First name .... Date ....

Last name .... Degree program name ....

Exercise 243

4.2. Studies on the temperature dependence of electric resistance for a metal and a semiconductor

Table I. Metal

Name of the experimental sample: Cu…….

t	[°C]				
R	[Ω]				
Temperature coefficient of resistance α [1/°C]					

Table II. Semiconductor

Name of the experimental sample: Th…….

t	[°C]					Activation energy	
T	[K]					E	
$1/T$	[K^{-1}]					[J]	[eV]
R	[Ω]						
$\ln R$							

Exercise 243. Studies on the temperature dependence of electric resistance for a metal and a semiconductor

The conductivity of metals and semiconductors

The quantity characterizing the ability of a substance to conduct a current is its *electrical resistivity* ρ (also called specific electrical resistance or volume resistivity), equal to the electric resistance of a conductive material 1 m long and a constant cross-sectional area of 1 m^2. The unit of ρ is the 1 Ω·m. On the basis of electrical resistance, all the substances can be divided into:

- conductors $\rho \langle 10^{-6}\,\Omega\cdot\mathrm{m}$,
- semiconductors $10^{-6}\,\Omega\cdot\mathrm{m} \langle \rho \langle 10^{8}\,\Omega\cdot\mathrm{m}$,
- insulators $10^{8}\Omega\cdot\mathrm{m}\ \langle \rho$.

Sometimes it is more convenient to use the inverse of the specific resistance, which is also known as the *electrical (specific) conductivity* σ.

$$\sigma = 1/\rho . \tag{1}$$

Based on a simple microscopic model of the current flow in a conductor, the following formula for specific electrical conductivity can be derived:

$$\sigma = q \cdot n \cdot \mu , \tag{2}$$

where q is the charge of the current carrier, n —carrier *concentration*, a μ —mobility of carriers (*carrier mobility*).

Equation (2) shows that the specific conductivity of a given substance is determined by the concentration of current carriers and their mobility. According to the dependence of these two quantities on external factors, the ability of a given material to conduct electricity changes.

In order to understand the very large differences in the values of the resistivity of different bodies, it is necessary to know the microscopic structure of an electrically conductive substance.

Conductors

The conductors are physical bodies in which there are so-called free charges that can move inside these bodies. Metals are typical representatives of conductors, whose atoms have one or two electrons in their outermost shells are called *valence shells*. Valence electrons are freed from their atoms when such atoms assemble into larger groups and do not occupy specific places in the crystal lattice, but can move freely between ionized metal atoms. Therefore, we call them free electrons or *conduction electrons*.

The conductivity of metals is described by the formula (2), in which q is replaced by the charge of an electron e:

$$\sigma = en\mu .$$

The concentration n of free electrons in the metal is high and does not depend on external conditions, including temperature. On the other hand, the mobility of carriers decreases with increasing temperature, because they are more efficiently dispersed as a result of an increase in the amplitude of vibrations of atoms in the crystal lattice. Thus, we observe a decrease in the conductivity of a metal (i.e. an increase in its resistance) with increasing temperature.

Semiconductors

Typical representatives of semiconductors are germanium (Ge) and silicon (Si). These elements belong to the Group IV of the periodic table, they have four valence electrons and each of these electrons forms a bond with one of the four nearest neighboring atoms. At low temperatures, the valence electrons in semiconductors are not free electrons and cannot move in the crystal - the semiconductor is an insulator. Typical representatives of semiconductors are germanium (Ge) and silicon

(Si). These elements belong to the IV group of the periodic table, they have four valence electrons and each of these electrons forms a bond with one of the four nearest neighboring atoms. At low temperatures, the valence electrons in semiconductors are not free electrons and cannot move in the crystal - the semiconductor is an insulator. It is possible to remove the valence electron from the atom, but it requires the supply of an appropriate amount of energy, not less than a minimum value called *activation energy*. The free electrons can transmit an electric current. One way to transfer energy to the electrons is to increase the thermal energy by increasing the temperature of the crystal. Activation energy value E is expressed in *electronvolts*: 1 eV = $1{,}6{\cdot}10^{-19}$ J; (1 eV is the measure of an amount of kinetic energy gained by a single electron accelerating from rest through an electric potential difference of one volt in vacuum. It is the amount of energy acquired or lost by an electron as it traverses through a potential difference of 1Volt).

