ELECTRICAL CONDUCTION IN SEMICONDUCTORS

OBJECTIVE

Determine band separation in germanium

SUMMARY

Semiconductors only exhibit measurable electrical conductivity at high temperatures. The reason for this dependence on temperature is the band structure of the electron energy levels, which comprise a conduction band, a valence band and an intermediate zone, which in pure, undoped semiconductor materials cannot be occupied by electrons at all. As the temperature increases, more and more electrons are thermally excited from the valence band into the conduction band, leaving behind "holes" in the valence itself. These holes move under the influence of an electric field as if they were positive particles and contribute to the current much as electrons do. In order to determine the conductivity of pure, undoped germanium, this experiment involves sending a constant current through the crystal and measuring the voltage drop as a function of temperature. The data measured can be described by an exponential function to a good approximation, whereby the separation of bands appears as a key parameter.

EXPERIMENT PROCEDURE

- **Measure the electrical conductivity of undoped germanium as a function of temperature.**
- **Determine the band separation between the valence band and conduction band.**

NOTE

In practice, the intrinsic conductivity of pure, undoped semiconductors is of minor importance. As a rule, the crystals have imperfections which adversely affect the flow of current. Often, highly pure crystals are specifically targeted by addition of donor or acceptor atoms to make them more conductive.

The effect of such doping becomes apparent when the investigations described here are carried out to include comparison of n and p-doped germanium. The conductivity of the doped crystals at room temperature is much higher than that of pure crystals, although at high temperatures, it approaches the intrinsic conductivity, see Fig. 4.

The way that Hall coefficients depend on temperature is investigated in greater detail in Experiment UE6020200.

REQUIRED APPARATUS

Quantity	Description	Number
1	Undoped Germanium on Printed Circuit Board	**1008522**
1	Hall Effect Basic Apparatus	**1009934**
1	Barrel Foot, 1000 g	**1002834**
1	Transformer with Rectifier 3/ 6/ 9/ 12 V, 3 A (230 V, 50/60 Hz)	**1003316 or**
	Transformer with Rectifier 3/ 6/ 9/ 12 V, 3 A (115 V, 50/60 Hz)	**1003315**
1	Digital Multimeter P3340	**1002785**
1	Pair of Safety Experiment Leads, 75 cm	**1002849**
1	Pair of Safety Experimental Leads, 75cm, red/blue	**1017718**
Additionally recommended:		
1	P-Doped Germanium on Printed Circuit Board	**1009810**
1	N-Doped Germanium on Printed Circuit Board	**1009760**
1	3B NET*log*™ (230 V, 50/60 Hz)	**1000540 or**
	3B NET*log*™ (115 V, 50/60 Hz)	**1000539**
1	3B NET*lab*™	**1000544**

BASIC PRINCIPLES

Electrical conductivity is highly dependent on the nature of the material. It is therefore common to classify materials according to their conductivity. Solid bodies for which conductivity only becomes measurable at relatively high temperatures are classified as semiconductors. The reason for this dependence on temperature is the band structure of the electron energy levels, which comprise a conduction band, a valence band and an intermediate zone, which in pure, undoped semiconductor materials cannot be occupied by electrons at all.

In the ground state, the valence band is the highest band occupied by electrons and the conduction band is the next band up, which is unoccupied. The separation between these bands is labelled E_g and depends on the material itself. For germanium this quantity is approximately 0.7 eV. As the temperature increases, more and more electrons are thermally excited from the valence band into the conduction band, leaving behind "holes" in the valence itself. These holes move under the influence of an electric field E as if they were positive particles and contribute to the current much as electrons do (see Fig.1).

(1) $$j = \sigma \cdot E$$

σ: Electrical conductivity of semiconductor material

Electrons and holes move with differing average drift velocities:

(2) $$v_n = -\mu_n \cdot E \quad \text{and} \quad v_p = \mu_p \cdot E$$

μ_n: Mobility of electrons
μ_p: Mobility of holes

This ability to conduct which results from electrons being thermally excited from the valence band into the conduction band is called intrinsic conduction.

