STUDY OF PHENOMENA RELATED WITH HEAT CONDUCTION AND ELECTRICITY FLOW

1. MARKINGS

c_w - specific heat of water;
E - energy;
ΔE - width of the energy gap;
ε - contact voltage at the junction of two conductors;
e - thermoelectric voltage;
F - cross-sectional area;
I - current;
k - number of thermocouple branches;
k_B - Boltzmann constant;
l - height of the semiconductor prism;
n - electron concentration;
$\dot{m}$ - mass water flow rate;
P - power;
p - concentration of holes;
$\dot{Q}$ - heat flux;
R - electrical resistance;
T - absolute temperature;
ε_A, ε_B, ε_AB - Seebeck coefficients for conductor A, conductor B and conductor pair AB, respectively;
ε,- excitation energy;
ε_n, ε_p - excitation energy from the donor and acceptor levels, respectively;
ε_{ch} - cooling cycle efficiency;
γ - Thomson coefficient;
η - efficiency of the motor circuit;
λ - thermal conductivity;
Π - Peltier coefficient;
σ- specific electrical conductivity;
ρ - specific electrical resistance.

Indexing:
t index - values for the thermocouple,
g index - values for the heater.

2. MECHANISM OF CONDUCTIVITY OF ELECTRIC CURRENT IN A SOLID BODY

Due to the value of electrical conductivity σ, solids are usually divided into:

- conductors - for which $\sigma > 10^{6}\ \Omega^{-1}m^{-1}$;
- semiconductors - $10^{-12} < \sigma < 10^{6}\ \Omega^{-1}m^{-1}$;
- insulators - with σ values $\sigma < 10^{-12}\ \Omega^{-1}m^{-1}$.

The above division does not reflect the nature of physical phenomena related to the conduction of electric current. The band theory of a solid body is much better suited to explaining them, and only an outline of this will be presented in this study (readers interested in details are referred to the literature on the subject [4]). Individual atoms give discrete energy levels. If they start coming closer to each other, they will split. According to the Pauli principle, energy levels described by different quantum numbers must be created in a set of interacting particles. When forming a solid crystal from many atoms, the split levels pass, from a macroscopic point of view, into a continuum of energy bands. The most important for the conduction phenomenon are: the penultimate band, called the valence band, and the last conduction band. If the last band is half filled with electrons (Fig. 1.a - this is the case with a monovalent metal), or the last two bands partially overlap (Fig. 1.b - a divalent metal), then we are dealing with a conductor. If the valence band is completely filled and the conduction band is empty (strictly speaking at a temperature of 0K), and there is an energy gap ΔE between them, it is an insulator (Fig. 1.c).

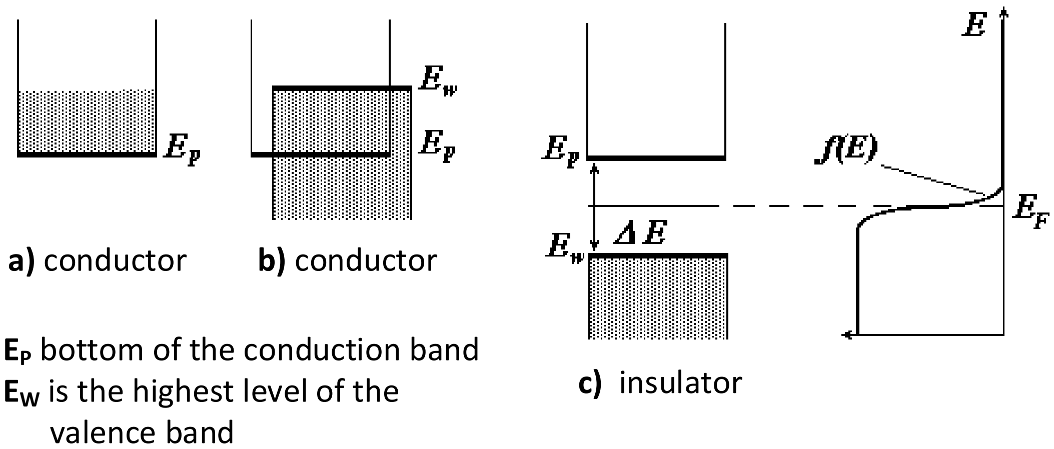


Fig. 1 Band model of electrical conduction

Semiconductor properties are determined by the possibility of the appearance of electric current carriers as a result of thermal excitations involving the transfer of an electron "over" the energy gap. The number of "free" carriers per unit volume of a solid body, i.e. the so-called carrier concentration, depends on the temperature and increases with its increase in accordance with the dependencies

$$n = C_n\, e^{-\frac{a_n}{T}} \;;\quad p = C_p\, e^{-\frac{a_p}{T}} \qquad (1)$$

where: n and p are the concentration of electrons and holes, respectively (see the content of the next paragraph),

T - absolute temperature,

C_n, a_n, C_p, a_p - constants.

The electrical conductivity of a semiconductor, which depends directly on the number of current carriers, can be represented by the formula

$$\sigma = C\, e^{-\frac{\varepsilon}{kT}} \qquad (2)$$

where: C - constant,

ε - excitation energy,

k_B - Boltzmann constant.

The electrical conductivity of a semiconductor increases with increasing temperature, in contrast to the decreasing conductivity of a metal.

