DOI: 10.63527/1607-8829-2024-1-2-34-45

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

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

MEASUREMENT OF ELECTRICAL CONTACT RESISTANCE OF THE "METAL – THERMOELECTRIC MATERIAL" STRUCTURE USING THE PELTIER EFFECT

The paper describes a method for determining the contact resistance of a "metal – thermoelectric material" using compensation for the cooling action of the Peltier effect, which occurs when a direct electric current passes through the contact of two dissimilar materials, by Joule heat released at the contact resistance. A physical model of such a process and the results of computer simulation are presented, confirming the possibility of its implementation in practice. 30 sources, 9 figures.

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

Introduction

The development of methods and equipment for analyzing the quality of contact structures in thermoelectric energy converters is a task both crucial and topical. This is stipulated by the need to reduce the size of thermoelectric energy converters, significantly reducing thus their cost and providing for their availability for wide practical application. The main obstacles here are certainly the large values of contact resistances, since their impact on the efficiency of thermoelectric energy converters increases with a decrease in the height of the thermoelement legs of the module [1 – 14].

To develop technologies for manufacturing contact structures with optimal contact resistance values, it is necessary to conduct a number of experimental studies, which are possible only with the availability of accurate methods and modern equipment for measuring contact resistances. At the same time, as the analysis of the literature [15, 16] shows, such equipment has not yet been created. The developed methods for measuring electrical contact resistance in thermoelectrics can be divided into those based on measuring the characteristics of "bundled" contact structures, those being a number of serially connected thermocouples with contact resistances; probe and microelectronic methods that require the manufacture of test structures.

In particular, in [17] the probe method for measuring electrical contact resistance "metal – thermoelectric material" is considered and the results of the analysis of possible measurement errors and computer optimization of this method to achieve their minimum values are presented.

One of the promising attempts of determining the contact resistance of a "metal – thermoelectric material" is to use the Peltier effect, occuring as a direct electric current passes through the contact of two dissimilar materials. Depending on the direction of the current, the contact is either cooled or heated.

The change in the contact temperature depends on the ratio of Peltier heat and Joule heat and is determined by the magnitude of the amplitude of the current that has passed through the contact. For thermoelectric materials with high values of the thermoelectric EMF coefficient, the cooling impact of the Peltier effect at low currents will prevail over Joule heat. However, as the current increases, due to the quadratic dependence of Joule heat on the current value and the linear dependence of Peltier heat on it, at a certain current value these heats will be equal. Then the value of the contact resistance can be found from the heat balance equation. The thermoelectric EMF that occurs in the sample after the passage of a current pulse can serve as an indicator of the change in the contact temperature (Fig. 1). Curves I_1, I_2 in Fig. 1 correspond to the case when Peltier heat prevails over Joule heat, whereas curves I_1, I_2 – to cases when Joule heat prevails, and curve I_3 to cases when these heats are approximately equal.

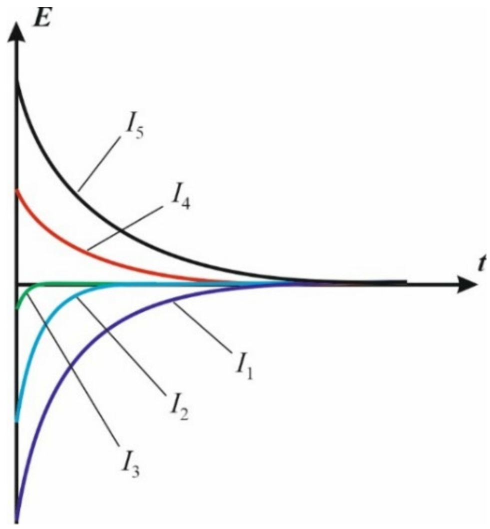


Fig. 1. Typical appearance of thermoEMF pulses for different values of current amplitude through the contact under study.

The possibility of implementing this method is influenced by various factors, such as Joule heat generated in the sample volume, heat exchange with the surrounding environment, etc.

Therefore, *the goal of this work* was to analyze the possibilities of determining the contact resistance of a "metal – thermoelectric material" using compensation for the cooling impact of the Peltier effect by Joule heat released at the contact resistance, through a detailed analysis of its physical model of such a process and computer simulation.

For this purpose, an approach was used that consists in analyzing a detailed physical model of the measurement process and computer modeling of the distributions of physical fields in the studied samples and structural elements of the measuring device. This approach was previously successfully applied at the Institute of Thermoelectricity (Ukraine) to create high-precision equipment for measuring thermoelectric parameters of materials [18 – 27].

1. Description of the measurement process and its physical model

The physical model of the process of measuring electrical contact resistance using the Peltier effect is shown in Fig. 2. It contains two samples of dissimilar materials, between which there is a transitional contact layer, an adjustable source of current pulses, current leads, an oscilloscope for recording the thermoEMF that occurs in the sample after the passage of a current pulse, and potential probes.

