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ON ENERGY OPPORTUNITIES IN ANISOTROPIC BIPOLAR ELECTRICALLY CONDUCTIVE MEDIA

A study was made of the features of electric current transformation by an anisotropic electrically conductive medium characterized by different types of conductivity (p- and n-types) in selected crystallographic directions under ohmic contact conditions. It has been established that in the case of an external sinusoidal electric current flowing through a device based on a rectangular plate of the above mentioned anisotropic material, electric current vortices occur in its bulk. Based on the analysis of the function m (K, α) (case | m |> 1), which determines the transformation coefficient of the device, a conclusion is made about the energy interaction between the bulk of the anisotropic plate and the external medium.. Studies have shown that the use of anisotropic electrically conductive bipolar material leads to a significant higher (m> 1) or lower (m <-1) value of the transformation coefficient m than in the case of unipolar anisotropic electrically conductive materialss. The phenomenon of electroohmic transformation is caused by the appearance of electric field vortices which are characterized by turbulent flow represented by the expression $\mathrm{rot}\ j = \pm\omega$, *, where ω is a circular frequency of vortex rotation, and signs «+» and «–» denote the direction of its rotation and are determined by the value of the anisotropy coefficient K=σ11/σ22. Such electric vortices with a turbulent flow are an efficient mechanism of pumping energy between the external medium and, in our case, the anisotropic plate of the device. It should be noted that in some cases there is an anomalous value of the abovementioned coefficient. The application of the considered method of electric current transformation with the help of the proposed devices, which are based on a plate made of anisotropic electrically conductive material, significantly expands the field of alternative electricity and other related fields of science and technology. Bibl.14, Fig. 7.*

Key words: *anisotropic medium; electrical conductivity; transformation; electric current; efficiency; heating; cooling; generation.*

Introduction

In [1], for the first time, the possibility of the transformation effect in anisotropic electrically conductive unipolar media was shown. In this case, the device called anisotropic electroohmic transformer is a rectangular plate of length *a*, height *b* and width *c*, made of anisotropic single-crystal or layered electrically conductive materials, characterized by linear volt-ampere characteristicss. The selected crystallographic axes of anisotropic material 1 and 2, having the values of electrical conductivity σ_{11} and σ_{22}, which are unipolar in sign, are located in the plane of lateral faces $a \times b$ of the plate, one of them being oriented at an angle α. On the end faces $b \times c$ and the upper and lower face $a \times c$ of this plate are the input and output electrical wires, respectively.

In the case of sinusoidal alternating electric current flowing through the end contacts 4 and 5 of the electric current J_{in}, the electric current J_{out} flows through the output contacts 6, 7, and the transformation coefficient *m* of such a device (Fig. 1) is represented by the following expression

$$J_{out} / J_{in} = m = p \cdot f \tag{1}$$

where *p* is transformation coefficient of plate material, $f = a / b$ is its form factor.

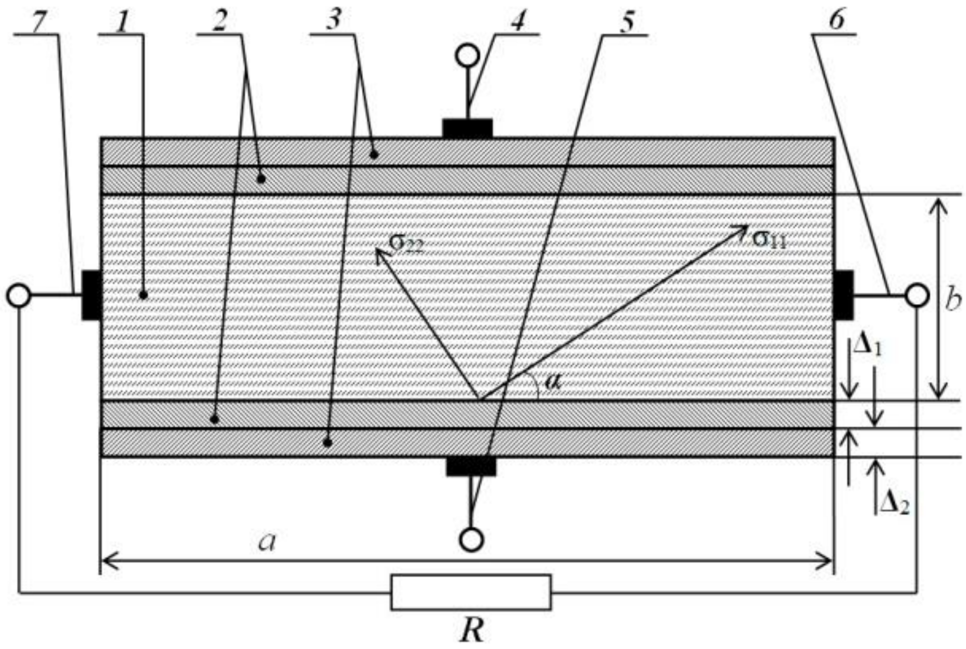


Fig. 1. Schematic of anisotropic transformer design
1 – Plate of anisotropic electrically conductive material; 2 – electrical insulating layers; 3 – electrically conductive layers; 4, 5 – input electrical wires; 6, 7 – output electrical wires.