In the above relationship, the excitation energy ε appears instead of ΔE. Well, only in **intrinsic semiconductors** (Fig. 2.a) electrons in the conduction band come from the valence band and ε = ΔE. However, in the remaining semiconductors, called **non-intrinsic semiconductors**, additional energy levels appear in the energy gap, related to donor (Fig. 2.b) or acceptor impurities (Fig. 2.c). In the case of the donor level $\varepsilon=\varepsilon_n$, the current carriers are electrons transferred to the conduction band, and the semiconductor is an **n-type semiconductor**. The acceptor level "captures" electrons from the valence band and the carriers are the holes remaining in the valence band. A semiconductor is called a **p-type semiconductor,** and $\varepsilon = \varepsilon_p$. In both cases, the value of ε corresponds to the distance of the dopant level from the border of the nearest band.

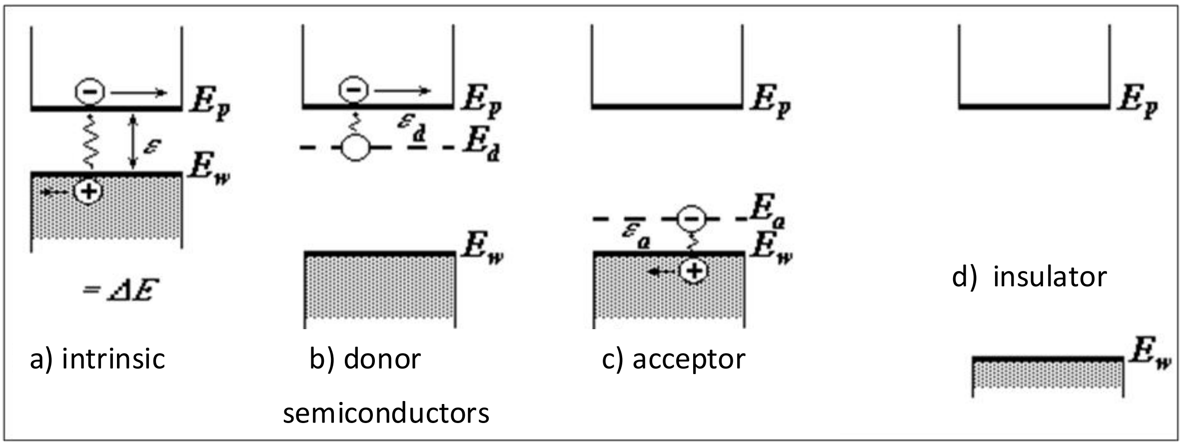


Fig. 2 Conduction mechanism in semiconductors

3 THERMOELECTRIC PHENOMENA

Thermoelectric phenomena occur in conductors and semiconductors. However, although the physical origins are the same in both cases, in order to present them more precisely, we will focus only on semiconductors. Firstly, because generalization would require going too deep into solid state theory, and secondly, because the subject of the experiment will be a semiconductor thermoelectric cell.

Thermoelectric phenomena include **Seebeck** (1829), **Peltier** (1834) and **Thomson** (predicted theoretically in 1856). The phenomenon associated with the release of Joule heat during the flow of electric current is not a thermoelectric phenomenon and will be treated as a side effect in this study.

The **Seebeck** effect can be observed in a circuit composed of two different semiconductors. For example, let's consider semiconductors: n-type and p-type (Fig. 3). A contact potential difference is created at the semiconductor contacts, depending on the temperature. When the junctions are at the same temperature, the contact voltages in the circuit cancel due to the same absolute values and opposite vector directions: $\varepsilon_{1a} = \varepsilon_{2a}$ (= 4 in the conventional units from Fig. 3).

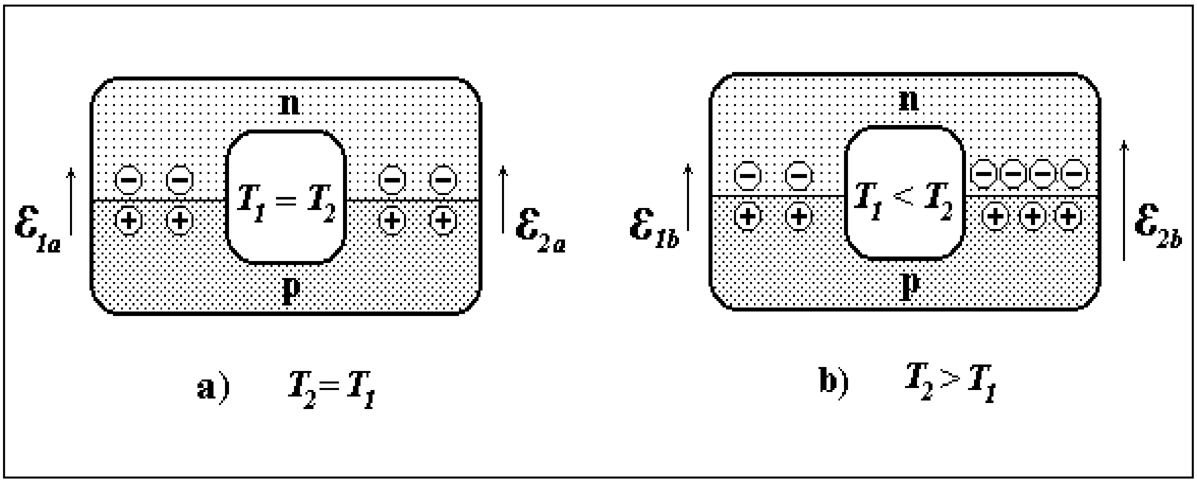


Fig. 3. Illustration of the Siebeck phenomenon. a) the contact potentials of junction 1 and junction 2 compensate each other. b) an increase in the concentration of carriers in both semiconductors in the area of the heated junction causes a change in the contact potential and the creation of a resultant thermoelectric voltage.

