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L.I. Anatychuk, *Acad. NAS Ukraine* [1,2]
V.V. Lysko, *Cand. Sc (Phys-Math)* [1,2]
K.I. Strusovskyi [2]

[1]Institute of Thermoelectricity of the NAS
and MES of Ukraine,
1, Nauky str., Chernivtsi, 58029, Ukraine;
[2]Yuriy Fedkovych Chernivtsi National University,
2, Kotsiubynsky str., Chernivtsi, 58012, Ukraine
e-mail: anatych@gmail.com

COMPUTER RESEARCH ON THE ACCURACY OF PROBE METHOD FOR MEASURING THE ELECTRICAL CONTACT RESISTANCE OF "METAL – THERMOELECTRIC MATERIAL"

Physical and computer models have been created to study possible errors in measuring the electrical contact resistance of "metal-thermoelectric material" using the probe method. By means of computer simulation, the distributions of electric potential and temperature in the studied physical model were obtained for different sample geometries, current through the sample, and contact electrical resistance. It has been found that deviations from isothermal conditions in the sample, caused by the influence of the Joule and Peltier effects, can lead to very significant (over 100%) measurement errors. The possibilities of minimizing these errors by thermostating one side of the sample are considered. Bibl. 12, Figs. 14.

Key words: electrical contact resistance, measurement, computer simulation, accuracy, thermoelectric thermoelectric energy converters.

Introduction

The development of methods and equipment for studying the quality of contact structures in thermoelectric energy converters and their subsequent comprehensive optimization is an important and urgent task. It is due to the need of modern thermoelectrics to miniaturize thermoelectric energy converters, which will allow significantly reducing their cost, approaching that acceptable for wide practical use. The main obstacle to this is the relatively large values of contact resistances, since, as is known, the influence of contact resistance on the efficiency of a thermoelectric energy converter increases as it becomes smaller [1 – 5].

It is also important to ensure high-quality contacts for conducting high-precision measurements of the thermoelectric properties of materials both in materials science research aimed at finding ways to increase their thermoelectric figure of merit, and in the processes of developing and manufacturing thermoelectric energy converters [6-8].

To create a technology for manufacturing contact structures with acceptable contact resistance values, it is necessary to conduct a complex of experimental studies, which are possible only with the availability of high-precision methods and equipment for measuring contact resistances. In doing so, as literature analysis shows [9, 10], reliable equipment for studying contact resistances of "metal –

thermoelectric material" has not yet been created. The developed methods for measuring electrical contact resistance in thermoelectricity can be divided into those based on measuring the characteristics of "pack" contact structures, which are a series of series-connected thermoelements with contact resistances; probe and microelectronic methods, which require the manufacture of test structures

Works devoted to measuring contact resistance in thermoelectricity are not of a comprehensive nature aimed at developing high-precision measuring equipment for widespread use.

Therefore, the *purpose of this work* was to analyze the accuracy of the probe method for measuring the electrical contact resistance of "metal – thermoelectric material" through a detailed analysis of its real physical model and computer optimization to achieve minimal error values. This approach to the development of measuring equipment was successfully used at the Institute of Thermoelectricity (Ukraine) in creating equipment for determining the properties of thermoelectric parameters of materials by a complex absolute method, which is several times more accurate than its analogues [11, 12].

1. Description of the probe method for measuring electrical contact resistance of "metal – thermoelectric material"

The physical model of the probe method for measuring the electrical contact resistance of "metal – thermoelectric material" is shown in Fig. 1. The structure under study consists of a thermoelectric material sample 1 with a metal (e.g., nickel) coating 3 applied to its ends, a transient contact layer 2, a solder layer 4, and metal (e.g., copper) contact plates 5. A pointed probe is located on the side surface of the sample, which measures the potential distribution along the sample when a constant electric current of magnitude *I* is passed through it.