In so doing, the optimal value of slope angle *α* is found from the relationship

$$\alpha = arctg\sqrt{K} \tag{2}$$

where $K = \sigma_{11} / \sigma_{22}$ is anisotropy coefficient of plate material.

Since in the case under study the condition $\frac{\partial E_{11}}{\partial x} \neq \frac{\partial E_{22}}{\partial y}$ is satisfied, an eddy electric current arises in the bulk of this anisotropic plate, which is characterized by a laminar flow [2].

The studies have shown that in the case under study the value of transformation coefficient does not exceed 1 ($m \leq 1$) for the cases of both $0 < K < 1$ and $1 < K < \infty$. In the case of $K = 1, n = 0$.

The method of transformation considered in [1, 3] is significantly different from the existing ones and has a number of relevant advantages and disadvantages.

Presentaton of the main material and analysis of the results

The situation will change if we move to an anisotropic electrically conductive medium characterized by different types of conductivity (*p*- and *n*-types) in the 1st and 2nd selected crystallographic directions (Fig. 2), while the contact between all layers is ohmic [4].

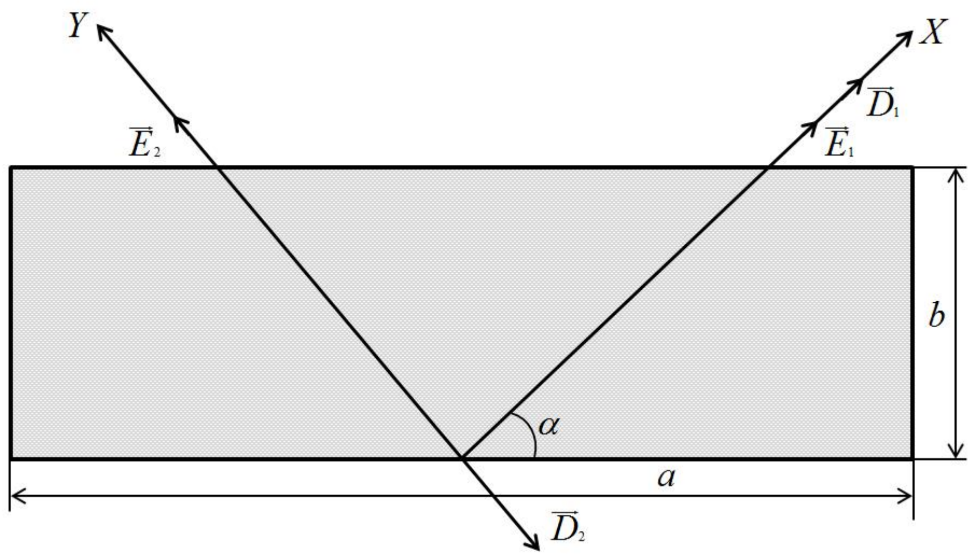


Fig. 2. Orientation of the OX, OY and OZ crystallographic axes of anisotropic electrically conductive plate and location of electric field vectors $\vec{E}_1$, $\vec{E}_2$, and induction vectors $\vec{D}_1$, $\vec{D}_2$

The electrical conductivity tensor of such a single-crystal or artificial anisotropic medium is given by

$$\hat{\sigma} = \sigma_0 \begin{vmatrix} \sigma_{11} & 0 & 0 \\ 0 & -\sigma_{22} & 0 \\ 0 & 0 & \sigma_{33} \end{vmatrix} = \begin{vmatrix} \sigma_n & 0 & 0 \\ 0 & -\sigma_p & 0 \\ 0 & 0 & \sigma_n \end{vmatrix} \tag{3}$$

Creation from this material of a rectangular plate with dimensions $a \times b \times c$ ($a \approx c >> b$) whose main crystallographic axes OX and OY are arranged in the plane of its lateral surface $a \times b$, and one of these axes is located at an angle α to the edge a ($0 < a < 90^\circ$) (Fig. 2), allows us to represent tensor $\hat{\sigma}$ as follows [5]:

$$\hat{\sigma} = \sigma_0 \begin{vmatrix} \sigma_{11}\cos^2\alpha - \sigma_{22}\sin^2\alpha & (\sigma_{11}+\sigma_{22})\sin\alpha\cos\alpha & 0 \\ (\sigma_{11}+\sigma_{22})\sin\alpha\cos\alpha & \sigma_{11}\sin^2\alpha - \sigma_{22}\cos^2\alpha & 0 \\ 0 & 0 & \sigma_{33} \end{vmatrix} \tag{4}$$

which is characterized by the presence of both longitudinal ($\sigma_{\|}$) and transverse ($\sigma_{\perp}$) components

$$\sigma_{\|} = \sigma_0\left(\sigma_{11}\cos^2\alpha - \sigma_{22}\sin^2\alpha\right) \tag{5}$$

$$\sigma_{\perp} = \sigma_0\left(\sigma_{11} + \sigma_{22}\right)\sin\alpha\cos\alpha\,. \tag{6}$$

In so doing, the transformation coefficient m_1 of the device based on the above rectangular plate is given by

$$m_1 = \frac{\sigma_{\perp}}{\sigma_{\|}} = \frac{\left(\sigma_{11} + \sigma_{22}\right)\sin\alpha\cos\alpha}{\sigma_{11}\cos^2\alpha - \sigma_{22}\sin^2\alpha} \tag{7}$$

Numerical estimates show that under $a \approx c >> b$ the boundary conditions on the end $b\times c$ and lateral $a\times b$ faces can be ignored [2].