However, when one of the junctions is heated, the contact potential will change due to the transfer of an additional number of electrons to the conduction band in the n-type semiconductor and the generation of holes in the p-type semiconductor. Since $\varepsilon_{1b} \neq \varepsilon_{2b}$ (ε_{1b} = 7, ε_{2b} = 4), a net electric field will be generated in the circuit, causing electric current to flow when the circuit is closed, or the creation of a voltage called thermoelectric at the point of its interruption. This voltage, for a small temperature difference, can be expressed using the formula

$$e_{AB} = \varepsilon_{AB} (T_2 - T_1) \tag{3}$$

where ε_{AB} is the electromotive force (EMF) coefficient.

The Seebeck effect is a reversible phenomenon. When electric current flows through a junction of two different semiconductors (conductors), heat is released or absorbed in its area. This phenomenon is called the Peltier effect, and whether heat is emitted or absorbed depends on the direction of current flow.

In order to present the physical essence of the Peltier effect, let us consider a circuit composed of two different semiconductors A and B (Fig. 4). The explanation of the effect is not very precise but illustrative: the junctions initially have the same temperature. Contact potential differences occur in their areas. If current begins to flow through the circuit, current carriers in the area of one junction will be accelerated in the contact potential field, and in the area of the other junction they will be decelerated. The acceleration will take place at the expense of thermal energy taken from the area of junction I, the temperature of which will begin to decrease. In junction II, the carriers will release some of their energy and its temperature will increase. When the direction of current flow changes, the connectors will reverse roles. The heat flux absorbed or released in each of them, called the Peltier heat flux, is proportional to the electric current

$$\dot{Q}_P (T) = \Pi_{AB}(T)\, I = (\Pi_B - \Pi_A)\, I \tag{4}$$

Where: I - electric current,

Π_{AB} - Peltier coefficient, for which the relationship (5) is valid

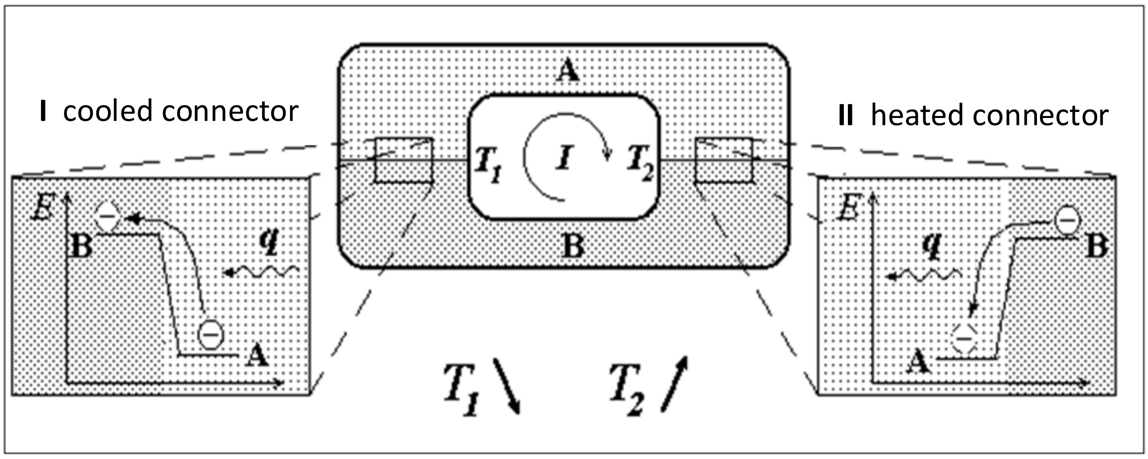


Fig. 4 Peltier effect. In the area of junction I, the absorbed heat q is used to increase the energy of the carrier (its acceleration in the contact potential field); in the area of junction II, the transition of the carrier from a higher to a lower energy level is accompanied by the release of heat.

$$\Pi_{AB}(T) = -\Pi_{BA}(T) \tag{5}$$

The Peltier coefficient П_AB depends on the temperature.

The following correlations exist between the Seebeck and Peltier coefficients [1]

$$\varepsilon_{AB} = \frac{\Pi_{AB}}{T}\ ;\ \ \varepsilon_A = \frac{\Pi_A}{T}\ :\ \ \varepsilon_B = \frac{\Pi_B}{T} \tag{6}$$

where: ε_A, ε_B are the Seebeck coefficients for conductors A and B, respectively,
Π_A, Π_B Peltier coefficients for these conductors (see [1]).

The Thomson effect, unlike the two previously discussed, is not related to the contact potential. They can be observed in one semiconductor (conductor) along which there is a temperature gradient (Fig. 5). This gradient, by causing differences in carrier concentration according to equation (1), affects the creation of an internal electric field. When current flows along such a semiconductor, depending on the direction of current flow, heat will be absorbed or released in its volume - let us emphasize once again that

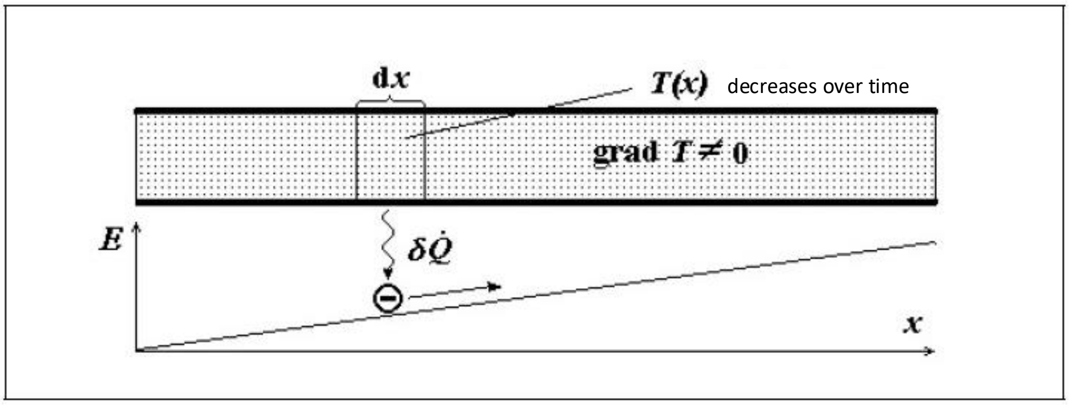


Fig. 5. Illustration of the Thompson phenomenon. In this case, the acceleration of the carrier in the potential field created by the thermally determined concentration gradient takes place at the expense of the volumetric heat absorbed. When the direction of current flow changes, heat will be released