In a state of thermal equilibrium, the number of electrons in the conduction band is equal to the number of holes in the valence band, so that the current density in the case of intrinsic conduction can be written out as follows:

(3) $$j_i = -e \cdot n_i \cdot v_n + e \cdot n_i \cdot v_p = e \cdot n_i \cdot (\mu_n + \mu_p) \cdot E\ ;$$

i.e. the intrinsic conductivity σ is

(4) $$\sigma_i = e \cdot n_i \cdot (\mu_n + \mu_p)\ ,$$

The temperature dependence of the current carrier density n_i for electrons or holes is given by the following:

(5) $$n_i = 2 \cdot \left(\frac{2\pi}{h^2} \cdot \sqrt{m_n m_p} \cdot kT \right)^{\frac{3}{2}} \cdot \exp\left(-\frac{E_g}{2kT} \right)$$

$k = 8{,}617 \cdot 10^{-5} \frac{\text{eV}}{\text{K}}$: Boltzmann constantv
h: Planck's constant
m_n: Effective mass of electrons
m_p: Effective mass of holes
T: Sample temperature

The mobilities μ_n and μ_p also depend on temperature. In the temperature range above room temperature, the following applies:

(6) $$\mu \sim T^{-\frac{3}{2}}$$

The dominant term with regard to temperature dependence, however, is the exponential expression. This means that the intrinsic conductivity at high temperature can be expressed in the following form:

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

In this experiment to determine the conductivity of pure, undoped germanium, a constant current I is sent through the crystal and the voltage drop U is measured as a function of temperature. The conductivity σ can be calculated from the measured data thanks to the relationship

(8) $$U = a \cdot E \ \text{resp.}\ I = b \cdot c \cdot j$$

a, b, c: dimensions of crystal

(9) $$\sigma = \frac{I}{U} \cdot \frac{a}{b \cdot c}$$

EVALUATION

Equation (7) can be rewritten in the following form:

$$\ln \sigma = \ln \sigma_0 - E_g \cdot \frac{1}{2kT}$$

Therefore $y = \ln\sigma$ is plotted against $x = \frac{1}{kT}$ and the band separation E_g can be found from the gradient of the resulting straight line.

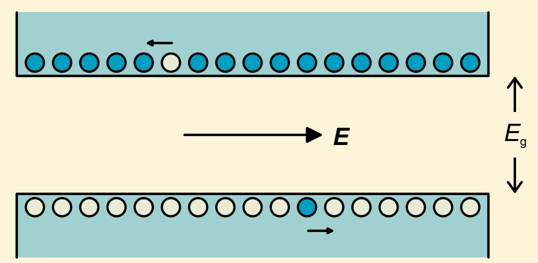

Fig. 1: Structure of semiconductor bands with one electron in the conduction band and a hole in the valence band, both of which drift due to the influence of an electric field E

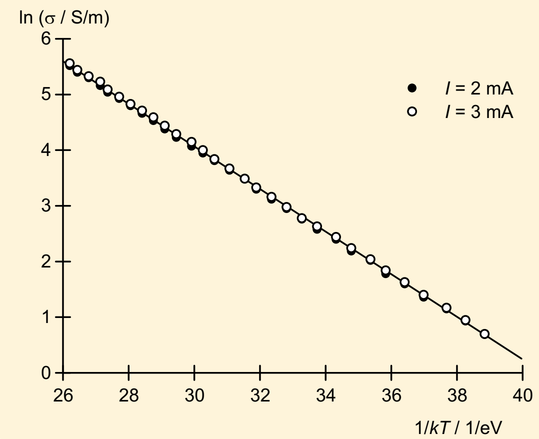

Fig. 2: Representation for the determination of band separation E_g in germanium

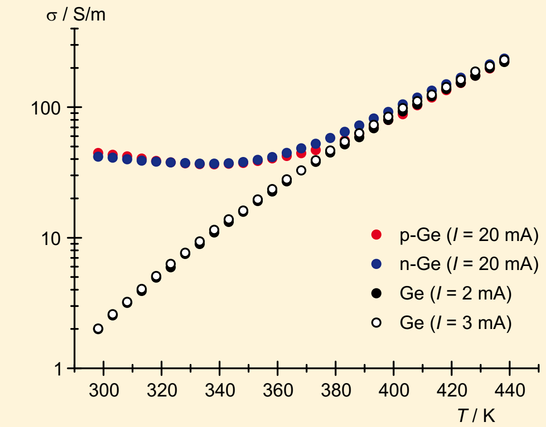

Fig. 4: Comparison between conductivities of pure and doped germanium