Investigation of function

$$m_1(K,\alpha) = \frac{(K+1)tg\alpha}{K - tg^2\alpha} \tag{8}$$

for extremum ($\partial m/\partial\alpha = 0, \partial^2 m/\partial\alpha^2 < 0$) demonstrates that function extremum points are absent.

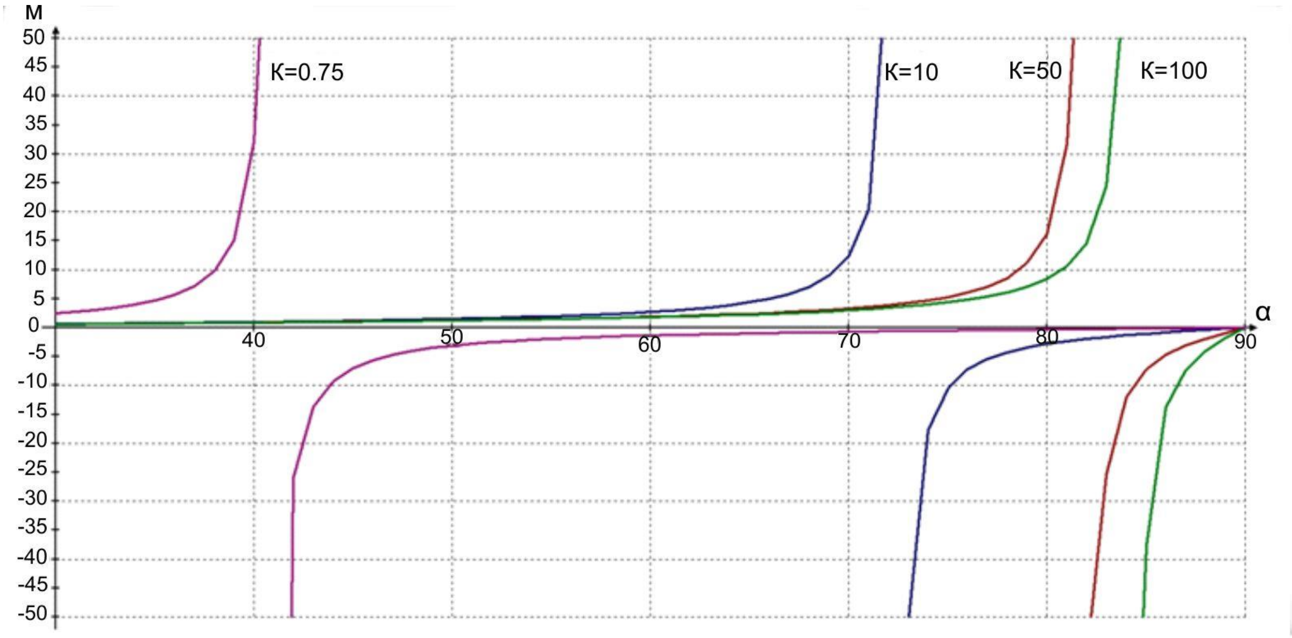


Fig. 3. Dependence of the transformation coefficient m on the angle α at fixed anisotropy coefficients of electrically conductive material K=0.75; 10; 50; 100.

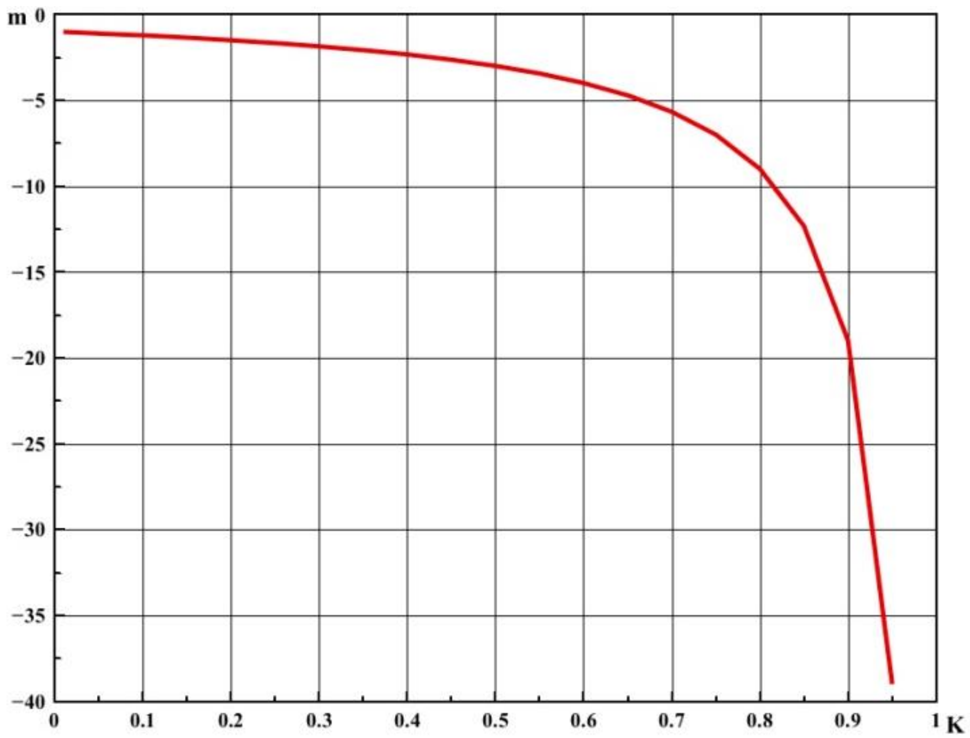
This allows one to vary the value of the coefficient *m* of this device in a wide range by selecting the appropriate angle α. This possibility is shown in Fig. 3 for four anisotropic electrically conductive bipolar materials with anisotropy coefficients 0.75, 10, 50 and 100. From this plot it follows that there is always the possibility of selecting the angle α for a given *m* with the required value and sign.