this heat is different from the Joule heat. Heat absorption is the result of providing carriers with energy to overcome the internal electric field, contrary to its release. The heat flux assigned to a semiconductor fragment of length dx can be expressed as:

$$\partial \dot{Q} = \gamma(T)\, I \left(\frac{\partial T}{\partial x}\right) dx \tag{7}$$

where: γ is the Thomson coefficient.

4. PRINCIPLE OF OPERATION OF THE GENERATOR AND THERMOELECTRIC REFRIGERATOR

Thermoelectric phenomena in semiconductors can be used for:

- generation of electric current when providing heat (Seebeck effect). The device then operates in the "engine" cycle (conversion of heat into work) and is called a **thermoelectric generator**;
- cooling the space around the connector while supplying electric current (Peltier effect). The device then operates in the cooling circuit and is called a **thermoelectric refrigerator**.

To derive the basic relationships for heat fluxes, an example of a thermoelectric generator will be used, the diagram of which is shown in Figure 6. The generator is made of two different semiconductors, having the shape of cuboidal prisms with cross-sectional areas F_A and F_B. In the area of the "hot" junction - the source - at temperature T_1, the conductors are connected with a conductor with negligible resistance, e.g. a copper spacer. In the area of the "cold" junction - bleed - at temperature T_2 - the circuit is closed by the external load L. The side surfaces of the semiconductors are thermally insulated. The heat flow Q̇d flows to the "hot" junction so that the temperature T1 does not change over time. At the same time, heat (Q_od ̇) is removed from the lower junction, also while maintaining its temperature T2 constant over time, and electrical energy with power P.

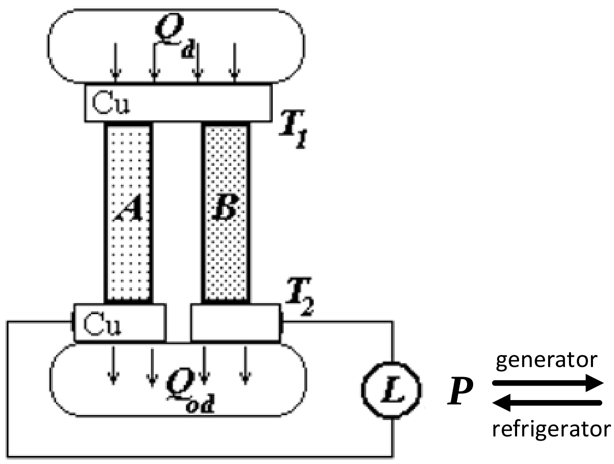


Fig. 6. Diagram of a thermoelectric cell

In the system, apart from the "reversible" thermoelectric phenomena discussed above, there are two irreversible phenomena:

- conduction of the heat flow Q_λ from the source to the sink, described by the Fourier relationship

$$\dot{Q}_\lambda = \lambda_z\,(T_1 - T_2) \tag{8}$$

where λ_z is the equivalent thermal conductivity of both semiconductor prisms;

- release of Joule heat flux (Joule-Lenz)

$$\dot{Q}_J = I^2\,(R_A + R_B) \tag{9}$$

where R_A and R_B are the resistances of conductor A and B, respectively.

In order to calculate the power P of a heat engine such as a generator [5]

$$P = \dot{Q}_d - \left|\dot{Q}_{od}\right| \tag{10}$$

and its efficiency

$$\eta = \frac{P}{\dot{Q}_d} = 1 - \frac{\left|\dot{Q}_{od}\right|}{\dot{Q}_d} \tag{11}$$

balances of heat flows supplied to the system at temperature T1 and heat flows removed at temperature T_2 should be prepared, with

$$T_1 > T_2 - \ generator \tag{12}$$

Before balancing, it can be assumed, due to the low values of the Thomson coefficients, that the Thomson heat flow is divided in half between the upper and lower junctions. This means that, depending on the sign, if $\dot{Q}_T/2$ flows into the upper junction, the same heat flux must flow from the lower junction. In other words, the volumetric Thomson effect giving rise to a heat flux

$$\dot{Q}_T = I \int_{T_1}^{T_2} (\gamma_B - \gamma_A)\, dT \tag{13}$$

surface character is given (cf. [1]).