To conduct electricity in a semiconductor not only free electrons are involved. As a result of the detachment of the electron from the atom, a free space is created, the so-called a hole that can be easily filled by an electron from a neighboring bond. As a result, the holes move in the opposite direction to the electrons, so they behave like free positive charges. If we are dealing with a pure semiconductor without internal defects, the concentration of holes and free electrons is the same and the conductivity, in this case, is called an *intrinsic conduction.* The concentration of intrinsic carriers in the semiconductor is low and it changes significantly with the change of external conditions, such as temperature or lighting. The concentration of intrinsic carriers in the semiconductor is low and it changes significantly with the change of external conditions, such as temperature or lighting. The number of holes or electrons in semiconductors can be easily increased not only by changing the external conditions but also by appropriately doping the crystal. If we introduce a small amount of a five-valent element (for example, phosphorus and antimony) into a four-valued semiconductor, we increase the number of free electrons. Such a semiconductor is an *n-type semiconductor*, and the ionized doping atoms providing one electron are called *donors*. The presence of trivalent atoms (such as boron and aluminum) in germanium or silicon increases the number of holes because such atoms have three valence electrons which will only bond with the three electrons of germanium or silicon atom. The fourth bond will remain incomplete - it creates a hole that can be easily filled by an electron from a neighboring Ge or Si atom. Such a semiconductor is a p-type semiconductor, and the dopant atoms increasing the number of holes are called *acceptors*.

▲

Additional information: Electronic band structure

In a solid, the energy levels of the electrons are split up, creating bands of allowed energies separated by forbidden bands. Electrons can only have energies within the permitted bands. The valence levels form a *valence band* or *base-band*, and a conduction band is formed above this band. These bands are separated by a band gap, called the energy gap E_g. The conductivity of the electric current is related to the presence of electrons in the conduction band. If in a given material the band is empty and the valence band is full, then such material is an insulator (Fig. 1a). Good conductors, which are metals, are characterized by the fact that the valence and conductivity bands touch each other or even overlap (Fig. 1b).

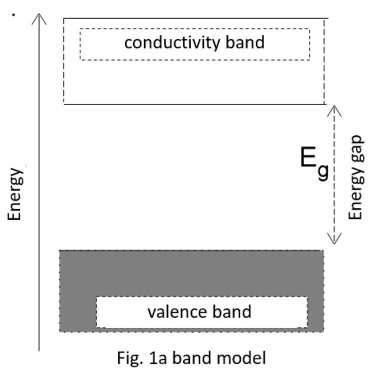

Fig. 1a band model of the insulator

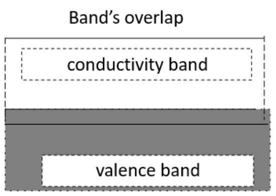

Fig. 1b band model of the metal

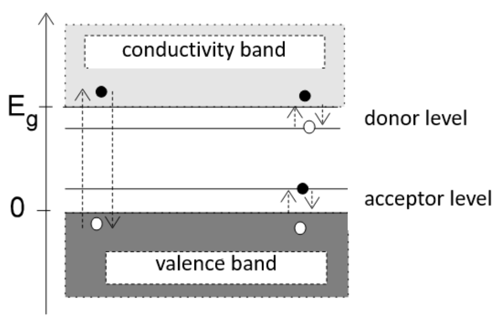

Fig. 2 band model of the insulator

If the distance between the baseband and the conduction band is not too great, some of the electrons will be able to move from the baseband to the conduction band when increasing the temperature, where they can move freely. Therefore, crystals with a relatively narrow forbidden band already at room temperature show the phenomenon of electric current conduction. Such materials, with properties intermediate between those of metals and insulators, are called *semiconductors*. The energy that an electron needs to jump from the baseband to the conduction band is called the *activation energy of the intrinsic conduction.* Semiconductor doping is related to the introduction of donor levels (close to the conductivity band) or acceptor levels (close to the valence band) in the band gap, which significantly reduces the energy necessary to generate free electrons or holes.

The energy gap for germanium is 0,68 eV, and for silicon, 1,10 eV. According to these values, only germanium has intrinsic conductivity at room temperature, while silicon has only doped conductivity at this temperature.