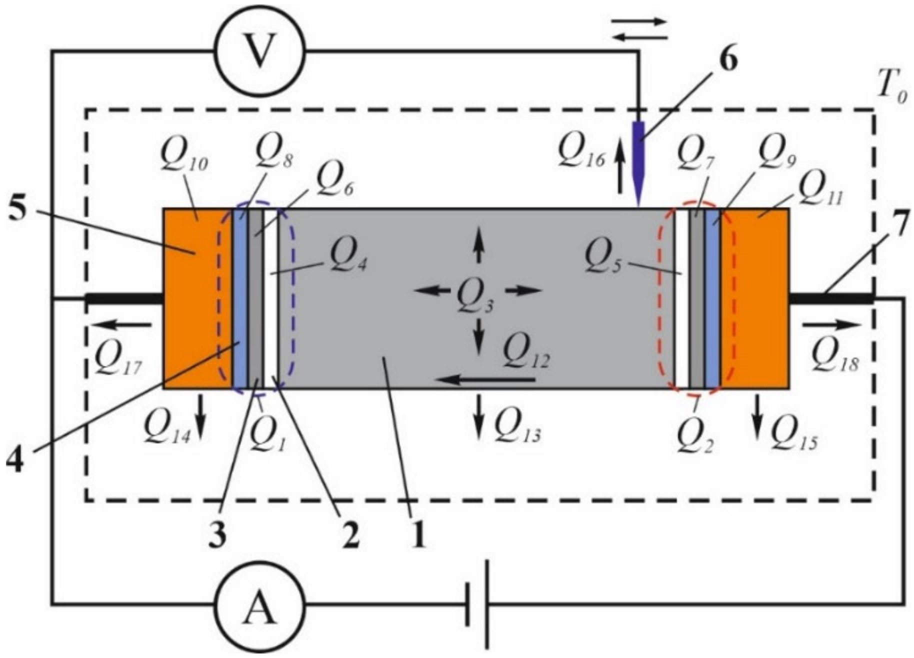


Fig. 1. Physical model of the probe method for measuring electrical contact resistance of "metal – thermoelectric material": 1 – thermoelectric material sample; 2 – transient contact layer; 3 – metal anti-diffusion coating; 4 – solder; 5 – metal contact plates; 6 – movable potential probe; 7 – current leads.

In Fig. 1: Q_1 is the Peltier heat absorbed at the “metal-thermoelectric material” contact; Q_2 is the Peltier heat released at the “metal-thermoelectric material” contact; Q_3 is the Joule heat released in the volume of thermoelectric material sample; Q_4, Q_5 is the Joule heat released on the transient contact layers; Q_6, Q_7 is the Joule heat released in the volume of metal anti-diffusion coatings; Q_8, Q_9 is the Joule heat released in the volume of solder layers; Q_{10}, Q_{11} is the Joule heat released in the volume of metal contact plates; Q_{12} is heat flow from the hot to cold “metal-thermoelectric material” contact; Q_{13}, Q_{14}, Q_{15} is heat transfer from the side surface of the sample and metal contact plates to the environment by radiation and convection; Q_{16}, Q_{17}, Q_{18} is heat transfer from the side surface of the sample and metal contact plates to the environment by thermal conductivity through the potential probe and current leads; T_0 is ambient temperature.

The value of electrical contact resistance of “metal – thermoelectric material” is determined by the formula

$$r_c = \frac{\Delta U}{I} \cdot S, \tag{1}$$

where r_c is specific electrical contact resistance of “metal-thermoelectric material”, ΔU is voltage drop across the contact, S is contact area.

The main sources of errors in determining contact resistance using this method will be the following:

1. Errors of instruments for measuring current and electric potential.
2. Errors in measuring the geometric dimensions of the sample and the coordinates of the probe location.
3. Deviations from isothermal measurement conditions caused by the influence of Joule heat generated when passing electric current through the volume of the sample, current leads and contact resistance, as well as heat generated or absorbed at the points of contact of dissimilar materials.

2. Computer model

To determine the errors, the influence of various factors on them, and optimize the measurement method, it is necessary to find the distribution of the electric potential φ and the temperature T in the sample, which can be obtained based on the laws of conservation of electric charge and energy, written in the form:

$$\begin{cases} -\nabla\left(\left(\kappa_j + \alpha_j^2\sigma_j T + \alpha_j\varphi\sigma_j\right)\nabla T\right) - \nabla\left(\left(\alpha_j\sigma_j T + \varphi\sigma_j\right)\nabla\varphi\right) = 0, \\ -\nabla\left(\sigma_j\nabla\varphi\right) - \nabla\left(\sigma_j\alpha_j\nabla T\right) = 0. \end{cases} \quad (j = 1...10), \tag{2}$$

where: α_i, σ_i, κ_i are the Seebeck coefficient, electrical conductivity and thermal conductivity of the model elements.

The boundary conditions for such a model:

– the side surfaces of the sample, metal coating, contact plates and current leads are electrically isolated

$$\mathbf{n} \cdot \mathbf{j} = 0 \;;$$

– a current of magnitude I flows through the current leads

$$\mathbf{n}\cdot\mathbf{j}=I/S_{cm.};$$

– the ends of current leads are maintained at ambient temperature T_0

$$T=T_0;$$

– the side surfaces of the sample, metal coating, contact plates and current leads are in a state of heat exchange with the environment

$$\mathbf{n}\cdot\mathbf{q}=h_i(T_0-T),$$

where h_i are heat transfer coefficients.

To calculate such a problem, computer object-oriented simulation was used by applying the finite element method (Fig. 2), implemented in the Comsol Multiphysics application software package.