Ultimately, the external heat flow $\dot{Q}_d$ and half of the Joule heat generated in the conductors $\dot{Q}_J$ flow into the imaginary "upper" tank. This heat must be dissipated because this is required by the assumption of constant temperature T_1 of the tank (with, of course, its finite heat capacity). Heat flow losses from the tank are the removed flows: Peltier heat $\dot{Q}_{P1}$, conducted heat $\dot{Q}_\lambda$ and half of the Thomson heat $\frac{\dot{Q}_T}{2}$. Therefore, the balance sheet can be written in the form

$$\dot{Q}_d + \frac{\dot{Q}_J}{2} = \dot{Q}_{P1} + \dot{Q}_\lambda + \frac{\dot{Q}_T}{2} \tag{14}$$

or as an expression of the external heat flux

$$\dot{Q}_d = \dot{Q}_{P1} + \dot{Q}_\lambda - \frac{\dot{Q}_J}{2} + \frac{\dot{Q}_T}{2} =$$
$$= \Pi_{AB}(T_1)\, I + \lambda_z\,(T_1 - T_2) - \frac{I^2 R}{2} + \frac{I}{2}\int_{T_2}^{T_1} (\gamma_B - \gamma_A)\, dT \tag{15}$$

A similar analysis leads to the following expression for the heat flux removed from the system

$$\left|\dot{Q}_{od}\right| = -\dot{Q}_{P2} + \dot{Q}_\lambda + \frac{\dot{Q}_J}{2} - \frac{\dot{Q}_T}{2} =$$
$$= \Pi_{AB}(T_2)\, I + \lambda_z\,(T_1 - T_2) + \frac{I^2 R}{2} - \frac{I}{2}\int_{T_2}^{T_1} (\gamma_B - \gamma_A)\, dT \tag{16}$$

Therefore, the power of the thermoelectric generator can be represented by the relationship

$$P = \dot{Q}_d - \left|\dot{Q}_{od}\right| =$$
$$= I\left[\Pi_{AB}(T_1) - \Pi_{AB}(T_2) + \int_{T_2}^{T_1} (\gamma_B - \gamma_A)\, dT - IR\right] \tag{17}$$

However, efficiency

$$\eta = 1 - \frac{\left|\dot{Q}_{od}\right|}{\dot{Q}_d} = \frac{P}{\dot{Q}_d} =$$

$$= \frac{I\left[\Pi_{AB}(T_1) - \Pi_{AB}(T_2) + \int_{T_1}^{T_2}(\gamma_B - \gamma_A)\,dT - IR\right]}{\Pi_{AB}(T_1)\,I + \lambda_z\,(T_1 - T_2) - \frac{I^2 R}{2} + \frac{I}{2}\int_{T_2}^{T_1}(\gamma_B - \gamma_A)\,dT} \tag{18}$$

In practice, semiconductor thermoelectric generators achieve efficiencies of several percent. They are used only when the benefits of their use outweigh the relatively low efficiency considerations, or when there is no other cost-effective way of converting heat into work. They are most often used to convert solar energy into electricity, both on Earth and in space. In order to obtain relatively high power, individual thermocouples are combined into thermoelectric batteries.

After changing the sign of the external work of the generator, the thermoelectric system considered above becomes a thermoelectric refrigerator. A change in the sign of external work is associated with a change in the sign of power P and means that instead of being received, the work of electric current is delivered to the system. In this case

$$T_1 < T_2 \quad - \quad chłodziarka \tag{19}$$

From a formal point of view, such an operation does not cause any changes in the prepared heat balances. **The expressions for the external heat fluxes $\dot{Q}_d$ supplied to the system, this time at a lower temperature T_1, and $\dot{Q}_{od}$ received from the system at a higher temperature T_2 look identical to those for the generator, i.e. they are described by equations (15) and (16). The same applies to the power of the device - the power of the thermocooler can be represented by formula (17).** Despite the formal similarity, expressions (14) ÷ (17) describe a physical case that is significantly different from the previous one. First of all, due to condition (19), the fluxes of conducted heat $\dot{Q}_\lambda$ and Thomson heat $\dot{Q}_T$ (see 8 and 13) change their signs. Moreover, the external heat flow supplied to the system $\dot{Q}_d$ is smaller in absolute value than the heat flow removed from the system $\dot{Q}_{od}$. The power sign P also changes.

The capacity of the refrigeration cycle is defined as [5]

$$\varepsilon_{ch} = \frac{\dot{Q}_d}{|P|} = \frac{\dot{Q}_d}{|\dot{Q}_{od}| - \dot{Q}_d} \tag{20}$$

which leads to dependency

$$\varepsilon_{ch} = \frac{\Pi_{AB}(T_1)\,I + \lambda_z\,(T_1 - T_2) - \frac{I^2 R}{2} + \frac{I}{2}\int_{T_2}^{T_1}(\gamma_B - \gamma_A)\,dT}{I\left[\Pi_{AB}(T_1) - \Pi_{AB}(T_2) + \int_{T_2}^{T_1}(\gamma_B - \gamma_A)\,dT - IR\right]} \tag{21}$$

Thermoelectric refrigerators, like generators, are not very energy efficient. Their disadvantages also include a disproportionate increase in power and dimensions when achieving greater differences in cooling temperature. Due to the above, their applications have been limited to special areas where the benefits resulting from relatively small dimensions, reliability, operability, simplicity of construction (without mechanical elements) and exceptional comfort of use outweigh the previously mentioned disadvantages. Typically, these are relatively low-power structures, such as coolers for low-temperature infrared detectors in thermal imaging cameras or homing missile heads, sample coolers in measuring devices, etc. There are also larger semiconductor battery-powered refrigerators used in the transport of medical biological preparations. - mostly blood.

Semiconductor cooling elements are often arranged in the so-called 'Thermopiles' in which, figuratively speaking, the cover from which the heat of one thermocouple must be removed is cooled by another, usually larger one. In such structures, it is possible to obtain temperature differences of approximately 180 K [2]

5. OPTIMAL CONDITIONS FOR OPERATING THERMAL CELLS IN THE REFRIGERATION CIRCUIT

The relationships derived in the previous point apply to the general case and take into account all three thermoelectric phenomena. In fact, due to relatively small temperature differences, it can be assumed that such material properties as resistivity ρA, ρB, thermal conductivity λ_A, λ_B and Thomson coefficients γ_A, γ_B are constant. However, the most important consequence of adopting the assumption of small temperature differences, in addition to the relatively small values of the γ(T) coefficient, is the possibility of omitting the Thompson heat from the considerations.

