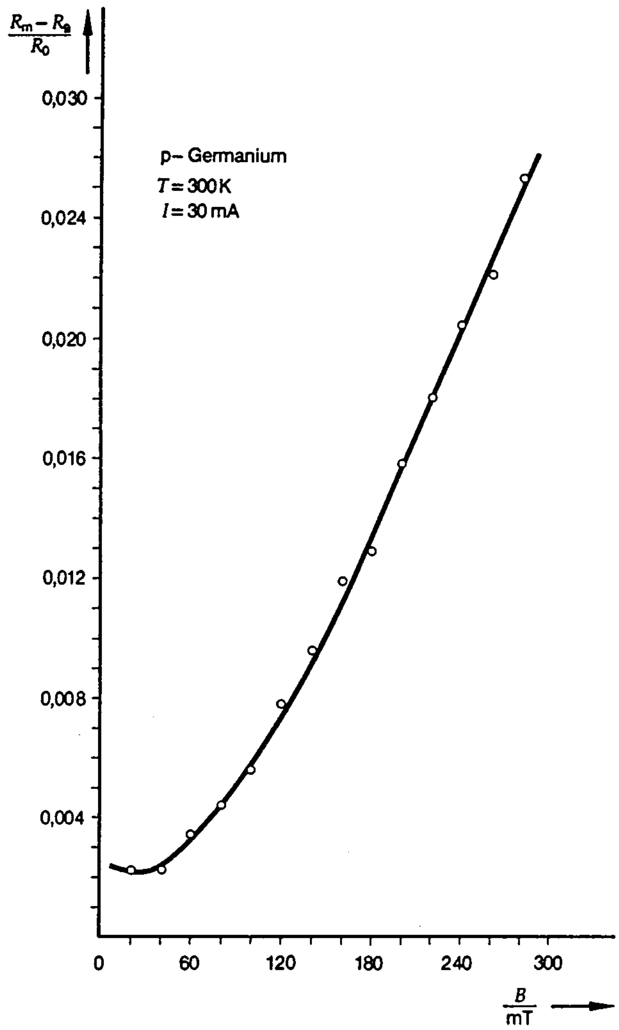


Fig. 5: Change of resistance as a function of magnetic induction.

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

3. In the region of intrinsic conductivity, we have

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

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

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

from which E_g can be determined.

From the measured values used in Fig. 6, the slope of the regression line

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

is

$$b = -\frac{E_g}{2k} = -3.62 \cdot 10^3 \text{ K}$$

with a standard deviation $s_b = \pm 0.09 \cdot 10^3$ K.

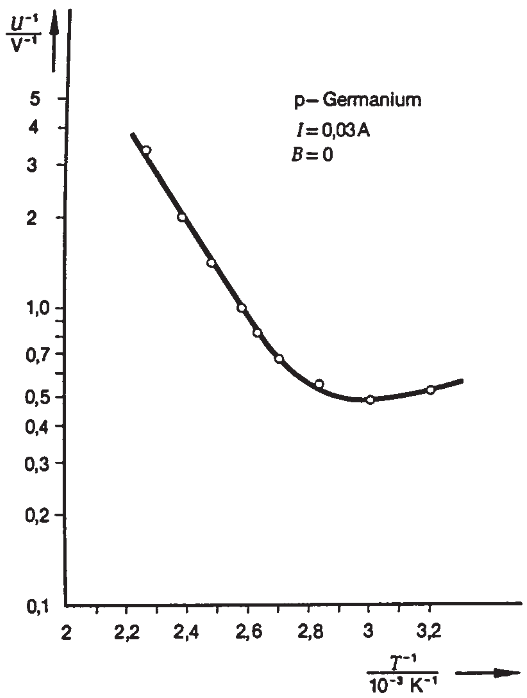
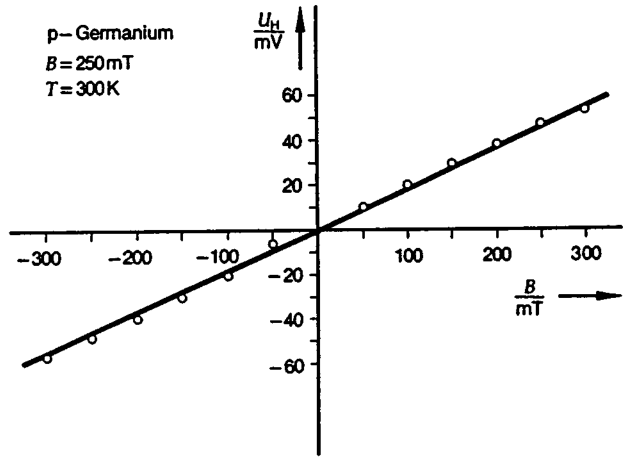


