

## Determining the band gap of germanium

### Objects of the experiments

- Determining the voltage drop at an undoped Ge crystal as a function of the temperature when the current through the crystal is constant, and calculating the conductivity  $\sigma$ .
- Determining the band gap  $E_g$  of germanium.

### Principles

For the current density  $j$  in a body under the influence of an electric field  $E$  the Ohm law states

$$j = \sigma \times E \quad (I).$$

The proportionality factor  $\sigma$  is called electric conductivity. Since this quantity strongly depends on the material, it is common to classify materials with regard to their conductivity. Semiconductors, for example, are solids that do not conduct electric currents at low temperatures, but show a measurable conductivity at higher temperatures. The reason for this temperature dependence is the specific band structure of the electronic energy levels of a semiconductor.

The valence band, i. e. the highest band that is completely or partially populated in the ground state, and the conduction band, i. e. the next unpopulated band, are separated by a band gap  $E_g$  (Ge:  $E_g \approx 0,7$  eV). The region between the two bands is not populated by electrons in an undoped, pure semicon-

ductor and is called the “forbidden zone“. At higher temperatures, more and more electrons are thermally activated from the valence band into the conduction band. They leave “holes” in the valence band which move like positive charged particles, thus contributing to the current density  $j$  as do the electrons (see Fig. 1).

The conduction which is made possible by the excitation of electrons from the valence band into the conduction band is called intrinsic conduction. Since under conditions of thermal equilibrium the numbers of holes in the valence band and of electrons in the conduction band are equal, the current density in the case of intrinsic conduction can be written in the form

$$j_i = (-e) \times n_i \times v_n + e \times n_i \times v_p \quad (II)$$

$e$ : elementary charge,

$n_i$ : concentration of electrons or holes respectively.

The average drift velocities  $v_n$  and  $v_p$  of the electrons and the holes are proportional to the field strength  $E$ . With

$$v_n = -\mu_n \times E \text{ and } v_p = \mu_p \times E \quad (III),$$

where the mobilities  $\mu_n$  and  $\mu_p$  are chosen to be positive quantities,

$$j_i = e \times n_i \times (\mu_n + \mu_p) \times E \quad (IV)$$

is obtained. Comparison with (I) leads to

$$\sigma_i = e \times n_i \times (\mu_n + \mu_p) \quad (V)$$

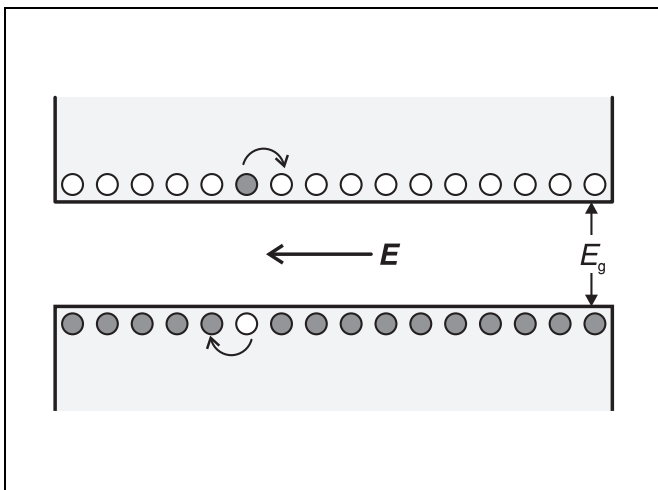
for the conductivity. Apart from the elementary charge  $e$ , all quantities in (V) depend on the temperature  $T$ . The concentration of intrinsic conduction  $n_i$  is

$$n_i \times = (N \times P)^{\frac{1}{2}} \times e^{-\frac{E_g}{2 \times kT}} \quad (VI),$$

$k$ : Boltzmann constant,

$E_g$ : band gap of the semiconductor.

Fig. 1 Simplified diagram of intrinsic conduction: a semiconductor with an electron in the conduction band and a hole in the valence band under the influence of an electric field  $E$ .