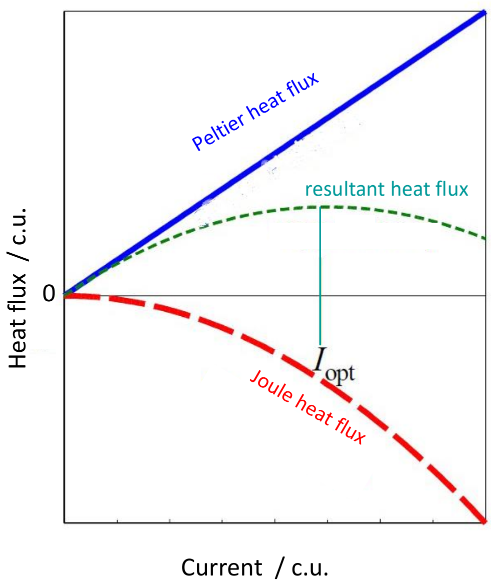
$$|(T_1 - T_2)| \ll T_2 \rightarrow \int_{T_2}^{T_1} (\gamma_B - \gamma_A)\, dT \approx 0 \tag{22}$$

This leads to a significant simplification of the expressions for heat fluxes from point 14. In particular, for the stream discharged from the cooled space, i.e. supplied to the refrigerator system, the following results are obtained

$$\dot{Q}_d = \dot{Q}_{P1} + \dot{Q}_\lambda - \frac{\dot{Q}_J}{2} =$$

$$= \Pi_{AB}(T_2)\, I + \lambda_z\, (T_1 - T_2) - \frac{I^2 R}{2} \tag{23}$$

In the above expression, there are two terms depending on the current **I** supplying the thermocouple: one describing the Peltier heat flux $\dot{Q}_{P1}$ and the other corresponding to the Joule heat flux $\frac{\dot{Q}_J}{2}$. The release of heat when current flows is an unfavorable effect - this heat causes a relative increase in temperature of both the heated and cooled junction. As the current I increases, the Peltier heat flux increases linearly, while the Joule-Lenz heat flux increases parabolically, as illustrated in Figure 7. When the critical value of the current I_{kr} is exceeded, the cooling effects are completely eliminated and the temperature of the T_1 junction increases instead of decreasing. However, there are optimal operating conditions for the thermocooler, corresponding to the extreme of the curve.



Rys. 7. Optimum operating conditions of the link

It is easy to check that differentiating (23) with respect to the current **I** and equating the result to zero

$$\frac{d\dot{Q}_d}{dI} = \frac{d\left(\dot{Q}_{P1} - \frac{\dot{Q}_J}{2}\right)}{dI} = \Pi_{AB}(T_1) - RI \qquad (24)$$

leads to the following expression for the optimal current supplying the device

$$I_{opt} = \frac{\Pi_{AB}}{R} \qquad (25)$$

At this current intensity, the cooling effects will be greatest. It should be emphasized, however, that achieving the maximum temperature difference between the "cold" and "hot" junction does not result in achieving the maximum efficiency of the thermo-cooler.

6. DESCRIPTION OF THE LABORATORY STAND

The laboratory exercise used a typical semiconductor element of thermoelectric refrigerators. The thermos-cell, shown in Figure 8, is made of semiconductors in the form of alloys of compounds:

- element A - 30% Bi_2Te_3 + 70% Sb_2Te_3 with an admixture of Pb;

- element B - 80% Bi_2Te_3 + 20% Bi_2Se_3 with an admixture of Hg_2Cl_2.

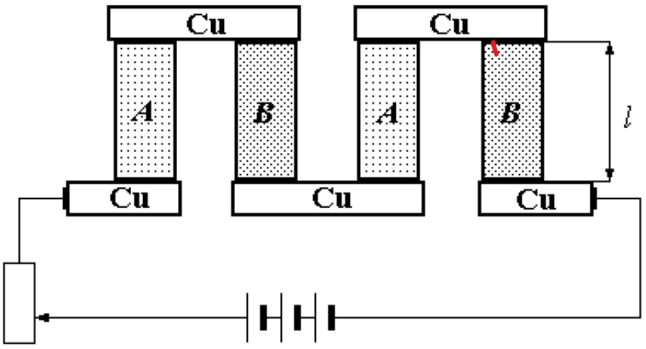
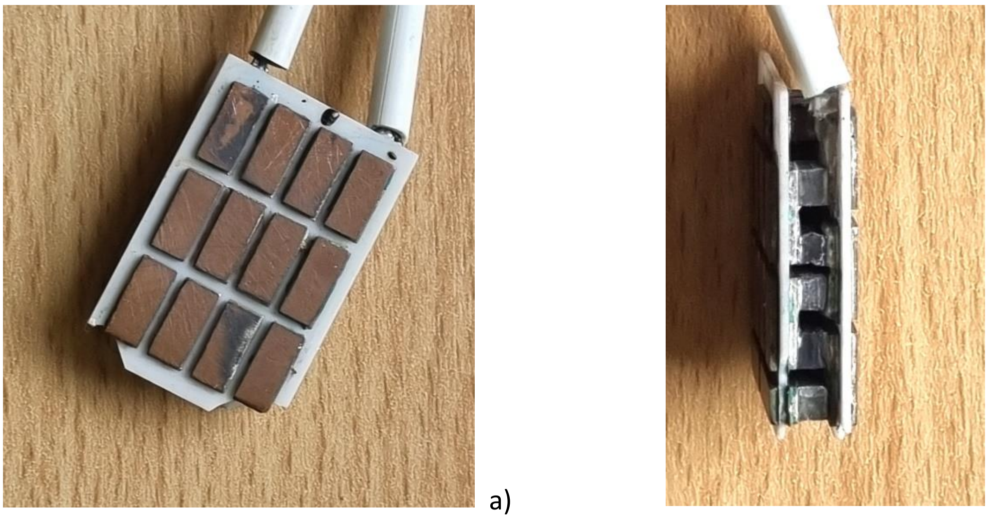