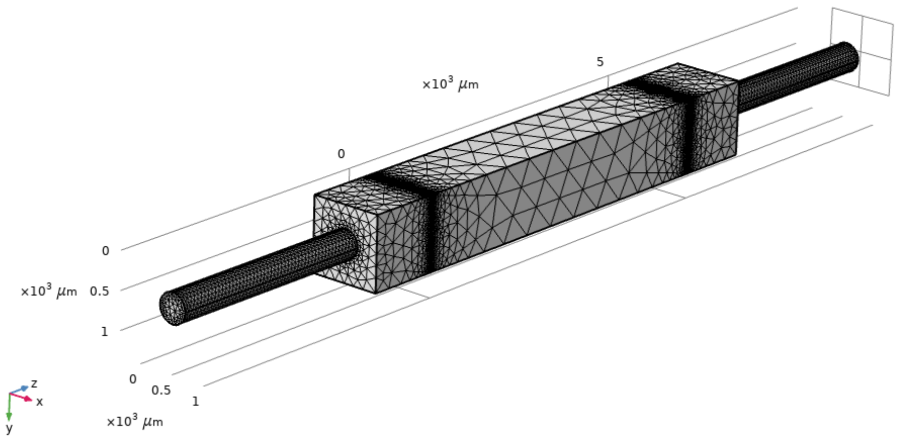
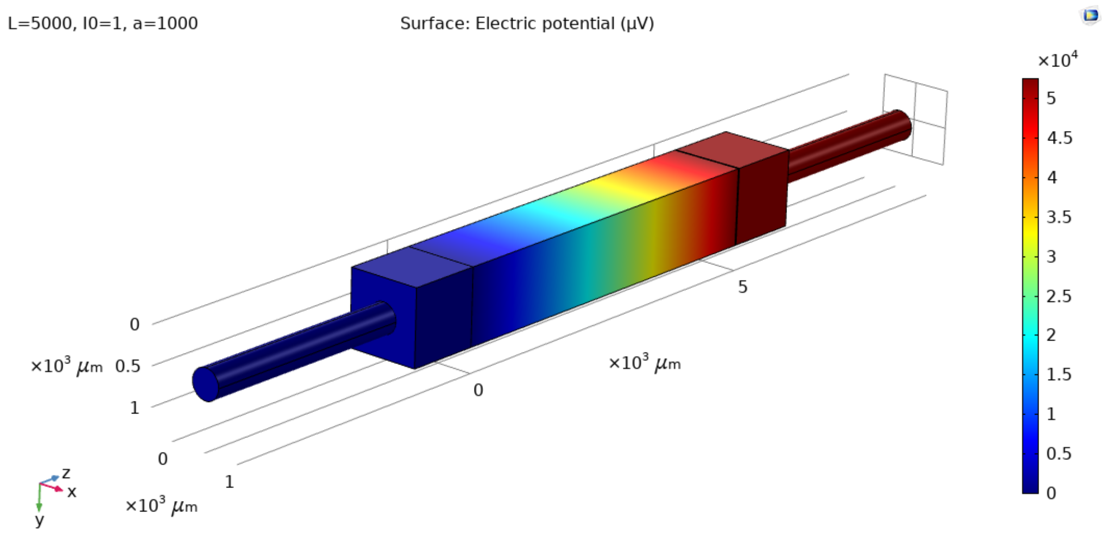
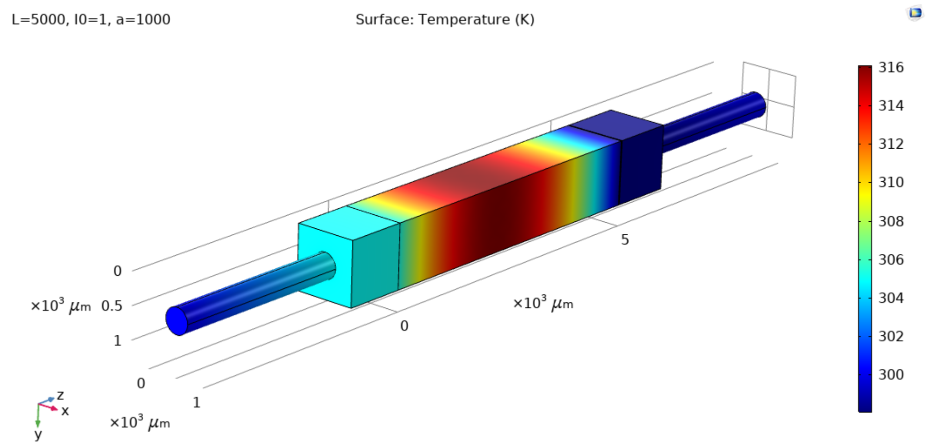


Fig. 2. Finite element method mesh for simulation of the probe method of measuring the electrical contact resistance in the Comsol Multiphysics application package.

Fig. 3 shows typical distributions of electric potential and temperature in the contact structure under study, obtained by computer simulation. Fig. 4 shows the distributions of electric potential and temperature along the line of movement of the measuring probe (for the case of a sample 5 mm long and 1 x 1 mm^2 in cross-section, with a current through the sample of 1 A; contact resistance is 10^{-6} Ohm·cm^2).