Fig. 6: Reciprocal sample voltage plotted as a function of reciprocal absolute temperature. (Since I was constant during the measurement, $U^{-1} \sim \sigma$ and the graph is therefore equivalent to a plot of conductivity against reciprocal temperature).

Fig. 7: Hall voltage as a function of magnetic induction.



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

$$\text{Since} \quad k = 8.625 \cdot 10^{-5} \frac{\text{eV}}{\text{K}}$$

we get

$$E_g = b \cdot 2k = (0.62 \pm 0.02) \text{ eV}.$$

4. With the directions of control current and magnetic field shown in Fig. 3, 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_H, and the charge-carrier concentration p are related through the Hall constant R_H:

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

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

Fig. 7 shows a linear connection between Hall voltage and B field. With the values used in Fig. 7, the regression line with the formula

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

has a slope b = 0.191 VT^{-1}, with a standard deviation $s_b \pm 0.002\ VT^{-1}$.

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,

$$R_H = 6.37 \cdot 10\text{–}3 \frac{\text{m}^3}{\text{As}}$$

with the standard deviation

$$s_{RH} = 0.07 \cdot 10{-}3 \ \frac{m^3}{As}.$$

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

$$l = 0.02 \text{ m}, R_0 = 45.0\ \Omega, A = 1.10^{-5} \text{m}$$

we have

$$\sigma_0 = 44.4\ \Omega^{-1}\ m^{-1}.$$

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

$$\mu_H = R_H \cdot \sigma_o$$

Using the measurements given above, we get:

$$\mu_H = (0.283 \pm 0.003)\ \frac{m^2}{Vs}.$$

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

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

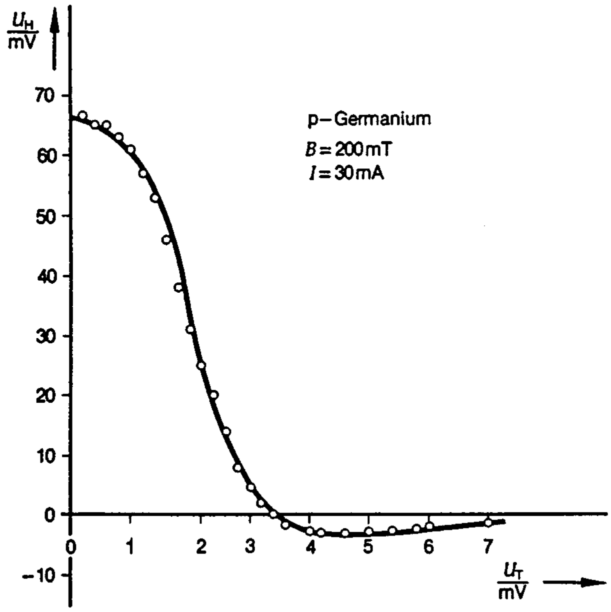
Using the value of the elementary charge

$$e = 1\ .602 \cdot 10^{-19} \text{ As}$$

we obtain

$$p = 9.7 \cdot 10^{-20}\ m^{-3}.$$

Fig. 8: Hall voltage as a function of temperature.



5. Fig. 8 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 instrinsic 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 $v = \mu \cdot E$) the greater mobility.

Fig. 8 shows accordingly the reversal of sign of the Hall voltage, typical of p-type materials, above a particular temperature.