Fig. 8. Method of making a single branch of a thermocouple. Semiconductor prisms A and B are connected by copper plates. Identical connectors adhere to one and the same cover: AB to the upper one, BA to the lower one

A typical view of a Peltier thermocouple is shown in Figure 9. Single copper plates connecting the semiconductor prisms are visible (Fig. 9a). Figure 9b shows individual semiconductor prisms.



a) b)

Fig. 9 View of a typical design of a Peltier thermocouple

The laboratory stand for testing the Peltier effect used in the exercise is shown in Figure 10. The control panel of the station and the view of the exposed measurement stack are shown in Figure 11

The block diagram of the laboratory station is shown in Figure 12.

The thermos-cell is powered by direct current from a DC power supply (power supply 1) with a current range of 0 to 30A. An ammeter connected in series in the circuit and a digital voltmeter allow for simultaneous measurement of the current I_t and the voltage U_t of the current supplying the semiconductor element. The values obtained as a result of the measurement allow determining the power of the thermocouple: $P_t = U_t{*}I_t$.

Fig. 10 General view of the laboratory stand

a) b)

Fig. 11 Elements of the laboratory station: a) control panel, b) exposed measurement stack

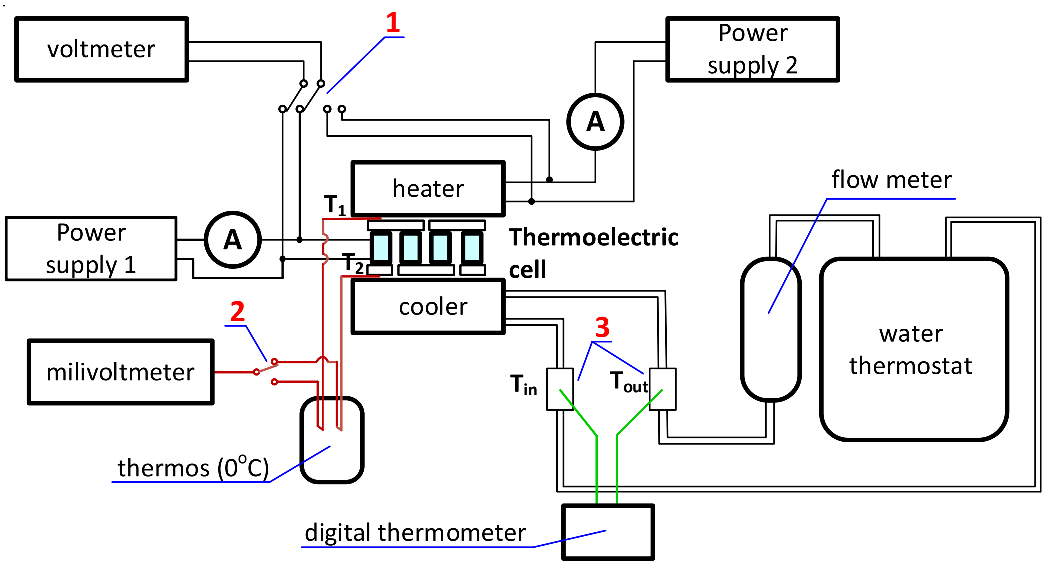


Fig. 12 Diagram of the laboratory system for testing a thermoelectric refrigerator

An electric heater is attached to the "cold" upper contacts of the thermocouple in the arrangement shown in Figure 12. It is powered by direct current from a stabilized power supply. The values of current I_g and voltage U_g supplying the heater are measured with a separate ammeter and a digital voltmeter, respectively. The same voltmeter measure the voltage supplying the thermoelectric cell . Switching for voltage measurements is made using switch **1** located on the control panel (Figure 11 and 12).

The "hot" lower contacts of the thermocouple are cooled by a water cooler. At the inlet and outlet of the cooling liquid supplied from the thermostat, there are thermocouples (marked **3** in Fig. 11 and 12) connected to a digital thermometer, enabling the measurement of temperatures T_{in} and T_{out}, respectively. A flow meter inserted between the water thermostat and the radiator is used to measure the cooling water flow rate. The side surfaces of the thermocouple are insulated with polystyrene covers.

Cu-Konstantan thermocouples were used to measure the temperature T_1 of the upper cover ("hot" contacts) and the temperature T_2 of the lower cover ("cold" contacts) of the thermoelectric cell. The reference welds are placed in a thermos with distilled water and ice. Thermoelectric voltages are measured using one millivoltmeter - the switch is located on the control panel (Fig. 11 and 12 - switch **2**).

Note: Calculate the T_1 and T_2 temperature values based on the characteristics of the Cu-Konstantan thermocouple (for the case of thermostatting of reference welds at 0°C) presented in Table 1.

Table 1

Temperature [°C]	0	10	20	30	40	50
Thermoelectric voltage [mV]	0,00	0,40	0,80	1,21	1,63	2,05

7. EXERCISE PROCEDURE

Purpose: to determine the parameters of a semiconductor thermocouple operating in a refrigeration cycle in a steady state.

Measurement procedure:

1. Determine the cooling water temperature using the contact thermometer in the water thermostat. Use the flowmeter knob to select the appropriate flow rate, from 4 to 8 l/h.