**Apparatus**

1 Ge undoped on plug-in board . . . . .	586 851
1 base unit for Hall effect . . . . .	586 850
1 sensor CASSY . . . . .	524010
1 CASSY Lab . . . . .	524 200
1 current-controlled power supply, 15 V <sub>r</sub> , 3 A, for example . . . . .	521 50
1 power supply, 12 V <sub>r</sub> , 50 mA for example	521 54
1 stand base, V-shape, 20 cm . . . . .	300 02
connection leads	

**Setup**

The experimental setup is illustrated in Fig. 2.

**Mounting and connecting the plug-in board:**

Notes:

*The Ge crystal is extremely fragile:*

*Handle the plug-in board carefully and do not subject it to mechanical shocks or loads.*

*Due to its high specific resistance, the Ge crystal warms up even if only the cross-current is applied:*

*Do not exceed the maximum cross-current  $I = 4$  mA.*

*Turn the control knob for the cross-current on the base unit for Hall effect to the left stop.*

- Insert the plug-in board with the Ge crystal into the DIN socket on the base unit for Hall effect until the pins engage in the holes.
- Turn the current limiter of the current-controlled power supply to the left stop, and connect the power supply to the input for the heating and electronics of the base unit for Hall effect.
- Switch the current-controlled power supply on, set the voltage limiter to 15 V and the current limiter to 3 A (for this, short-circuit the output of the power supply temporarily).
- Turn the control knob for the cross-current on the base unit for Hall effect to the left stop, and supply the current source by connecting the other power supply. Switch this power supply on and set its output voltage to 12 V.

$$N = 2 \times \left( \frac{2\pi \times m_n \times kT}{h^2} \right)^{\frac{3}{2}} \text{ and } P = 2 \times \left( \frac{2\pi \times m_p \times kT}{h^2} \right)^{\frac{3}{2}} \quad \text{(VII),}$$

$h$ : Planck constant,  
 $m_n$ : effective electron mass,  
 $m_p$ : effective hole mass,

are the effective state densities in the conduction band and in the valence band. The mobilities  $\mu_n$  and  $\mu_p$  also depend on the temperature. At low temperatures, the proportionality  $\mu \propto T^{-\frac{3}{2}}$  holds roughly, as does the proportionality  $\mu \propto T^{-\frac{3}{2}}$  at high temperatures.

Because of the predominance of the exponential function (see Eq. (VI)), conductivity is well approximated and represented by

$$\sigma_i = \sigma_0 \times e^{-\frac{E_g}{2 \times kT}} \times \quad \text{(VIII)}$$

or

$$\ln \sigma_i = \ln \sigma_0 - \frac{E_g}{2 \times kT} \quad \text{(IX)}$$

With the object of confirming Eq. (VIII) and determining the band gap  $E_g$ , the conductivity of undoped germanium is determined as a function of the temperature  $T$  in the experiment. At a constant current

$$I = j \times b \times c \quad \text{(X),}$$

$b$ : breadth of the crystal,  $c$ : thickness of the crystal,

the voltage drop

$$U = E \times a \quad \text{(XI),}$$

$a$ : length of the crystal,

is measured at an undoped Ge crystal.

Because of (I), (X), and (XI) the conductivity

$$\sigma = \frac{a}{b \times c} \times \frac{I}{U} \quad \text{(XII)}$$

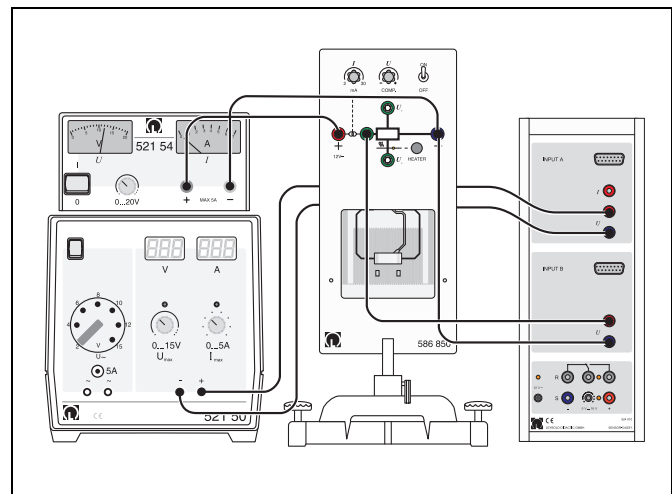





Fig. 2 Experimental setup for the determination of the band gap of germanium

**Preparation for data logging:**

- Connect the output for the temperature measurement to input A and the output for the voltage drop to input B of sensor CASSY.
- Connect sensor CASSY to the serial interface of the PC (usually COM1 or COM2) with the nine-pole V24 cable.
- If necessary, install the "CASSY Lab" program under Windows 95/98/NT and choose the desired language.
- Get the "CASSY Lab" program started and check whether connection of the CASSY sensor is correct.