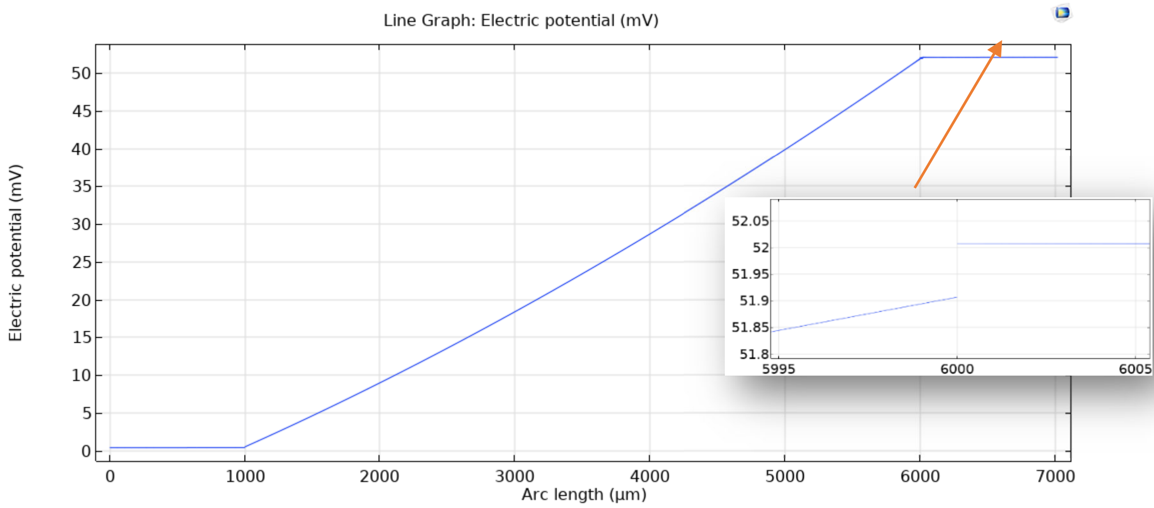


a)

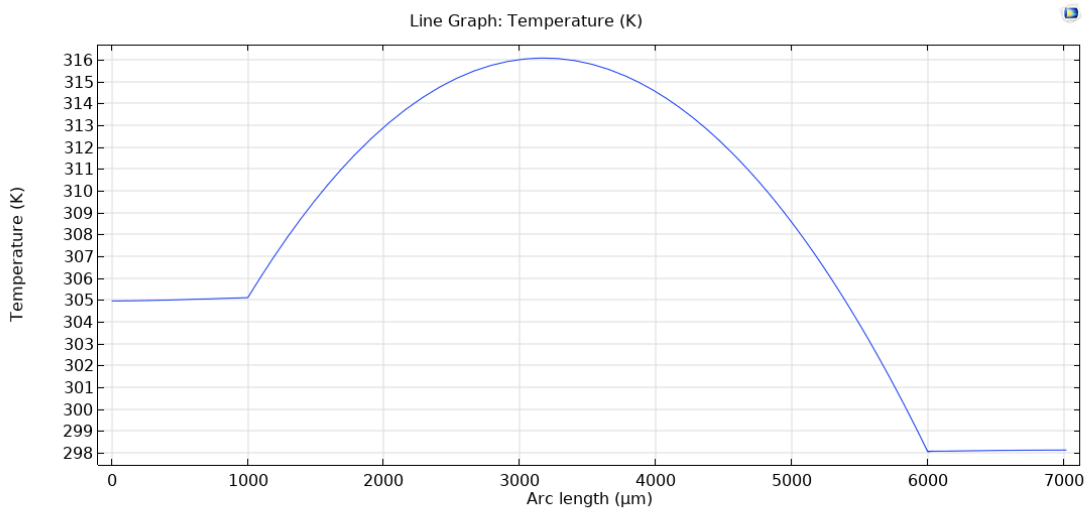


b)

Fig. 3. Typical distributions of electric potential (a) and temperature (b) in the studied contact structure, obtained by computer simulation using the Comsol Multyphysics package.



a)



b)

Fig. 4. Distributions of electric potential (a) and temperature (b) on the surface of the studied contact structure along the line of movement of the measuring probe (for the case of a sample with a length of 5 mm and a cross-section of 1 mm², at a current of 1 A; contact resistance – 10⁻⁶ Ohm·cm²).

3. Results of the study of possible measurement errors and conditions for their minimization

By means of computer simulation, the distributions of electric potential and temperature in the studied model were obtained for different sample geometries, current through the sample, and contact electrical resistance.

Fig. 5 shows an example of the dependences of the voltage drop at the contact and on a section of the sample with a length of 50 μm on the current through the sample for different sample geometries, with a contact resistance of 10^{-6} Ohm·cm^2. From these dependences it is clear that to ensure sufficient accuracy of measurements of electric current and voltage by modern measuring devices (up to 0.05% with a resolution of 1 μV), it is necessary to use samples with a cross section of at least 1 mm^2 and a current of 0.5 – 1 A.