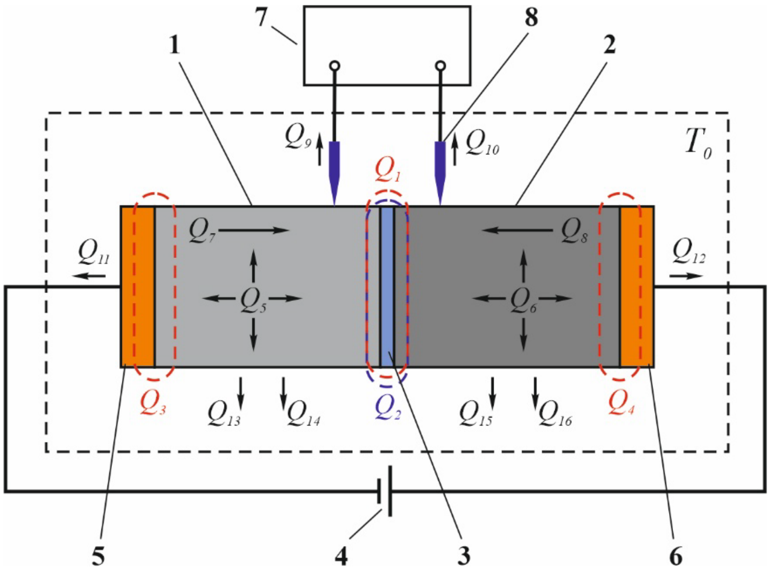


Fig. 2. Physical model of the process of measuring electrical contact resistance using the Peltier effect: 1, 2 – samples of dissimilar materials under study; 3 – transition contact layer; 4 – adjustable source of current pulses; 5, 6 – metal contact plates; 7 – oscillograph; 8 – potential probes.

Fig. 2 also shows the heat flows Q_i, occurring in the structure under study: Q_1 is Joule heat released at the contact resistance between the samples under study; Q_2 is Peltier heat absorbed at the contact between the samples; Q_3, Q_4 is Peltier heat released at the contacts of the samples with the current leads; Q_5,Q_6 is Joule heat released in the volume of the samples; Q_7,Q_8 are heat flows by thermal conductivity in the samples; Q_9 to Q_{12} are heat flows from the contact structure under study to the environment through current conductors and potential probes; Q_{13}, Q_{15} are heat flows from the contact structure under study to the environment by convection; Q_{14}, Q_{16} are heat flows from the contact structure under study to the environment by radiation.

According to the idea of the measurement method, the value of the contact resistance is found from the balance of Peltier and Joule heats at the contact.

$$Q_1 = Q_2 \tag{1}$$

or

$$I_0^2 R_{cont.} = (\alpha_1 - \alpha_2) I_0 T\,, \tag{2}$$

where I_0 is the current at which the cooling impact of the Peltier effect is compensated by Joule heat (i.e. at zero thermoEMF after passing a current pulse); $R_{cont.}$ is the contact resistance; α_1, α_2 are the thermoEMF coefficients of the sample material (determined separately).

Accordingly, the specific contact resistance $\rho_{cont.}$ can be determined by the formula

$$\rho_{cont.} = \frac{(\alpha_1 - \alpha_2) T}{I_0} S\,, \tag{3}$$

where S is the contact area.

To analyze the influence of heat fluxes Q_i on the possibility of applying formula (3), a computer simulation of the measurement process was carried out, which corresponds to the physical model shown in Fig. 2.

2. Computer model

The temperature distributions *T(x,y,z,t)* and electric potential φ*(x,y,z,t)* in the structure under study can be obtained based on the laws of conservation of electric charge and energy.

To do this, it is necessary to solve a system of differential equations with the corresponding boundary conditions, for each element of the physical model shown in Fig. 2, written in the form

$$\begin{cases} \rho C\dfrac{\partial T}{\partial t}-\nabla\left(\left(\kappa+\alpha^2\sigma T+\alpha\varphi\sigma\right)\nabla T\right)-\nabla\left(\left(\alpha\sigma T+\varphi\sigma\right)\nabla\varphi\right)=0, \\ \nabla\left(\varepsilon\nabla\dfrac{\partial\varphi}{\partial t}\right)-\nabla\left(\sigma\nabla\varphi\right)-\nabla\left(\sigma\alpha\nabla T\right)=0. \end{cases}, \tag{4}$$

where α is the thermoelectric power coefficient, σ is the electrical conductivity, κ is the thermal conductivity, ρ is the density, *C* is the heat capacity, ε is the dielectric constant.

The computer model was built using the COMSOL Multiphysics application package [28], which uses the finite element method for calculations [29, 30]. The boundary conditions for such a model are:

– the side surfaces of the samples, contact plates, current leads and potential probes are electrically insulated

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

– a rectangular current pulse $I(t)$ flows through the power supply lines

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

– the ends of the power cables are maintained at an ambient temperature of T_0

$$T=T_0\ ;$$

– the lateral surfaces of the samples, contact plates, current leads and potential probes are in a state of heat exchange with the environment

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

where h is the heat transfer coefficient.