- Erase existing data from previous measurements with the button  or the key F4.
- Open the pop-up window "Settings" with the button  or the key F5, and click "Update Setup".
- Click channel A and measurand "UA1", zero "Left", and choose the measuring range "0 ... 3 V". Perform the same settings for channel B.
- In the register "Display" set:  
x-axis UA1 x  
y-axis UB1 y
- Click "Display Measuring Parameters" and choose the measuring parameters "Automatic Recording" and "Meas. Interv.: 2s".

**Carrying out the experiment**

Press the key HEATER on the base unit for Hall effect, and start recording of the measuring values with the key F9 or the button .

- In the window "Voltage UA1" check if the voltage UA1, which is proportional to the temperature of the crystal, increases.


As soon as the voltage UB1 has fallen below 1 V:

- Click the window "Voltage UB1" with the right mouse button, and change the measuring range to "0 ... 1 V".

As soon as the voltage UB1 has fallen below 0.3 V:

- change to the measuring range "0 V.. 0.3 V".

When the LED on the base unit for Hall effect goes out:

- Stop the record of the measuring values with the key F9 or the button .

For the further evaluation:

- Define the following as new quantities in the register "Parameter/Formula/FFT":

Quantity	Temperature	Conductivity
Formula	UA1*100+273,15	4/UB1
Symbol	T	&s
Unit	K	1/Wm
from	290	0
to	440	200
Decimals	1	2

- In the register "Display" choose as new representation:

x-axis T 1/x  
y-axis  $\sigma$  log y

- After clicking the graphics window with the right mouse button, activate the item "Fit function" → "Best-fit straight line", and mark the desired range of adjustment with the left mouse button.

**Measuring example**

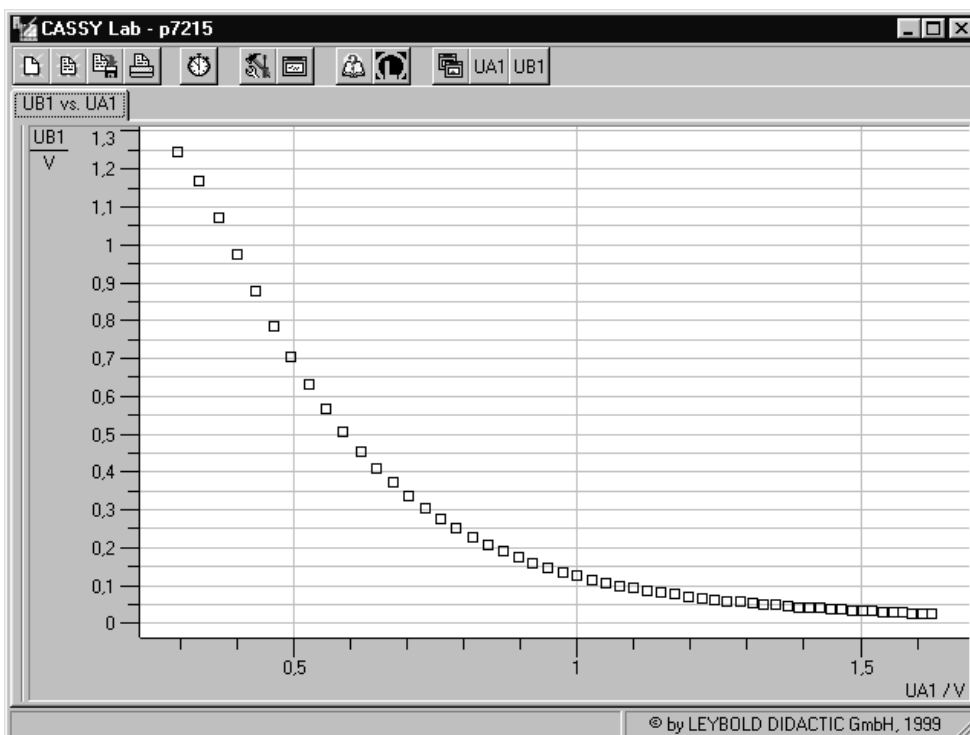


Fig. 3 Graph of the measuring values in the form  $UB1 = f(UA1)$   
UA1: voltage at the output for temperature measurement  
UB1: voltage drop at the Ge crystal at a cross-current of 2 mA