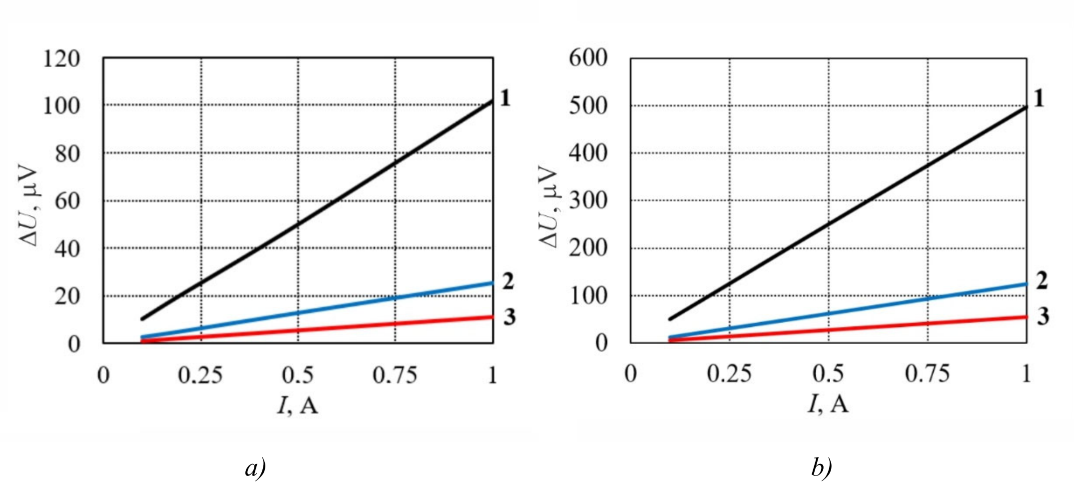


Fig. 5. Dependence of the voltage drop at the contact (a) and on a section of the sample 50 μm long (b) on the current through the sample. Sample cross-section S: 1 – 1 x *1 mm ^{2}; 2 – 2* x *2 mm^2; 3 – 3* x *3 mm^2.*

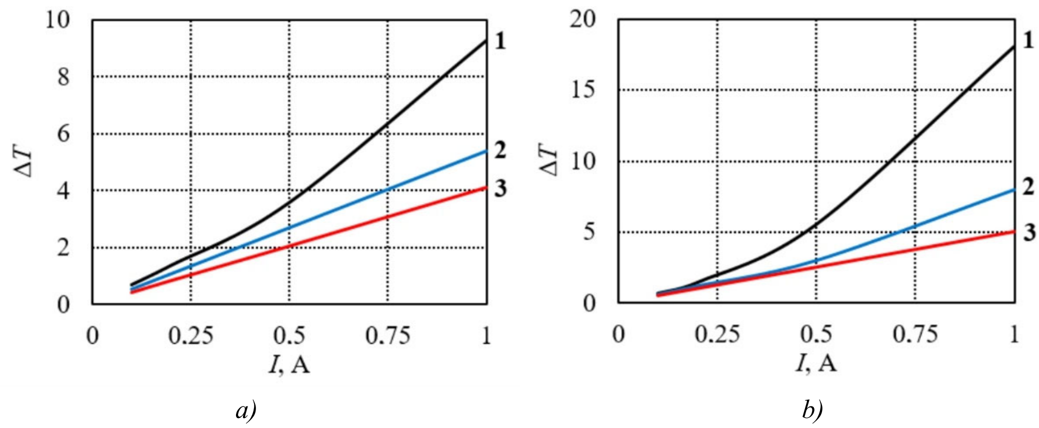


Fig. 6. Dependence of the temperature difference on the sample on the current through the sample (for samples with a length of 3 mm (a) and 5 mm (b)): Section of the sample S: 1 – 1 x *1 mm2; 2 – 2* x *2 mm2; 3 – 3* x *3 mm2.*

However, this poses a problem with ensuring the isothermality of the sample. Fig. 6 shows the dependences of the temperature difference on the sample, which will arise during measurements due to the Peltier and Joule effects (for the case of heat exchange of the sample with the environment by free convection and radiation). As can be seen from the figure, the temperature difference on the sample can reach 18 K, which will lead to very significant (over 100 %) measurement errors caused by the fact that thermoEMF will be added to the measured ohmic voltage drop, and the values of thermoEMF and ohmic voltage drop on the sample will be commensurate.

To minimize the influence of the Peltier and Joule effects, glue one side of the sample to an electrical insulator with high thermal conductivity (for example, beryllium oxide ceramics) and place it on a thermostatic surface (Fig. 7).

The heat flows to the thermostat from this side of the sample, as well as from the corresponding sides of the metal contact plates, are designated Q_{19}, Q_{20}, Q_{21}, respectively. Other designations of heat flows $Q_1 - Q_{18}$ correspond to those given earlier for the physical model shown in Fig. 1.

As computer simulation has shown, when using thermostating of even one of the sides, the non-isothermality of the sample is significantly reduced. This is clearly seen by comparing the temperature distributions in the studied contact structure (Fig. 8) and along the line of movement of the measuring probe (Fig. 9) with similar distributions without thermostating (Fig. 3*b* and Fig. 4*b*).