▼

The specific conductivity of a semiconductor, in which the concentration of free electrons and holes is ρ_e and ρ_p , respectively, is given by the formula:

$$\sigma = e\rho_e\mu_e + e\rho_p\mu_p ,$$

μ_e, μ_p is the mobility of electrons and holes. With increasing temperature, the specific conductivity increases as the concentration of carriers in the semiconductor increase significantly. The slight reduction in mobility μ of the free carriers that occurs is of secondary importance. As a result, the resistance of the semiconductor clearly decreases with increasing temperature.

The dependence of the electrical resistance of a metal and a semiconductor on temperature

Metal

In a not very large temperature range (up to 100°C), the resistance of metals increases linearly with the temperature increase (Fig. 3). This can be expressed in a formula

$$R = R_0\left(1+\alpha t\right), \tag{3}$$

where: R_0 — resistance of a given conductor at 0°C ; R — resistance at temperature t, [°C]; α — temperature coefficient of resistance (TCR)

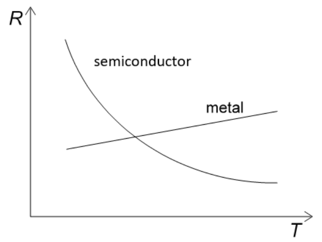

Fig. 3 The dependence of the electrical resistance of a metal and a semiconductor on temperature

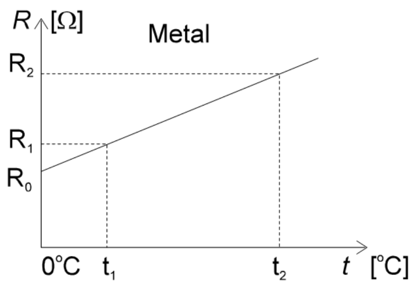

Fig. 4 determination of the alpha coefficient

To determine the average value α in a given temperature range, it is necessary to plot a graph showing the temperature dependence of resistivity. We adjust the **straight line** to the experimental results obtained, as in Fig. 4. **From the plot of the straight line**, we read two resistance values, R_1 and R_2, for two different temperatures t_1 and t_2. We can then calculate α from equation (3) without knowing R_0. From the equations for the two resistances:

$$R_1 = R_0\left(1+\alpha t_1\right), \quad R_2 = R_0\left(1+\alpha t_2\right),$$

calculate

$$\alpha = \frac{R_2 - R_1}{R_1 t_2 - R_2 t_1}. \tag{4}$$

The two resistance values in equation (4) are read from the plot at two different temperatures.

Semiconductor

In semiconductor resistors (*thermistors)* their conductivity is very strongly dependent on temperature, because the number of current carriers increases exponentially with increasing temperature. According to equation (1), an increase in conductivity means a decrease in specific resistance.

The dependence of the semiconductor resistance on temperature (Fig. 3) can be presented as follows:

$$R = A\exp\left(\frac{E}{2kT}\right), \qquad (5)$$

where A is a constant quantity (with a good approximation), E – activation energy T – temperature in Kelvin, k – Boltzmann's constant. In an intrinsic semiconductor, the activation energy E is equal to the width of the band gap. In doped semiconductors, E determines the absolute value of the energy distance of the donor level from the conductivity band or the acceptor level from the valence band. Taking the logarithm of the equation (10), we get:

$$\ln R = \ln A + \frac{E}{2k}\cdot\frac{1}{T}. \qquad (6)$$

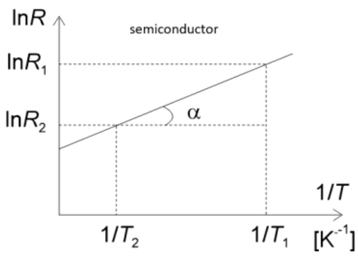

Fig. 5 determination of activation energy

The dependency graph plot $\ln R$ from T^{-1} it should represent a straight line inclined at an angle α determined by the coefficient $E/2k$, from which the activation energy can be determined.

In order to calculate E, we fit the **straight line** to the experimental results obtained for the semiconductor, as in Fig. 5. For two different values of $1/T_1$ and $1/T_2$ we read the values of $\ln R_1$ and $1/T_2$ respectively from the graph of the **straight line**, using formula (6) calculate the slope of the straight line. For two different values of A and A, we read the values respectively from the plot of the straight line

$$\operatorname{tg}\alpha = \frac{\ln R_1 - \ln R_2}{T_1^{-1} - T_2^{-1}} = \frac{E}{2k}.$$

Thus, the activation energy of the tested semiconductor is

$$E = \frac{2k(\ln R_1 - \ln R_2)}{T_1^{-1} - T_2^{-1}}. \qquad (7)$$

where k = 1,38·10^{-23} J/K = 8,613·10^{-5} eV/K .