For the angle α = 45º the expression (7) acquires the following form

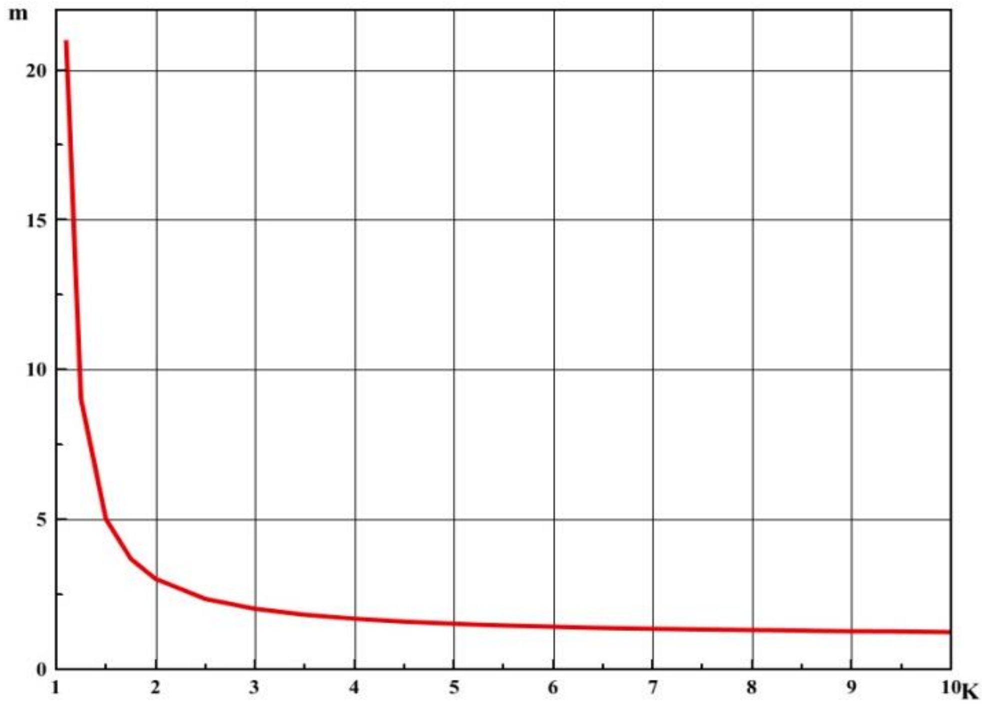
$$m=\frac{\sigma_{11}+\sigma_{22}}{\sigma_{11}-\sigma_{22}}=\frac{K+1}{K-1} \tag{9}$$

Analysis of these functions shows that the value of coefficient $|m| > 1$ allows making a conclusion on the energy interaction between the bulk of anisotropic plate 1 and the external medium. Thus, the use of anisotropic electrically conductive bipolar material leads to a much higher value of transformation coefficient *m* than in the case of unipolar anisotropic electrically conductive materials (Fig. 4.).

The explanation of this phenomenon can be presented using the concepts of vortex electrodynamics. If an external electric current of a sinusoidal shape is passed through the plate, then electric current vortices appear in its bulk, which are characterized by a turbulent flow. [6, 7] In our case, similarly to [8, 9], the change in the nature of a vortex with a laminar flow to a turbulent one is due to the reorientation of the directions of the corresponding components of the electric current and field vectors. In this case, the longitudinal component of the electric current and field vector is located parallel to the crystallographic direction of the second selected crystallographic axis. In so doing, the direction of the electric current is parallel to the direction of the electric field.



a)



b)

Fig. 4. Dependence of the transformation coefficient m on the value of anisotropy to electrically conductive material at α=45° a) Dependence of the transformation coefficient m on the anisotropy value at 0<K<1 and the angle α=45°; b) Dependence of the transformation coefficient m on the anisotropy value at 1<K<∞ and the angle α=45°.

The flow of input electric current through the end contacts J_{on} causes an electric current J_{out} to appear at the output contacts.

In this case, the vortex of electric current according to [10, 11] is as follows:

$$rot\,\vec{J} = -\omega, \qquad \text{для} \quad 0<K<1, \tag{10}$$

$$rot\,\vec{J} = \omega, \qquad \text{для} \quad 1<K<\infty \tag{11}$$

where $\omega = F(\sigma_{11}, \sigma_{22}, a, b, c, \alpha)$ is the circular frequency of rotation of the electric vortex, the signs «+» and «–» denote the direction of its rotation.

Such electric vortices are an efficient mechanism of pumping energy between the external medium and, in our case, the bulk of the anisotropic electrically conductive alternating bipolar plate.

The presented mechanism of energy interaction has a good outlook for modern science and technology.