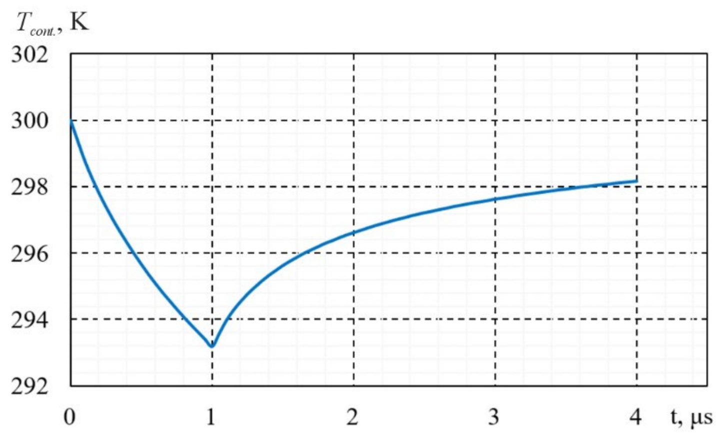
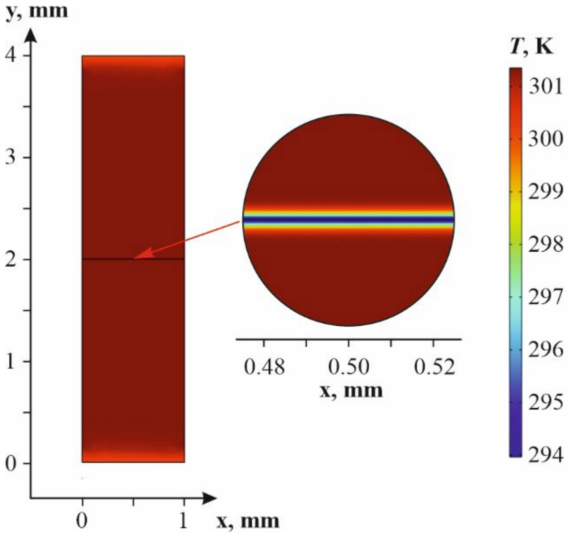
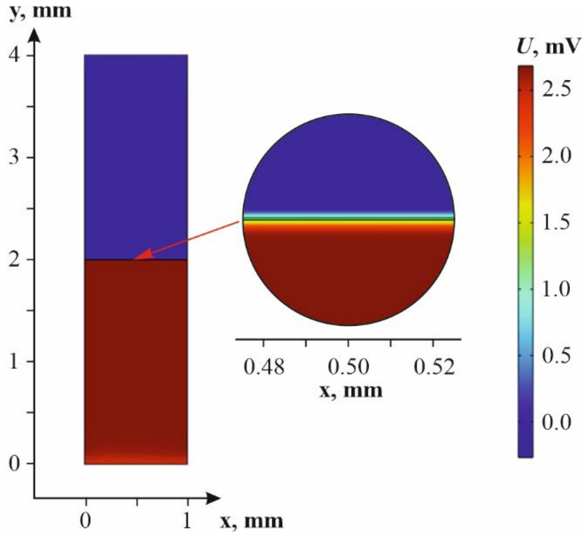


Fig. 3. Example of the time dependence of the temperature at the point of contact of two samples of Bi-Te based thermoelectric material of different types of conductivity when passing a rectangular current pulse through it.

As an example, Fig. 3, 4 show the results of computer calculations of the time dependences of temperature and electric potential in the studied contact structure in the case of contact between two samples of Bi-Te based thermoelectric material of different conductivity types (α_1 = 200 μV/K; α_2 = – 200 μV/K; $\kappa_1 = \kappa_2$ = 2 W/(m^2·K); $\sigma_1 = \sigma_2$ = 1000 $\Omega^{-1}\cdot$cm^{-1}) with a length of 2 mm and a cross-sectional area of 1x1 mm^2. The ambient temperature is T_0 = 300 K, the contact resistance is $1\cdot10^{-6}$ $\Omega\cdot$cm^2, the amplitude of the rectangular current pulse is 400 A, and its duration is $1\cdot10^{-6}$ s.



a)



b)

Fig. 4. Typical view of temperature distributions (a) and electric potential (b) in two contacting samples of Bi-Te based thermoelectric material of different conductivity types when a rectangular current pulse is passed through them.

3. Computer simulation results

To analyze the possibilities of determining the contact resistance of the "metal – thermoelectric material" using the Peltier effect, the case of contact between a sample of a *Bi-Te* based thermoelectric material (α = 200 μV/K; σ = 1000 $\Omega^{-1}\cdot$cm^{-1}; κ = 2 W/(m^2·K)) and a nickel sample was considered. The length of the samples is 2 mm, the cross-sectional area is 1x1 mm^2. The ambient temperature is T_0 = 300 K.

Fig. 5 shows the time dependences of the thermoEMF for different values of the amplitude of current pulses through the studied contact with the value of the electrical contact resistance of $5\cdot10^{-6}$ $\Omega\cdot$cm^2; the duration of the current pulses is 1·μs.