Performance of the task

Measuring system

W – measuring cavity
P –temperature control knob
T –a hole for a thermometer
K –switching off (0),
switching on (1)
O – ohmmeter

Study the temperature dependence of resistance for a metal wire and a semiconductor. During the measurements, place the tested resistances in the cavity (W) in the thermostat. The temperature in the thermostat is changed with the knob (P) on the surface of the thermostat, which allows you to set it in four positions: (1) - thermostat off (room temperature), (2,3,4) successively higher and higher temperatures. The exact temperature of the tested conductors is read on a measuring thermometer inserted into the hole (T) in the thermostat. The resistance of the tested conductor is measured with an ohmmeter (O).

Measurement instruction

Metal

1. Write the name of the tested metal sample in the table. We put the sample into the cavity (W) of the thermostat and the thermometer into the adjacent hole (T).
2. Set the thermostat temperature control knob (P) to position 1. Turn on the thermostat with the button (K) on the front of the housing in position 1. Read and write temperature and resistance values in a table.
3. Set the temperature control knob to position 2. Wait 10 minutes for the temperature of the sample to stabilize. Read and write temperature and resistance values in a table.
4. Repeat the activities in point 3 for higher temperatures, with the knob in pos. 3 then 4.
5. Take a metal sample out of the thermostat, and leave the knob in pos. 4.

Semiconductor

6. Write the name of the tested semiconductor sample in the table. We connect an ohmmeter to the sample. We put the sample in the thermostat cavity and the thermometer in the adjacent hole.
7. The temperature control knob should be in position 4. We wait 15 minutes for the temperature to stabilize. Read and write the temperature and resistance values in the table.
8. Czynności w punkcie 7 powtarzamy dla niższych temperatur, z pokrętłem ustawionym w poz. 3 a następnie 2 i 1. Za każdym razem czekamy 10 minut do ustabilizowania się temperatury próbki.

<u>After completing the measurements, turn off the thermostat with the button (K) on the front of the housing in position 0</u>.

Calculation of the uncertainties

Based on the measurement data, we make charts on graph paper.

Metal:. the graph as described in Fig. 4. Calculate the α coefficient according to formula (4). In order to select the error rectangles in the graphs we will assume: Δt lub ΔT — temperature reading error ([°C] or [K]) equal 0.5°C; ΔR — measurement error with a digital ohmmeter, equal to 2% of the measured value. Error $\Delta\alpha$ results from the inaccuracy of determining the slope of the line on the graph. Figure 7 shows the method of estimating the change in the slope of the line due to measurement errors. Using this method, we obtain the following formula for estimating the error:

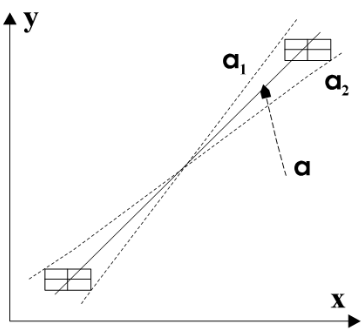

Fig. 7 line slope error

$$\frac{\Delta\alpha}{\alpha} \approx \left(\frac{\Delta R}{R_{max}}\right)\frac{2R_{max}}{R_{max} - R_{min}} \quad ,$$

where ‘min’ i ‘max’ are the minimum and maximum **measured** values, respectively, $(\Delta R/R_{max})$=0,02 for digital meter.

Semiconductor: graph as described in Fig. 5. We calculate the error values as follows:

$\Delta(\ln R)=\Delta R/R$ oraz $\Delta(1/T)=\Delta T/T^2$. We calculate the activation energy E according to formula (7). The method of estimating the inaccuracy of the slope of the straight line allows us to obtain the following formula for the relative error E:

$$\frac{\Delta E}{E} \approx \left(\frac{\Delta R}{R_{max}}\right)\frac{2}{\ln(R_{max}) - \ln(R_{min})} + \frac{2\Delta T}{T_{max} - T_{min}}$$

Based on the equations $\Delta\alpha=(\Delta\alpha/\alpha)\cdot\alpha$ and $\Delta E=(\Delta E/E)\cdot E$, also calculate the absolute errors $\Delta\alpha$ and ΔE.