Possible applications of the proposed method of energy conversion

In the general case, the choice of a specific design of the anisotropic device is determined by its purpose and functional features, as well as the conditions of its operation.

In all possible designs of this device the basis is a rectangular plate 1 of anisotropic material which in the selected crystallographic axes *Ox* and *Oy* is characterized by *p*- and *n*- types of conductivity, respectively. When using artificial anisotropic electrically conductive material, it will be an alternating layered structure based on the layers of electrically conductive material 1 with thickness τ_1 and electrically conductive material 2 with thickness τ_2. The method of calculating this structure and its optimization is similar to the method described in [12].

Selecting the appropriate value of the anisotropy coefficient of layers 1 and 2 of this plate, as well as its geometrical dimensions makes it possible to create the required instruments and devices with respective parameters. Consider the designs of specific devices based on the above anisotropic plates.

Anisotropic electroohmic generator (AEG)

In this case, the converter is AEG which is based on a rectangular anisotropic plate characterized by the positive value of transformation coefficient m ($1<K<\infty$) and the orientation of crystallographic axis σ_{11} at certain selected angle α.

The schematic design of such a generator is represented in Fig. 5, consisting of plate 1; electrical insulating layer 2 and electrically conductive layer 3; input electrical wires 4, 5 connected to external source of electric energy created by the master generator; output electrical wires 6, 7 to which the external load is connected, with resistance Z.

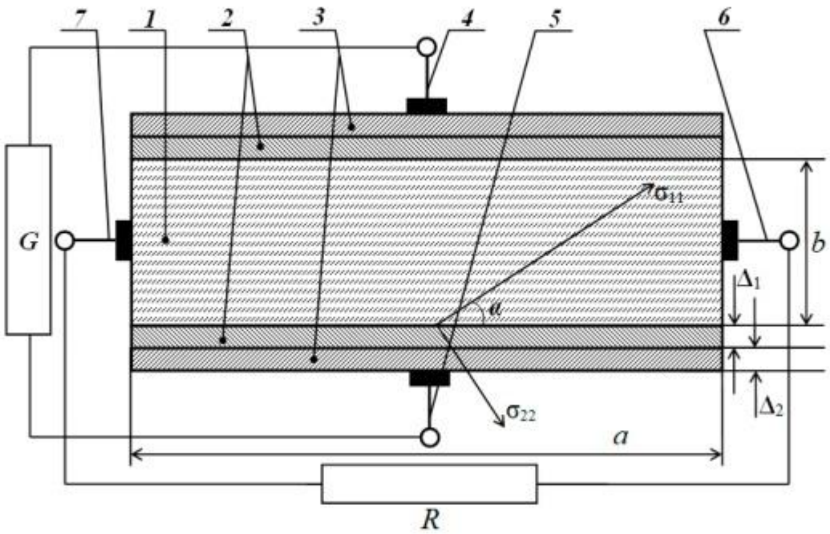


Fig. 5. Schematic of AEG design
1 – Plate of anisotropic electrically conductive material; 2 –electrical insulating layers; 3 –electrically conductive layers; 4, 5 – input electrical wires; 6, 7 – output electrical wires.

When some power $P(t)=P_0 \sin(\omega_1 t)$ is supplied in the form of a master generator to AEG input, electric vortices with turbulent flow appear in the bulk of plate 1, which then interact with the external medium. This leads to origination of energy flows directed from this medium to the bulk of the plate which is converted into electrical one. This results in the appearance on the output electrical wires 6, 7 of some electrical power P_{out} which is represented as follows:

$$P_{out} = P_0 \sin(\omega_1 t_0) \frac{(K+1) \cdot tg\alpha}{K - tg^2\alpha}, \quad (12)$$

Thus, right-hand rotation of electric vortices with turbulent flow determines the possibility of operation of the plate in the mode of electricity generationn. Here, ω_1 is the frequency of the electric vortex which is determined by the master generator.

The efficiency η_1 in this case is as follows:

$$\eta_1 = \frac{1}{1 + P_1/P_2}, \quad (13)$$

where P_1/P_2 are powers released in the bulk of both the plate and the external load of resistance Z, respectively.

Maximum value of electrical power P_{max} which can be generated by AEG is determined as follows:

$$P_{max.} = (s \cdot M \cdot \Delta T)/(P_1/P_2), \quad (14)$$

where $M = a \cdot b \cdot c \cdot d$ is the weight of the plate; d is the density of its material; s is specific heat of material; T_0 is ambient temperature; T_{max} is boundary operating temperature of plate 1 material.

Numerical estimates show that the efficiency value of the proposed device is within 0.5÷0.99

It should be noted that under certain conditions the AEG under study can also actively function in the mode of thermal power generation.

Anisotropic electroohmic heater (AEH)

A feature of this heater in comparison with the generator is the increased values of the internal resistance of the plate. The schematic design of such AEH (Fig. 6) is similar to the design of the above AEG with the difference that the resistance $R=0$.