From the figure it is clear that Peltier heat absorbed at the contact of the two samples is completely compensated for by the Joule heat released at the contact resistance, at a current pulse with an amplitude of 120 A, which corresponds to the specified value of the contact resistance.

Fig. 6 shows similar time dependences of thermoEMF for the case of a contact electrical resistance of $1\cdot10^{-6}$ Ohm·cm^2. The duration of the current pulses is 1·μs, the amplitude of the current pulse, at which neither heating nor cooling of the contact is observed, is 1200 A.

As can be seen from the comparison of the dependences shown in Fig. 5 and 6, the value of the thermoEMF signals after the passage of current pulses increased, and, therefore, the sensitivity of the measurements increases with a decrease in the contact resistance, in contrast to the probe method of measuring the contact resistance.

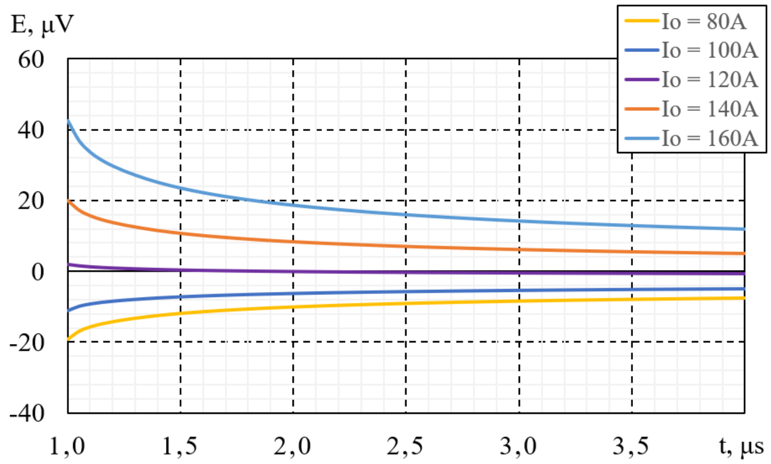


Fig. 5. Time dependences of thermoEMF for different values of the amplitude of current pulses through the studied contact "Bi-Te – Ni based material" (contact resistance value $5 \cdot 10^{-6}$ Ohm·cm², pulse duration 1·μs).

A further decrease in contact resistance requires greater amplitude of current pulses. This leads to significant heating of the samples by Joule heat released in their volume and an increase in the influence of this heat on the temperature in the contact area of the samples. This problem is solved by reducing the duration of the current pulse.

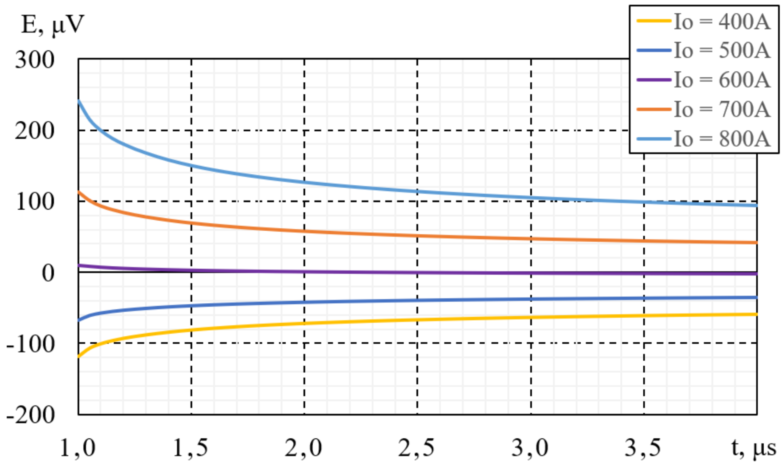


Fig. 6. Time dependences of thermoEMF for different values of the amplitude of current pulses through the studied contact "Bi-Te – Ni based material" (contact resistance value $1 \cdot 10^{-6}$ Ohm·cm², pulse duration 1·μs).

Fig. 7 – 9 shows the time dependences of thermoEMF for contact resistances of $5 \cdot 10^{-7}$ $\Omega \cdot cm^2$, $1 \cdot 10^{-7}$ $\Omega \cdot cm^2$ and $5 \cdot 10^{-8}$ $\Omega \cdot cm^2$, respectively (current pulse durations are 0.2, 0.1 and 0.05 μs).

The values of the current amplitude determined in this way, at which Peltier heat is compensated by Joule heat released at the contact resistance, are within 10% of those corresponding to the contact resistance values specified in the model.

