Related topics

Semiconductor, band theory, forbidden zone, intrinsic conduction, extrinsic conduction, valency band, conduction band, Lorentz force, magneto resistance, Neyer-Neldel rule.

Principle

The resistance and Hall voltage are measured on a rectangular strip of germanium as a function of the temperature and of the magnetic field. From the results obtained the energy gap, specific conductivity, type of charge carrier and the carrier mobility are determined.

Equipment

1	Cobra4 Mobile-Link set, incl. rechargeable batteries, SD memory card, USB cable and software "measure"	12620-55
1	Cobra4 Sensor Tesla, magnetic field strength, resolution max. ±0.01 mT	12652-00
1	Hall effect module,	11801-00
1	Hall effect, n-Ge, carrier board	11802-01
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 PHYWE	02002-55
1	Support rod PHYWE, square, l = 250 mm	02025-55
1	Right angle clamp PHYWE	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	Digital multimeter 2010	07128-00

Fig. 1: Experimental setup.

Task

1. At constant room temperature and with a uniform magnetic field measure the Hall voltage as a function of the control current and plot the values on a graph (measurement without compensation for error voltage).

2. At room temperature and with a constant control current, measure the voltage across the specimen as a function of the magnetic flux density B.
3. Keeping the control current constant measure the voltage across the specimen as a function of temperature. From the readings taken, calculate the energy gap of germanium.

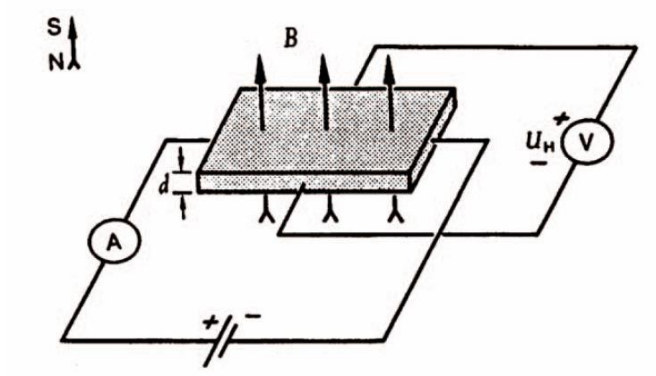


Fig. 2: Hall effect on a rectangular specimen. The polarity of the Hall voltage indicated is for negative charge carriers.

4. At room temperature measure the Hall Voltage U_H as a function of the magnetic flux density B. From the readings taken, determine the Hall coefficient R_H and the sign of the charge carriers. Also calculate the Hall mobility μ_H and the carrier density n.

5. Measure the Hall voltage U_H as a function of temperature at uniform magnetic flux density B, and plot the readings on a graph.

Setup and Procedure

The experimental setup 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 back-side 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 Cobra4 Sensor-Unit Tesla 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.

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.

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.

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 170°C.

   You will receive a typical curve as shown in Fig.5.

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.

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

When a current-carrying conductor in the form of a rectangular strip is placed in a magnetic field with the lines of force at right angles to the current, a transverse e. m. f. – the so called Hall voltage – is set up across the strip.

This phenomenon is due to the Lorentz force: the charge carriers which give rise to the current flow through the specimen are deflected in the magnetic field B as a function of their sign and of their velocity v:

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

Fig. 3: Hall voltage as a function of current

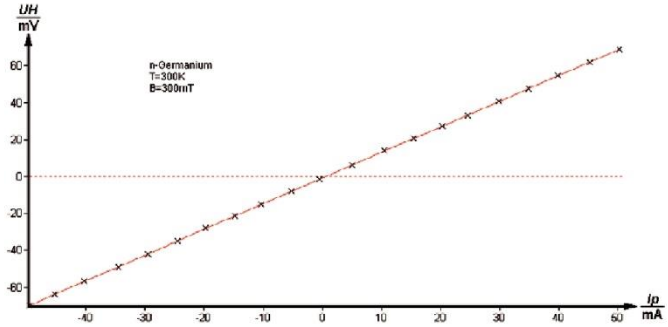


Fig. 4: Change of resistance as a function of the magnetic flux density.

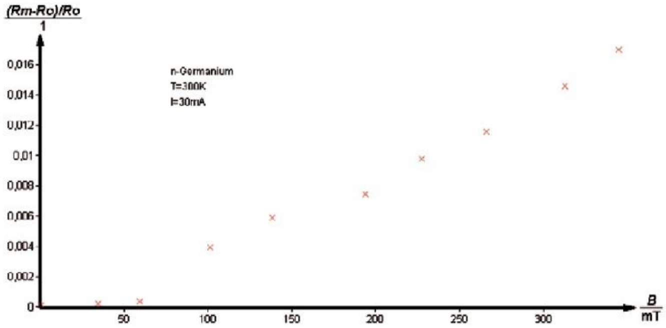


Fig. 5: The reciprocal specimen voltage as a function of the reciprocal absolute temperature (Since I was constant during the experiment, U–1 is approximately equal to s; the graph is therefore the same as a plot of the conductivity against the reciprocal temperature.)