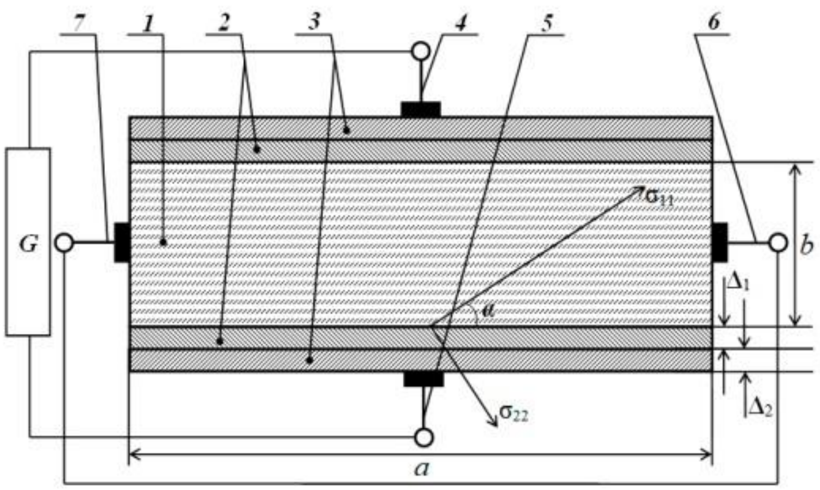


Fig. 6. Schematic of AEH design
1 – Plate of anisotropic electrically conductive material;
2 – electrical insulating layers;
3 – electrically conductive layers;
4, 5 – input electrical wires;
6, 7 – output electrical wires.

Anisotropic electroohmic cooler (AEC)

Unlike AEG and AEH, the design of AEC consists of anisotropic rectangular plate 1 and electrical wires 4, 5 (Fig. 7). The anisotropy of electrical conductivity of the materials of plate 1 is selected with the coefficient $0<K<1$.

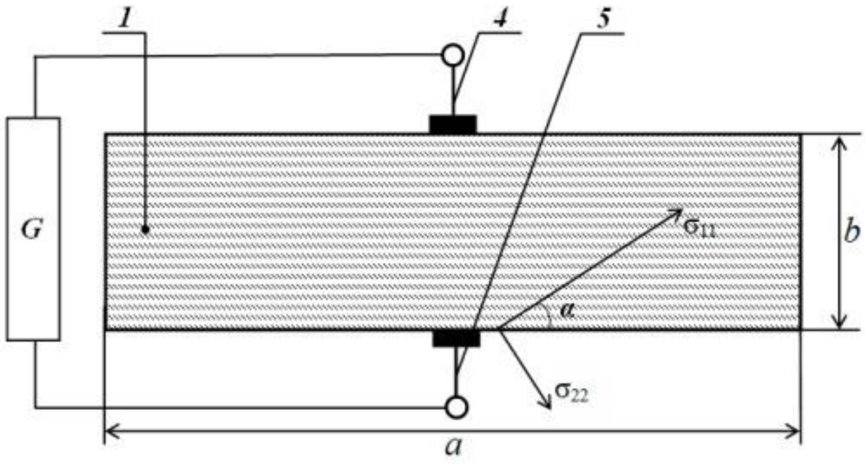


Fig.7. Schematic of AEC design
1 – Plate of anisotropic electrically conductive material;
4, 5 – input electrical wires; 6, 7 – output electrical wires.

In this case, the application to contacts 4, 5 of the generator power leads to the occurrence in its bulk of turbulent vortices of electric current with left-hand rotation. This leads to a decrease in the internal energy of the anisotropic plate, which ultimately leads to a corresponding decrease in the plate temperature *T*.

With a positive half-cycle of power supplied to the input of such a device, part of its internal energy is absorbed by the external medium through one of the lateral faces ($a \times b$), with a negative half-cycle – through the opposite lateral face ($a \times b$).

In this case, cooling capacity *Q* is determined as follows [13]:

$$Q = W_{out} \frac{(K+1)\cdot tg\alpha}{K - tg^2\alpha}, \tag{15}$$

and temperature difference ΔT between the external medium and the anisotropic device, which is achieved by the adiabatic isolation of the faces of the plate,

$$\Delta T = \left(Q - q_{los}\right)/\left(s \cdot M\right), \tag{16}$$

where q_{los} are losses due to cooling of electrically conductive and metal layers on the upper and lower faces of the converter, *s* is heat capacity, *M* is its weight.

The efficiency ϑ of the analysed cooling process is represented by the classical expression:

$$\vartheta = (T_1 - T_2)/T_1$$

where T_1 is ambient temperature, T_2 is anisotropic plate temperature which is achieved on cooling.

It should be noted that as materials for the plate it is possible to use both semiconductors with a narrow energy gap, semiconductors of *p*- and *n*- type conductivity, semimetals and metals of appropriate conductivity.

The results of the studies show the outlook for using this device as highly efficient cooling elements. This method allows for efficient utilization and accumulation of thermal energy released by specific objects, various instruments and devices, pumping it into the external medium.

Conclusions

For the first time, an original physical model is proposed for energy interaction between vortex electric field of a plate made of anisotropic electrically conductive material characterized by different types of conductivity in the selected crystallographic axes and the external medium. The analysis of this model shows that in the range $0<K<1$ the transformation coefficient m is characterized by the negative value, and in the range $1<K<\infty$ - by the positive value. In the former case, there is cooling effect, in the latter – the mode of electric energy generation and heat release.

The use of single-crystal and artificial anisotropic electrically conductive materials with different conductivity types in the selected crystallographic axes makes it possible to obtain the value of module $m > 1$ which is caused by the action of electric field vortices with a turbulent flow in the bulk of the anisotropic plate.