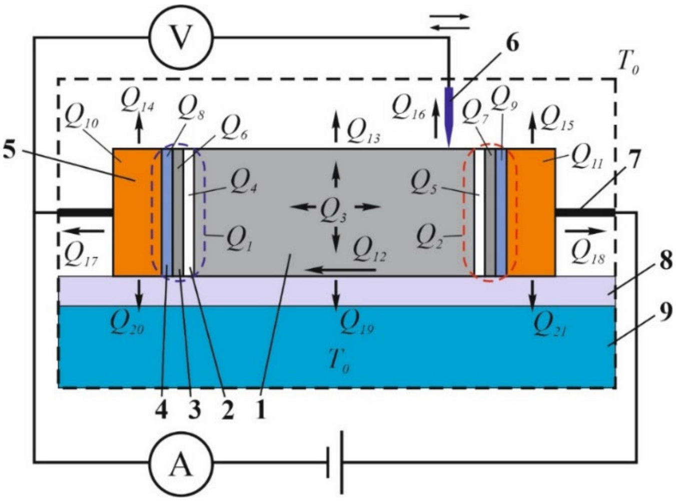


Fig. 7. Thermostating a sample when measuring electrical contact resistance using the probe method: 1 – sample of thermoelectric material; 2 – transient contact layer; 3 – metal anti-diffusion coating; 4 – solder; 5 – metal contact plates; 6 – movable potential probe; 7 – current leads; 8 – electrical insulator; 9 – thermostat.

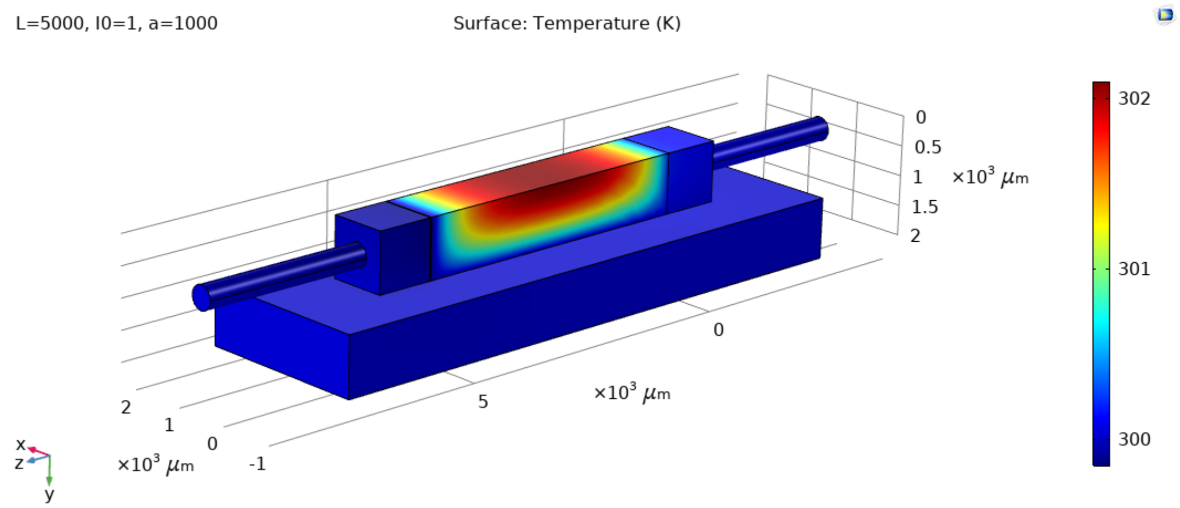


Fig. 8. Temperature distribution in the contact structure under study during thermostating of one of its surfaces.

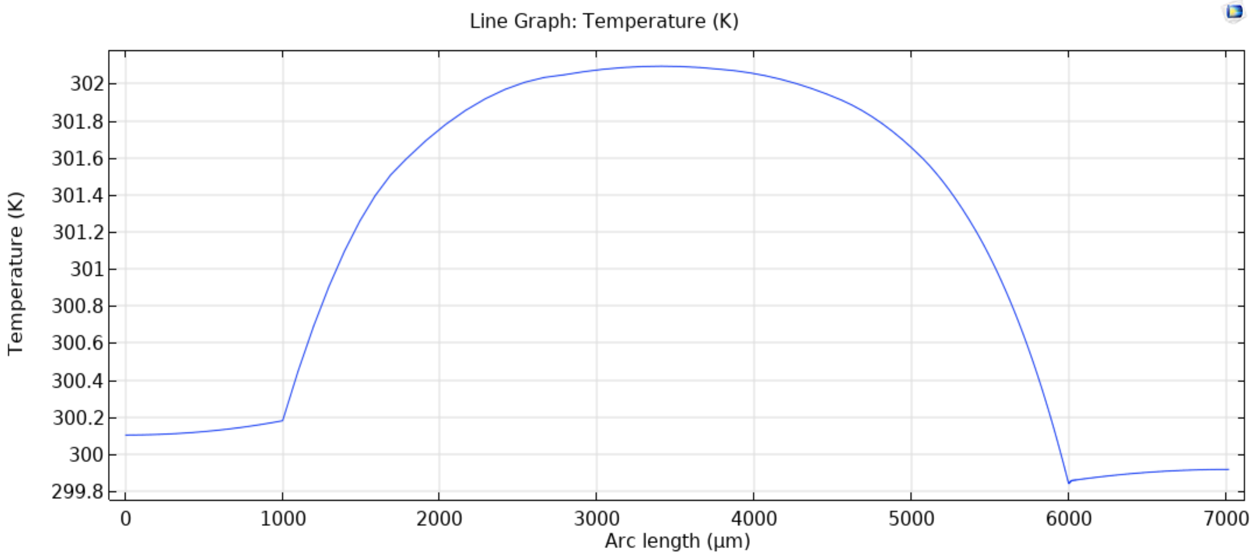


Fig. 9. Temperature distribution along the line of motion of the measuring probe over the surface of the investigated contact structure during thermostating of one of its surfaces (for the case of a sample with a length of 5 mm and a cross-section of 1 mm^2, at a current of 1A; contact resistance – 10^{-6} Ohm·cm^2).