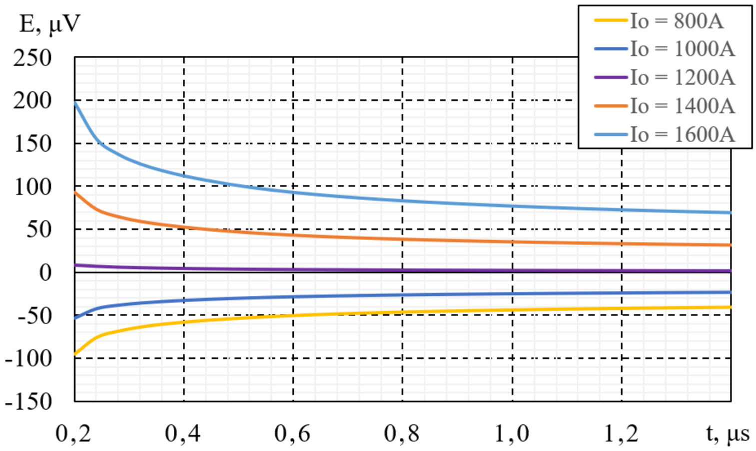


Fig. 7. Time dependences of thermoEMF for different values of the amplitude of current pulses through the studied contact “Bi-Te – Ni based material” (contact resistance value $5\cdot10^{-7}$ Ohm·cm^2, pulse duration 0.2·μs).

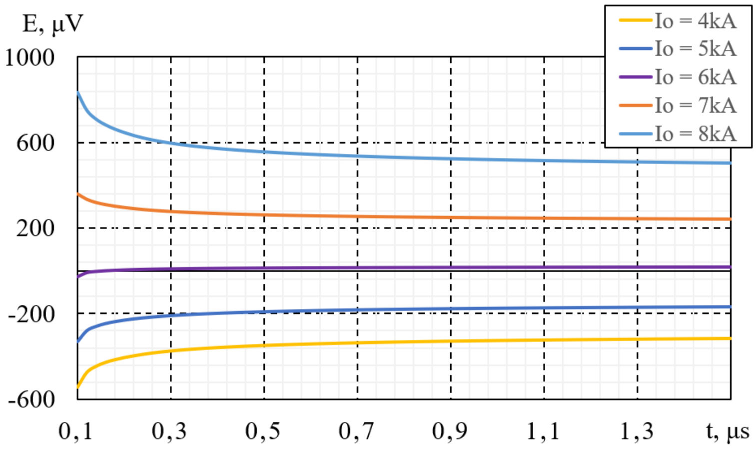


Fig. 8. Time dependences of thermoEMF for different values of the amplitude of current pulses through the studied contact “Bi-Te – Ni based material” (contact resistance value $1\cdot10^{-7}$ Ohm·cm^2, pulse duration 0.1·μs).

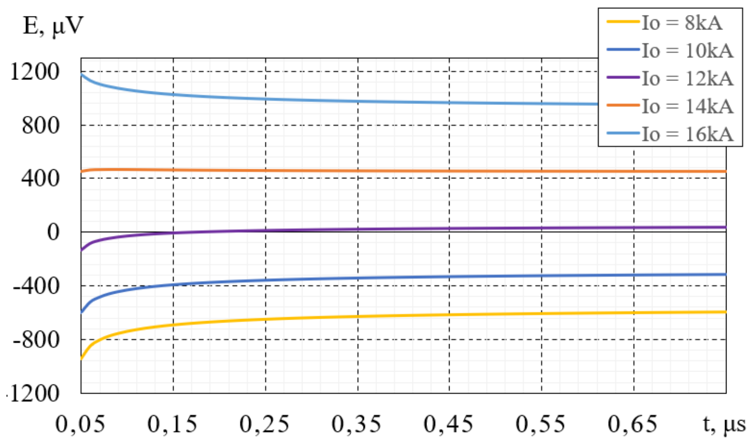


Fig. 9. Time dependences of thermoEMF for different values of the amplitude of current pulses through the studied contact “Bi-Te – Ni based material” (contact resistance value $5\cdot10^{-8}$ Ohm·cm^2, pulse duration 0.05·μs).

The obtained computer simulation results confirm the possibility of measuring electrical contact resistance using the Peltier effect and are the basis for elaborating appropriate measuring equipment.

Conclusions

1. A detailed physical model of the process of measuring the electrical contact resistance "metal – thermoelectric material" was built using compensation of the cooling impact of the Peltier effect, which occurs when a direct electric current passes through the contact of two dissimilar materials, by the Joule heat released at the contact resistance. A computer model was developed on its basis.
2. Using computer modeling, the time dependences of the thermoEMF that occurs after the passage of a current pulse through the contact "*Bi-Te*- nickel based material " were obtained for different values of the contact resistance in the range from $5\cdot10^{-6}$ $\Omega\cdot cm^2$ to $5\cdot10^{-8}$ $\Omega\cdot cm^2$, as well as the amplitude of the current pulses and their duration. The possibility of measuring electrical contact resistance using the Peltier effect was confirmed.
3. It has been established that the value of thermoEMF, and, consequently, the sensitivity of measurements increases with the decrease in contact resistance, which differs from the data obtained by the probe method of measuring contact resistance.