Promising areas of practical application of such devices in the form of generators of electricity, heat and cold are determined, calculated expressions are obtained for their efficiency, which is in the range $\eta = 0.5 \div 0.98$, and the cooling temperature of this device when using appropriate materials with the necessary temperature dependence of their kinetic coefficients can reach the temperature of liquid helium.

The proposed model will promote the emergence of new scientific and technical lines in the field of electricity and all related areas.

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ПРО ЕНЕРГЕТИЧНІ МОЖЛИВОСТІ У АНІЗОТРОПНОМУ БІПОЛЯРНОМУ ЕЛЕКТРОПРОВІДНОМУ СЕРЕДОВИЩІ

Проведено дослідження особливостей перетворення електричного струму анізотропним електропровідним середовищем яке характеризується різними типами провідності (p- та n- типи) у вибраних кристалографічних напрямках в умовах омічного контакту. Встановлено, що у випадку протікання зовнішнього електричного струму синусоїдальної форми через пристрій в основі якого є прямокутна пластина із згадуваного вище анізотропного матеріалу, в її об'ємі виникають вихори електричного струму. На основі аналізу функції m(K, α) (випадок $|m| > 1$*), що визначає коефіцієнт перетворення пристрою, зроблено висновок про енергетичну взаємодію між об'ємом анізотропної пластини і зовнішнім середовищем. Проведені дослідження показали, що використання анізотропного електропровідного біполярного матеріалу призводить до значно вищої* ($m>1$) *або нижчої* ($m<-1$) *величини коефіцієнта перетворення m ніж у випадку уніполярних анізотропних електропровідних матеріалів. До феномену електроомічного перетворення веде поява вихорів електричного поля, які характеризуються турбулентною течією, що представляються виразом* $\mathrm{rot}\ j = \pm\omega$, *де ω – кругова частота обертання вихору, а знаки «+» та «–» – позначають напрямок його обертання та визначаються величиною коефіцієнта анізотропії* $K=\sigma_{11}/\sigma_{22}$. *Такі електричні вихори з турбулентним характером течії є ефективним механізмом, що перекачує енергію між зовнішнім середовищем і в нашому випадку, анізотропною пластиною пристрою. Слід відмітити, що в окремих випадках спостерігається аномальне значення згадуваного коефіцієнта. Застосування розглянутого методу перетворення електричного струму за допомогою запропонованих пристроїв, в основі роботи яких є пластина виготовлена з анізотропного електропровідного матеріалу, значно розширює галузі альтернативної електроенергетики та інших пов'язаних з ним областей науки та техніки. Бібл. 14, рис.7.*

Ключові слова: анізотропне середовища; електропровідність; перетворення; електричний струм; коефіцієнт корисної дії; нагрів; охолодження; генерація.

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О ЭНЕРГЕТИЧЕСКИХ ВОЗМОЖНОСТЯХ В АНИЗОТРОПНЫХ БИПОЛЯРНЫХ ЭЛЕКТРОПРОВОДНЫХ СРЕДАХ

Проведено исследование особенностей преобразования электрического тока анизотропной электропроводной средой, характеризующейся разными типами проводимости (р- и n-типы) в выбранных кристаллографических направлениях в условиях омического контакта. Установлено, что в случае протекания внешнего электрического тока синусоидальной формы через устройство, в основе которого имеется прямоугольная пластина из вышеупомянутого анизотропного материала, в ее объеме возникают вихри электрического тока. На основе анализа функции m(K, α) (случай $|m| > 1$*), определяющий коэффициент преобразования устройства, сделан вывод об энергетическом взаимодействии между объемом анизотропной пластины и внешней средой. Проведенные исследования показали, что использование анизотропного электропроводного биполярного материала приводит к значительно более высокой (*$m > 1$*) или более низкой (*$m < -1$*) величине коэффициента преобразования m, чем в случае униполярных анизотропных электропроводных материалов. К феномену электрохимического превращения ведет появление вихрей электрического поля, характеризующихся турбулентным течением, представляемым выражением* $\operatorname{rot} j = \pm\omega$ *где ω – круговая частота вращения вихря, а знаки «+» и «–» – обозначают направление его вращения и определяются величиной коэффициента анизотропии K=σ11/σ22. Такие электрические вихри с турбулентным характером течения являются эффективным механизмом, перекачивающим энергию между внешней средой и в нашем случае, анизотропной пластиной устройства. Следует отметить, что в редких случаях наблюдается аномальное значение упомянутого коэффициента. Применение рассматриваемого метода преобразования электрического тока с помощью предложенных устройств, в основе работы которых пластина изготовлена из анизотропного электропроводящего материала, значительно расширяет области альтернативной электроэнергетики и другие, связанных с ней области науки и техники. Библ. 14, рис.7.*

Ключевые слова: анизотропная среда; электропроводность; превращение; электрический ток; коэффициент полезного действия; нагрев; охлаждение; генерация.

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INFLUENCE OF ELECTRICAL AND THERMAL RESISTANCES OF CONTACTS AND INTERCONNECTS ON THE COEFFICIENT OF PERFORMANCE OF THERMOELECTRIC MODULE

The paper describes a method for calculating the maximum coefficient of performance for a real model of a thermoelectric module, which takes into account the influence of the electrical resistance of contacts and interconnects and the thermal resistance of interconnect and insulating plates. The dependences of the maximum coefficient of performance of the module on the height of its legs and temperature difference are calculated. A comparative analysis of the coefficient of performance of a real module model with its "ideal" value, which does not take into account the influence of electrical and thermal resistances of contacts, interconnects and insulating plates, is carried out. Bibl. 7, Fig. 4, Tabl. 2.