2. Turn on the heater's power supply by setting the voltage value given by the instructor on power supply 2.

3. Turn on the thermocouple power. Change the current intensity until the temperature T_1 of the cold contact drops to the assumed value. If the measured temperatures do not change over time for more than 5 minutes, it can be assumed that the thermocouple is in a steady state.

4. Take readings from the measuring instruments and enter the results into the table (formula - table 2).

Table 2

Lp	T_{in}	T_{out}	$\dot{m}$	U_g	I_g	U_t	I_t	T_1		T_2	
	K	K	g/s	V	A	V	A	mV	K	mV	K

5. Increase the heater's power by changing the supply voltage.

6. Increase the current flowing through the thermocouple so that the temperature of the cold contact takes on the previous value (from point **3** of the procedure) while the temperature of the hot contact remains the same as before.

7. After establishing the heat transfer conditions, take readings from the measuring instruments and write them in the table.

8. Repeat the steps **5 ÷ 7** of the procedure two or three times.

Preparation of results:

<u>Note</u>: all calculations should be carried out assuming the Thomson heat flux becomes zero, as in point 5.

1. Calculate the Peltier heat flux of the "cold" junction for each measurement case using the relationship (15), which, after taking into account assumption (22), gives:

$$\dot{Q}_{P1} = \dot{Q}_d - \dot{Q}_\lambda + \frac{\dot{Q}_J}{2} \tag{26}$$

When determining the Joule heat flux (see 9) from the formula

$$\dot{Q}_J = I_t^2 \left(R_A + R_B\right) = I_t^2 R_t \tag{27}$$

assume the same values of electrical resistance for both branches of the thermocouple $R_A = R_B$. As a result, this will lead to the following relationship for the total resistance of the thermoelectric system

$$R_t = 2k \frac{\rho l}{F} \tag{28}$$

where: $\rho = 1.21 \cdot 10^{-5}$ Ωm - specific resistance of the semiconductor thermo-cell material;

l = 7 mm - length of the thermocouple branch (height of a cuboid semiconductor prism);

F = 0.0001 m^2 - cross-sectional area of the thermocouple branch;

k = 12 - number of thermocouple branches.

Determine the conducted heat flux based on the relationship

$$\dot{Q}_d = P_g = U_g I_g \tag{30}$$

2. Based on the measurement results, calculate the external heat flow removed from the system for each case. Use the relationship for calculations

$$\left|\dot{Q}_{od}\right| = \dot{m}\, c_W \left(t_{wyl} - t_{wl}\right) \tag{31}$$

Where $\dot{m}$ is the cooling water mass flow rate,

c_W - specific heat of water,

T_{wyl} and T_{wl} - water temperatures at the outlet and inlet to the radiator, respectively.

3. Calculate the power of the thermocouple for each case

$$P_t = U_t\, I_t \tag{32}$$

Then determine the experimental values of the thermo-cooler's efficiency $\varepsilon_{chł,eksper}$ based on formula (20) and the calculated values of external heat flows $\dot{Q}_d$ and $\left|\dot{Q}_{od}\right|$, from points 1 and 2, and power P_t.

4. Peltier coefficients in the room temperature are poorly variable functions of temperature. With small temperature differences between the "cold" and "hot" junctions in the steady state, it can be assumed that

$$\dot{Q}_{P2} = -\dot{Q}_{P1} \tag{33}$$

Taking into account the above assumption together with assumption (22), calculate from the equation (16) the approximate theoretical value of the external heat flux $\left|\dot{Q}_{od}\right|_{teor}$ removed from the system. Then, using the obtained values and the values of $\dot{Q}_d$ and P_t from points 1 and 3, determine the approximate theoretical and experimental efficiency values of the thermo-cooler $\varepsilon_{ch,teor}$. based on formula (20). Compare the obtained results with the calculation results from point 3.

5. Plot the relationship $\dot{Q}_{P1} = f(I)$ with T_1 = const. Based on the linearization of the obtained characteristic, determine the value of the Peltier coefficient $\Pi_{AB}(T_1)$ (formula 4).

6. Determine the optimal power supply current for the thermocooler (formula 25) and calculate the power in optimal conditions using the relationship

$$P_{opt} = I_{t,opt}^2\, R \tag{34}$$

7. Evaluate the obtained calculation results.

8. SAMPLE REVIEW QUESTIONS

1. Discuss the mechanism of electrical conduction in semiconductors.
2. Explain the essence of the Seebeck phenomenon.
3. Explain the essence of the Peltier phenomenon.
4. Discuss the motor cycle based on the diagram in T-s coordinates.
5. Discuss the refrigeration cycle based on the diagram in T-s coordinates.
6. Give examples of applications of semiconductor thermoelectric cells.
7. Discuss the operation of a thermoelectric refrigerator.
8. What are the optimal operating conditions of a thermo-cooler and what do they involve?

9. Provide a method for experimentally determining the Peltier coefficient Π_{AB}.

LITERATURE

[1] Warren H. Giedt *Thermophysics*. Van Nostrand Reinhold Company, New York, 1971.

[2] Mirosław Grudzień *Eksperymentalno-numeryczna granicznych parametrów detektorów podczerwieni z CgHgTe z uwzględnieniem absorpcji promieniowania i chłodzenia termoelektrycznego*. Rozprawa doktorska WAT, Warszawa, 1979.

[3] Ludwik Michalski, Krystyna Eckersdorf *Pomiary temperatury*. WNT, Warszawa, 1986.

[4] Peter Wilkes *Fizyka ciała stałego dla metaloznawców*. PWN, Warszawa, 1979.

[5] Stefan Wiśniewski *Termodynamika techniczna*. WNT, Warszawa, 1987.