References

1. T. Tritt. (2000). *Recent Trends in Thermoelectric Materials Research*, Part Two (Semiconductors and Semimetals, Volume 70). Academic Press, 320 p. ISBN-13: 978-0127521794.
2. D.M. Rowe. *Thermoelectrics Handbook: Macro to Nano* (1st ed.). CRC Press, 2006. https://doi.org/10.1201/9781420038903.
3. Rowe D.M. (Ed.). (2012). Modules, Systems, and Applications in Thermoelectrics (1st ed.). CRC Press. https://doi.org/10.1201/b11892.
4. Kania T., Schilder B., Kissel T. et al. (2013). Development of a Miniaturized Energy Converter Without Moving Parts. Flow Turbulence Combust 90, 741 – 761. https://doi.org/10.1007/s10494-012-9418-8
5. C. Yuan, D. Hohlfeld, T. Bechtold. (2021). Design optimization of a miniaturized thermoelectric generator via parametric model order reduction. Microelectronics Reliability. Volume 119, 114075, ISSN 0026-2714, https://doi.org/10.1016/j.microrel.2021.114075.
6. J. Vondrak, M. Schmidt, A. Proto, M. Penhaker, J. Jargus and L. Peter. (2019). "Using Miniature Thermoelectric Generators for Wearable Energy Harvesting," 2019 4th International Conference on Smart and Sustainable Technologies (SpliTech), Split, Croatia, pp. 1 – 6, doi: 10.23919/SpliTech.2019.8782997.
7. Gustavo G. Dalkiranis, João H.C. Bocchi, Osvaldo N. Oliveira Jr., and Gregório C. Faria. (2023). *ACS Omega*, 8 (10), 9364 – 9370 DOI: 10.1021/acsomega.2c07916.
8. Li J., Ma B., Wang R., Han L. (2011). Study on a cooling system based on thermoelectric cooler for thermal management of high-power LEDs. *Microelectron. Reliab*, 51, 2210 – 2215.
9. Shen L., Chen H., Xiao F., Yang Y., Wang S. (2014). The step-change cooling performance of miniature thermoelectric module for pulse laser. *Energy Convers*. *Manag*, 80, 9 – 45.
10. Zhang W., Shen L., Yang Y., Chen H. (2015). Thermal management for a micro semiconductor laser based on thermoelectric cooling. *Appl. Therm*. Eng. 90, 664 – 673.
11. Piotrowski A., Piotrowski J., Gawron W., Pawluczyk J., Pedzinska M. (2009). Extension of usable spectral range of Peltier cooled photodetectors. *Acta Phys*. Pol. A, 116, 52 – 55.

12. L.M. Vikhor, L.I. Anatychuk, and P.V. Gorskyi (2019). Electrical resistance of metal contact to Bi_2Te_3 based thermoelectric legs. *Journal of Applied Physics*, 126, 164503-1 – 164503-8.
13. Anatychuk L.I., Vikhor L.M., Mitskaniuk N.V. (2019). Contact resistance due to potential barrier at thermoelectric material – metal boundary. *Journal of Thermoelectricity*, 4, 74 – 88.
14. Vikhor L., Kotsur M. (2023). Evaluation of Efficiency for Miniscale Thermoelectric Converter under the Influence of Electrical and Thermal Resistance of Contacts. *Energies*, 16, 4082-1 – 22. https://doi.org/10.3390/en16104082.
15. Vikhor L.M., Gorskyi P.V., Lysko V.V. (2022). Methods for measuring contact resistances of "metal – thermoelectric material" structures (part 1). *Journal of Thermoelectricity*, 2, 5 – 24.
16. Vikhor L.M., Gorskyi P.V., Lysko V.V. Methods for measuring contact resistances of "metal – thermoelectric material" structures (part 2). *Journal of Thermoelectricity*. 2022. No. 3-4. P. 5-17.
17. Anatychuk L.I., Lysko V.V., Strusovskyi K.I. Computer research on the accuracy of probe method for measuring the electrical contact resistance of "metal – thermoelectric material". *Journal of Thermoelectricity*. 2023. No. 4. P. 38-48.
18. Anatychuk L. I., Havryliuk M. V., Lysko V. V. Absolute Method for Measuring of Thermoelectric Properties of Materials. *Materials Today: Proceedings*. 2015. Vol. 2, no. 2. P. 737–743. https://doi.org/10.1016/j.matpr.2015.05.110.
19. Anatychuk L.I., Lysko V.V. On Improvement of the Accuracy and Speed in the Process of Measuring Characteristics of Thermoelectric Materials. *Journal of Electronic Materials*. 2014. Vol. 43, No. 10. P. 3863–3869. https://doi.org/10.1007/s11664-014-3300-5.
20. Anatychuk L.I., Lysko V.V. Investigation of the effect of radiation on the precision of thermal conductivity measurement by the absolute method. *Journal of Thermoelectricity*. 2012. No. 1. pp. 65–73.
21. Anatychuk L.I., Lysko V.V. Modified Harman's method. (2012) *AIP Conference Proceedings*, 1449, pp. 373 – 376. DOI: 10.1063/1.4731574.
22. Anatychuk L.I., Havrylyuk N.V., Lysko V.V. Methods and equipment for quality control of thermoelectric materials. (2012) *Journal of Electronic Materials*, 41 (6), pp. 1680 – 1685. DOI: 10.1007/s11664-012-1973-1.
23. Anatychuk L.I., Lysko V.V. Determination of the temperature dependences of thermoelectric parameters of materials used in generator thermoelectric modules with a rise in temperature difference. *Journal of Thermoelectricity*, 2021 (2), pp. 71 – 78.
24. Anatychuk L.I., Lysko V.V. Method for determining the thermoelectric parameters of materials forming part of thermoelectric cooling modules. *Journal of Thermoelectricity*, 2021 (3), pp. 71 – 82.
25. Anatychuk L.I., Kobylianskyi R.R., Konstantinovich I.A., Lys'ko V.V., Puhantseva O.V., Rozver Y., Tiumentsev V.A. Calibration bench for thermoelectric converters of heat flux. (2016) *Journal of Thermoelectricity*, (5), pp. 65 – 72.
26. Anatychuk L.I., Lysko V.V., Havryliuk M.V. Ways for quality improvement in the measurement of thermoelectric material properties by the absolute method. *Journal of Thermoelectricity*, 2018 (2), pp. 90 – 100.
27. Anatychuk L.I., Lysko V.V., Havryliuk M.V., Tiumentsev V.A. Automation and computerization of measurements of thermoelectric parameters of materials. *Journal of Thermoelectricity*, 2018 (3), pp. 80 – 88.
28. COMSOL Multiphysics, v. 6.0. www.comsol.com. COMSOL AB, Stockholm, Sweden. 2021.
29. Kenneth H. Huebner, Donald L. Dewhirst, Douglas E. Smith, Ted G. Byrom. (2001). *The Finite*