The dependence of the temperature difference on the sample on the current through the sample for different sample geometries is shown in Fig. 10.

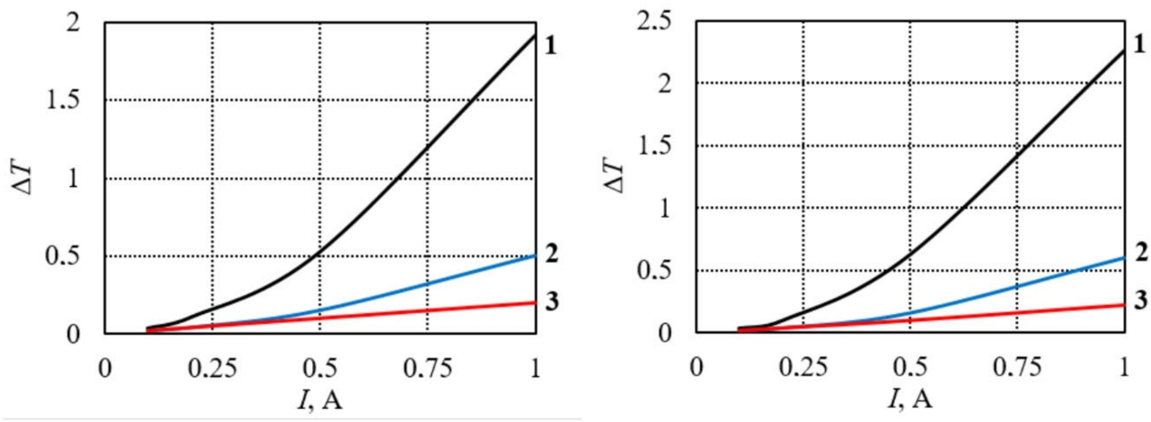


Fig. 10. Dependence of the temperature difference on the sample on the current through the sample when thermostating one of its side surfaces (for samples with a length of 3 mm (a) and 5 mm (b)): Section of the sample S: 1 – 1 x 1 mm^2; 2 – 2 x 2 mm^2; 3 – 3 x 3 mm^2.

Thus, the error in determining the contact resistance, caused by the non-isothermal nature of the measurement conditions, will be significantly reduced – to a value of ~ 8 % (at a contact resistance of 10^{-6} Ohm·cm^2).

Additional improvement can be achieved by using samples with a rectangular cross-section of the same area and placing them on a thermostatic surface with their wider side. The temperature distributions in the contact structure under study and along the line of movement of the measuring probe are shown in Figs. 11 and 12 (for a sample length of 5 mm, a cross-section of 0.5 mm by 2 mm, at a current of 1 A; contact resistance is 10^{-6} Ohm·cm^2).

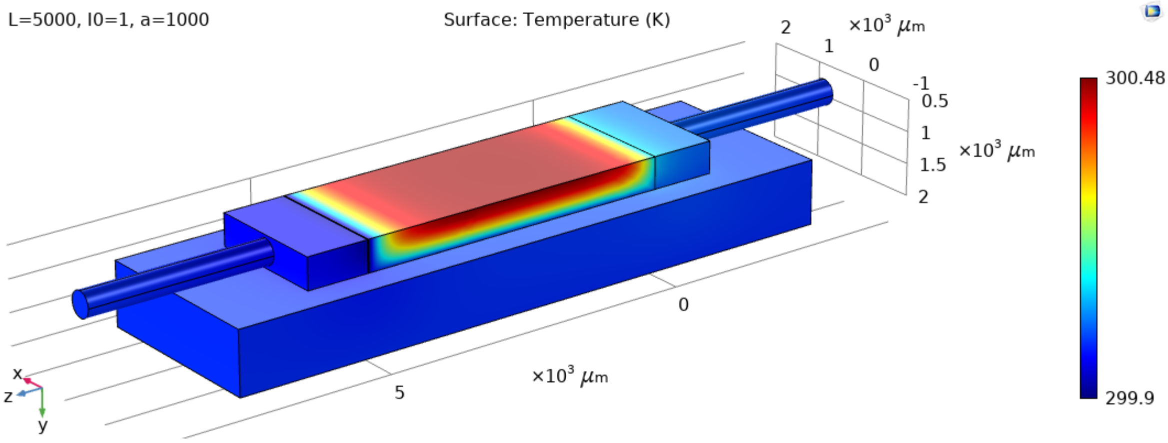


Fig. 11. Temperature distribution in the studied contact structure during thermostating of one of its surfaces (for the case of a sample with a length of 5 mm and a cross section of 0.5 mm by 2 mm, at a current of 1 A; contact resistance – 10^{-6} Ohm·cm²).