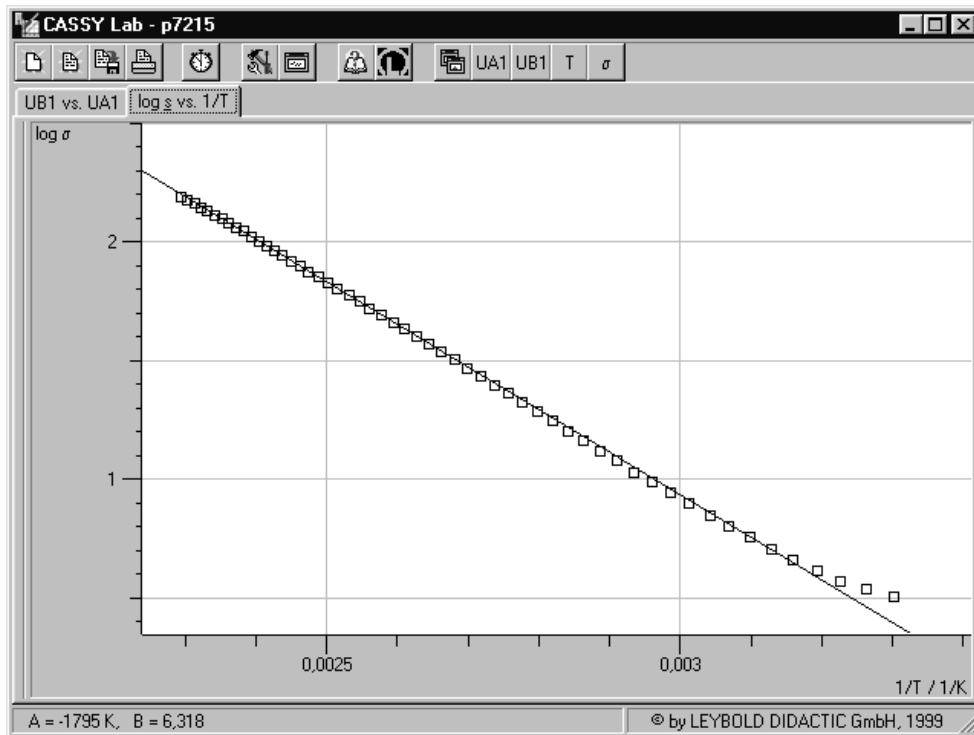


Fig. 4 Graph of the measuring values in the form  $\log \sigma = f\left(\frac{1}{T}\right)$

$$\sigma = \frac{2mA}{UB1} \times \frac{20\text{mm}}{10\text{mm} \times 1\text{mm}} \quad (\text{conductivity, cf. (XII)})$$

$$T = 100\text{K} \times \frac{UA1}{V} + 273.15 \text{ K} \quad (\text{temperature})$$

### Evaluation and results

In the graph  $\log \sigma = f\left(\frac{1}{T}\right)$ , the data points are well approximated on a straight line with the slope  $A = -1795 \text{ K}$  (see Fig. 4).

According to (IX), the slope of the straight line is

$$A = -\frac{1}{\ln 10} \times \frac{E_g}{2 \times k} \quad (\text{XIII}),$$

with  $k = 1.3807 \times 10^{-23} \text{ J K}^{-1}$ .

From this the band gap

$$E_g = 1.149 \times 10^{-19} \text{ J} = 0,71 \text{ eV}$$

is obtained.

### Values quoted in the literature:

$$E_g(0 \text{ K}) = 0.74 \text{ eV}, \quad E_g(300 \text{ K}) = 0.67 \text{ eV}$$

### Supplementary information

The temperature measurement is distorted by hysteresis in the lower temperature range. Therefore, the corresponding data points in Fig. 4 are systematically higher than the straight line drawn in the graph.