Element Method for Engineers, 4th Edition. ISBN: 978-0-471-37078-9. Wiley-Interscience. 744 p.
30. J.N. Reddy (2005). *An Introduction to the Finite Element Method*. 3rd Edition (McGraw-Hill Mechanical Engineering). 784 p.

Submitted: 20.03.2024.

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

[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

ВИМІРЮВАННЯ ЕЛЕКТРИЧНОГО КОНТАКТНОГО ОПОРУ СТРУКТУРИ «МЕТАЛ – ТЕРМОЕЛЕКТРИЧНИЙ МАТЕРІАЛ» З ВИКОРИСТАННЯМ ЕФЕКТУ ПЕЛЬТЬЄ

У роботі описано методику визначення контактного опору «метал – термоелектричний матеріал» з використанням компенсації охолоджуючої дії ефекту Пельтьє, що виникає при проходженні постійного електричного струму через контакт двох різнорідних матеріалів, теплом Джоуля, що виділяється на контактному опорі. Наведено фізичну модель такого процесу та результати комп'ютерного моделювання, що підтверджують можливість його реалізації на практиці. Бібл. 30, рис. 9.

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

Література

1. T. Tritt. *Recent Trends in Thermoelectric Materials Research*, Part Two (Semiconductors and Semimetals, Volume 70). Academic Press, 2000. 320 p. ISBN-13: 978-0127521794.
2. D.M. Rowe. *Thermoelectrics Handbook: Macro to Nano* (1st ed.). CRC Press, 2006. https://doi.org/10.1201/9781420038903.
3. Rowe, D.M. (Ed.). (2012). Modules, Systems, and Applications in Thermoelectrics (1st ed.). CRC Press. https://doi.org/10.1201/b11892.
4. Kania, T., Schilder, B., Kissel, T. et al. Development of a Miniaturized Energy Converter Without Moving Parts. Flow Turbulence Combust 90, 741–761 (2013). https://doi.org/10.1007/s10494-012-9418-8
5. C. Yuan, D. Hohlfeld, T. Bechtold. (2021). Design optimization of a miniaturized thermoelectric generator via parametric model order reduction. Microelectronics Reliability. Volume 119, 114075, ISSN 0026-2714, https://doi.org/10.1016/j.microrel.2021.114075.
6. J. Vondrak, M. Schmidt, A. Proto, M. Penhaker, J. Jargus and L. Peter, "Using Miniature Thermoelectric Generators for Wearable Energy Harvesting," 2019 4th International Conference on Smart and Sustainable Technologies (SpliTech), Split, Croatia, 2019, pp. 1-6, doi: 10.23919/SpliTech.2019.8782997.