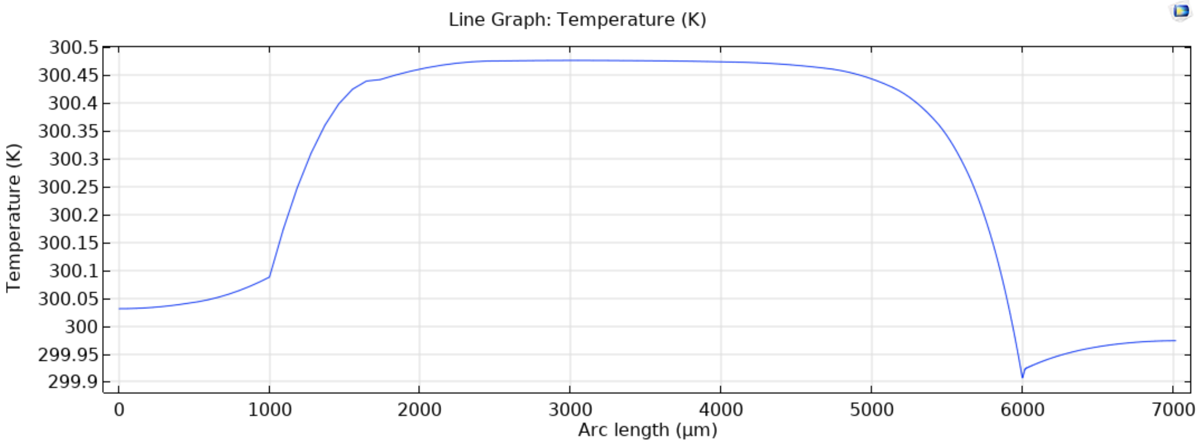


Fig. 12. Temperature distribution along the line of movement of the measuring probe on the surface of the contact structure under study during thermostating of one of its surfaces (for the case of a sample 5 mm long and 0.5 mm by 2 mm in cross-section at a current of 1 A; contact resistance is 10^{-6} Ohm·cm²).

In this case, the error in determining the contact resistance, caused by the non-isothermal nature of the measurement conditions, for a sample with a cross section of 0.5 mm by 2 mm and a length of 5 mm, will not exceed 2 %.

Conclusions

1. A computer model has been created to study possible errors in measuring the electrical contact resistance of "metal – thermoelectric material" using the probe method. By means of computer simulation, the distributions of electrical potential and temperature in the physical model under study have been obtained for different sample geometries, current values through the sample, and electrical contact resistance.
2. It has been established that deviations from isothermal conditions in the sample, caused by the influence of the Joule and Peltier effects, can lead to very significant (over 100 %) measurement errors, caused by the fact that the thermoEMF will be added to the measured ohmic voltage drop, and the values of the thermoEMF and the ohmic voltage drop on the sample will be commensurate.

3. It is shown that thermostating one side of the sample allows reducing measurement errors to 8 % for samples with a square cross-section and to 2 % for samples with a rectangular cross-section of a similar area, located with the wider side on the thermostat (with a contact resistance of 10^{-6} Ohm·cm^2).

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Анатичук Л.І., *акад. НАН України* [1,2]
Лисько В.В., *канд. фіз.-мат. наук* [1,2]
Струсовський К.І. [2]

[1] Інститут термоелектрики НАН та МОН України,
вул. Науки, 1, Чернівці, 58029, Україна;
[2] Чернівецький національний університет імені Юрія Федьковича,
вул. Коцюбинського 2, Чернівці, 58012, Україна, *e-mail: anatych@gmail.com*

КОМП'ЮТЕРНІ ДОСЛІДЖЕННЯ ТОЧНОСТІ ЗОНДОВОГО МЕТОДУ ВИМІРЮВАННЯ ЕЛЕКТРИЧНОГО КОНТАКТНОГО ОПОРУ «МЕТАЛ – ТЕРМОЕЛЕКТРИЧНИЙ МАТЕРІАЛ»

Створено фізичну та комп'ютерну моделі для дослідження можливих похибок вимірювань електричного контактного опору «метал – термоелектричний матеріал» зондовим методом. Шляхом комп'ютерного моделювання отримано розподіли електричного потенціалу та температури у досліджуваній фізичні моделі для різної геометрії зразків, величини струму через зразок та контактного електричного опору. Встановлено, що відхилення від ізотермічних умов у зразку, викликані впливом ефектів Джоуля та Пельтьє, можуть призводити до дуже значних (понад 100%) похибок при вимірюваннях. Розглянуто можливості мінімізації цих похибок за допомогою термостатування однієї зі сторін зразка. Бібл. 12, рис. 14.

Ключові слова: електричний контактний опір, вимірювання, комп'ютерне моделювання, точність, термоелектричні перетворювачі енергії.

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