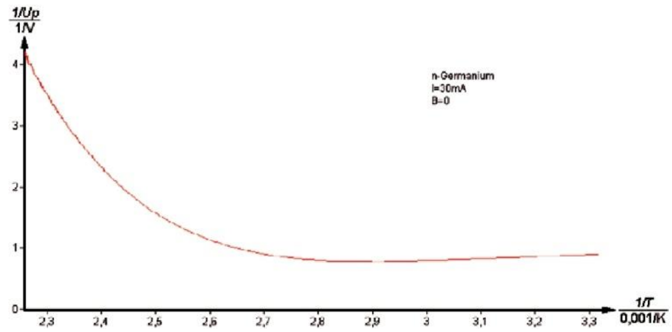
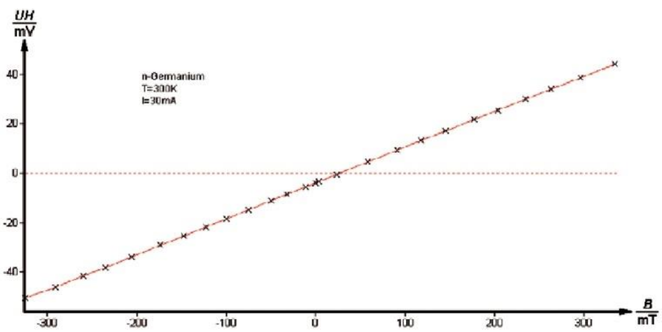


Fig. 6: Hall voltage as a function of the magnetic flux density.



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

Since negative and positive charge carriers have opposite directions of motion in the semiconductor, both are deflected in the same direction.

If the directions of the current and magnetic field are known, the polarity of the Hall voltage tells us whether the current is predominantly due to the drift of negative charges or to the drift of positive charges.

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

   $$U_H = \alpha \cdot I$$

   (α = proportionality factor.)

2. The change of resistance of the specimen in a magnetic field is connected with a decrease of the mean free path of the charge carriers. Fig. 4 shows a non-linear, obviously quadratic change of resistance with increasing field strength.

3. For intrinsic conduction, the relationship between the conductivity σ and the absolute temperature T is:

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

where E_g is the energy gap between the valency and conduction bands, and k is Boltzmann's constant.
A graph of $log_e\ \sigma$ against $1/T$ will be linear with a slope of

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

Hence E_g is obtained.
With the measured values in Fig. 5, the regression formulation

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

gives slope

$$b = -\frac{E_g}{2\,k} = -2.87 \cdot 10^3\,\mathrm{K}$$

with a standard deviation $s_b = \pm 0.3 \cdot 10^3$ K.
(Since the experiment was performed with a constant current, σ can be replaced by U^{-1} [U = voltage across the specimen]).

Taking

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

we obtain

$$E_g = b \cdot 2k = (0.50 \pm 0.04)\ \text{eV}.$$

4. With the directions of control current und magnetic field illustrated in Fig. 2, the charge carriers which produce the current are deflected to the front edge of the specimen. If, therefore, the current is due mainly to electrons (as in the case of an n-doped specimen), the front edge becomes negatively charged. In the case of hole conduction (p-doped specimen) it becomes positively charged.

The conductivity σ_0, carrier mobility μ_H, and the carrier density n are all connected by the Hall coefficient R_H:

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

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

Fig. 6 shows a linear relation between the Hall voltage and the magnetic flux density B. Using the values from Fig. 6, regression with the formulation

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

gives the slope b = 0.144 VT^{-1}, with the standard deviation s_b + 0.004 VT^{-1}.

The Hall coefficient R_H is then given by

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

Thus, if the thickness of specimen $d = 1 \cdot 10^{-3}$m and I = 0.030 A, then

$$R_H = 4.8 \cdot 10^{-3} \frac{\text{m}^3}{\text{As}}$$

with the standard deviation

$$s_{RH} = \pm 0.2 \cdot 10^{-3} \frac{\text{m}^3}{\text{As}} \ .$$

The conductivity at room temperature is calculated from the length l of the specimen, its cross-sectional area A and its resistance R_0 (cf. Experiment 2):

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

Thus if

$l = 0.02$ m, $R_0 = 37.3\ \Omega$, $A = 1 \cdot 10^{-5}\text{m}^2$, then

$$\sigma_0 = 53.6\ \Omega^{-1}\ \text{m}^{-1}.$$

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

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

Using the same values above, this gives

$$\mu_H = (0.257 \pm 0.005)\ \frac{m^2}{Vs}\ .$$

The electron concentration n of n-doped specimen is given by

$$n = \frac{1}{e \cdot R_H}\ .$$

Taking e = elementary charge = $1.602 \cdot 10^{-19}$ As, we obtain

$$n = 13.0 \cdot 10^{20}\ m^{-3}.$$

5. Fig. 7 shows that the Hall voltage decreases with increasing temperature. Since the experiment was performed with a constant current, it can be assumed that the increase of charge carriers (transition from extrinsic to intrinsic conduction) with the associated reduction of the drift velocity v is responsible for this.

   (The same current for a higher number of charge carriers means a lower drift velocity). The drift velocity is in turn related to the Hall voltage by the Lorentz force.

Note

For the sake of simplicity, only the magnitude of the Hall volt-age and Hall coefficient has been used here. These values are usually given a negative sign in the case of electron conduction.