7. Gustavo G. Dalkiranis, João H. C. Bocchi, Osvaldo N. Oliveira Jr., and Gregório C. Faria ACS Omega 2023 8 (10), 9364 – 9370 DOI: 10.1021/acsomega.2c07916.
8. Li J., Ma B., Wang R., Han L. (2011). Study on a cooling system based on thermoelectric cooler for thermal management of high-power LEDs. Microelectron. Reliab. 51, 2210 – 2215.
9. Shen, L.; Chen, H.; Xiao, F.; Yang, Y.; Wang, S. The step-change cooling performance of miniature thermoelectric module for pulse laser. Energy Convers. Manag. 2014, 80, 9–45.
10. Zhang, W.; Shen, L.; Yang, Y.; Chen, H. Thermal management for a micro semiconductor laser based on thermoelectric cooling. Appl. Therm. Eng. 2015, 90, 664–673.
11. Piotrowski, A.; Piotrowski, J.; Gawron, W.; Pawluczyk, J.; Pedzinska, M. Extension of usable spectral range of Peltier cooled photodetectors. Acta Phys. Pol. A 2009, 116, s52–s55.
12. L.M. Vikhor, L.I. Anatychuk, and P.V. Gorskyi. Electrical resistance of metal contact to Bi_2Te_3 based thermoelectric legs. *Journal of Applied Physics*, 2019, V.126, p.164503-1 – 164503-8.
13. Anatychuk L.I., Vikhor L.M., Mitskaniuk N.V. Contact resistance due to potential barrier at thermoelectric material–metal boundary. *Journal of Thermoelectricity*, 2019, №4, p. 74-88.
14. Vikhor, L.; Kotsur, M. Evaluation of Efficiency for Miniscale Thermoelectric Converter under the Influence of Electrical and Thermal Resistance of Contacts. *Energies*, 2023, 16, 4082-1 - 22. https://doi.org/10.3390/en16104082.
15. Vikhor L.M., Gorskyi P.V., Lysko V.V. Methods for measuring contact resistances of "metal – thermoelectric material" structures (part 1). *Journal of Thermoelectricity*. 2022. No. 2. P. 5-24.
16. Vikhor L.M., Gorskyi P.V., Lysko V.V. Methods for measuring contact resistances of "metal – thermoelectric material" structures (part 2). *Journal of Thermoelectricity*. 2022. No. 3-4. P. 5-17.
17. Anatychuk L.I., Lysko V.V., Strusovskyi K.I. Computer research on the accuracy of probe method for measuring the electrical contact resistance of "metal – thermoelectric material". *Journal of Thermoelectricity*. 2023. No. 4. P. 38-48.
18. Anatychuk L. I., Havryliuk M. V., Lysko V. V. Absolute Method for Measuring of Thermoelectric Properties of Materials. *Materials Today: Proceedings*. 2015. Vol. 2, no. 2. P. 737–743. https://doi.org/10.1016/j.matpr.2015.05.110.
19. Anatychuk L.I., Lysko V.V. On Improvement of the Accuracy and Speed in the Process of Measuring Characteristics of Thermoelectric Materials. *Journal of Electronic Materials*. 2014. Vol. 43, No. 10. P. 3863–3869. https://doi.org/10.1007/s11664-014-3300-5.
20. Anatychuk L.I., Lysko V.V. Investigation of the effect of radiation on the precision of thermal conductivity measurement by the absolute method. *Journal of Thermoelectricity*. 2012. No. 1. P. 65–73.
21. Anatychuk L.I., Lysko V.V. Modified Harman's method. (2012) AIP Conference Proceedings, 1449, pp. 373 – 376. DOI: 10.1063/1.4731574.
22. Anatychuk L.I., Havrylyuk N.V., Lysko V.V. Methods and equipment for quality control of thermoelectric materials. (2012) Journal of Electronic Materials, 41 (6), pp. 1680 – 1685. DOI: 10.1007/s11664-012-1973-1.
23. Anatychuk L.I., Lysko V.V. Determination of the temperature dependences of thermoelectric parameters of materials used in generator thermoelectric modules with a rise in temperature difference. Journal of Thermoelectricity, 2021 (2), pp. 71 – 78.
24. Anatychuk L.I., Lysko V.V. Method for determining the thermoelectric parameters of materials forming part of thermoelectric cooling modules. Journal of Thermoelectricity, 2021 (3), pp. 71 – 82.
25. Anatychuk L.I., Kobylianskyi R.R., Konstantinovich I.A., Lys'ko V.V., Puhantseva O.V., Rozver

Y., Tiumentsev V.A. Calibration bench for thermoelectric converters of heat flux. (2016) Journal of Thermoelectricity, (5), pp. 65 – 72.

26. Anatychuk L.I., Lysko V.V., Havryliuk M.V. Ways for quality improvement in the measurement of thermoelectric material properties by the absolute method. Journal of Thermoelectricity, 2018 (2), pp. 90 – 100.
27. Anatychuk L.I., Lysko V.V., Havryliuk M.V., Tiumentsev V.A. Automation and computerization of measurements of thermoelectric parameters of materials. Journal of Thermoelectricity, 2018 (3), pp. 80 – 88.
28. COMSOL Multiphysics, v. 6.0. www.comsol.com. COMSOL AB, Stockholm, Sweden. 2021.
29. Kenneth H. Huebner, Donald L. Dewhirst, Douglas E. Smith, Ted G. Byrom. (2001). *The Finite Element Method for Engineers*, 4th Edition. ISBN: 978-0-471-37078-9. Wiley-Interscience. 744 p.
30. J. N. Reddy (2005). *An Introduction to the Finite Element Method*. 3rd Edition (McGraw-Hill Mechanical Engineering). 784 p.

Надійшла до редакції: 20.03.2024.