Key words: thermoelectric cooling module, coefficient of performance, electrical contact resistance, thermal resistance of interconnect and insulating plates

Introduction

Thermoelectric cooling technology has been widely used in various spheres of human life for over 50 years due to its main advantages, such as the absence of harmful refrigerants, quiet operation, the ability to operate in any orientation in space, the ability to accurately maintain temperatures, long service life, etc. Thermoelectric devices are used for cooling, controlling thermal conditions and stabilizing the temperature of elements and systems of electronics and optoelectronics, such as photodetectors, IR radiation sensors [1], CCD matrices, laser diodes, integrated chips, microprocessors [2 – 10], LEDs [11, 12]. The thermoelectric cooling method is used in biological and medical equipment: in cryodestructors, cold-heat stimulators, mini thermostats for medicines, in biocalorimeters, spectrometers and bioanalyzers [13-18]. Household appliances with thermoelectric cooling modules are diverse, these are household air conditioners [19 – 21], portable household refrigerators, minibars for drinks, cooler bags for picnics [22 – 25]. Thermoelectric coolers (TECs) are used in the automotive and transport industries for cooling-heating seats [26, 27] and in air conditioners for vehicles [28].

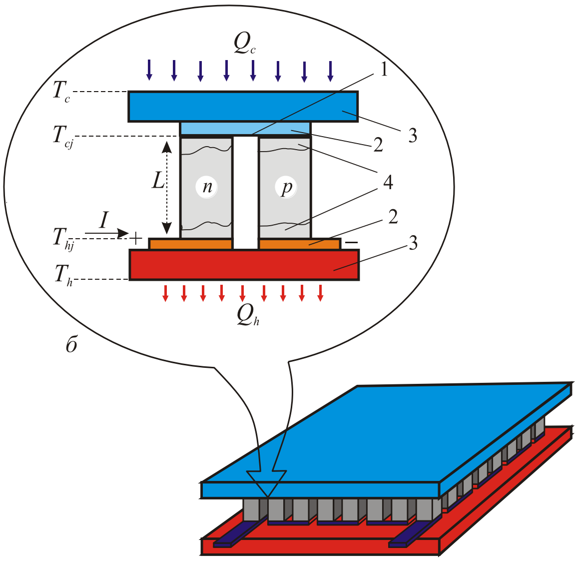
It is well known that the main disadvantage of thermoelectric coolers is the low coefficient of performance compared to mechanical cooling methods. Increasing the coefficient of performance is an urgent task [29, 30]. The coefficient of performance of a thermoelectric module as the main element of the cooler depends on the figure of merit of the materials of the thermoelement legs and the electrical and thermal resistance of the contacts, inetrconnect and insulating plates of the module. These resistances lead to electrical and thermal losses in the efficiency of thermoelectric energy conversion [31, 32]. An increase in the figure of merit of materials contributes to an increase in the coefficient of performance. However, since the 1950s, cooling modules have been manufactured from materials based on Bi_2Te_3, the dimensionless figure of merit of which remains at the level of 1 – 1.2 [30]. The search for new materials with increased figure of merit has not yet yielded tangible positive results. Electrical and thermal losses in modules reduce the coefficient of performance and are one of the main reasons why thermoelectric coolers do not fully realize the properties of materials.

The works [31, 32] describe approximate analytical methods for calculating the coefficient of performance, taking into account the electrical and thermal resistances of contacts, interconnect and insulating plates in the module. It is shown that the coefficient of performance decreases if the height of the thermoelement legs is reduced.

The purpose of this work is to theoretically establish the influence of the combined action of the contact resistance, the electrical resistance of interconnects, the thermal resistance of interconnect and insulating plates on the value of the maximum coefficient of performance of the module and to determine which of the resistances more significantly affects the coefficient of performance with a decrease in the height of thermoelement legs.

Method for calculating the maximum coefficient of performance

A model of thermoelectric module is shown in Fig. 1.



a

Fig. 1. A model of cooling module (a) and thermoelement (b). 1 – heat-absorbing thermoelement junction, 2 – interconnect plate, 3 – insulating plate, 4 – contact zone.

The module contains a number of thermoelements from semiconductor legs of n- and p-types of conductivity. Typically, the legs are connected in a series electrical circuit by metal plates and are mounted between two insulating plates in parallel with respect to the heat flow. If we pass an electrical current I, of indicated in Fig. 1*b* polarity, then heat is absorbed at the junctions of thermoelements 1, and is released at the opposite junctions. If the heat-releasing surface of the module is maintained at a temperature T_h close to the ambient temperature, the heat-absorbing surface will be cooled down to a certain temperature T_c.

The energy efficiency of the module is determined by the coefficient of performance

$$\varepsilon = \frac{Q_c}{W}, \tag{1}$$

where $W = Q_h - Q_c$ is power consumption, Q_c is cooling capacity, Q_h is heat productivity of each thermoelement in the module.

The following approximations were used to calculate and optimize the coefficient of performance:

1. In the stationary state, the temperature distribution in the legs of thermoelements is one-dimensional, i.e. $T = T(x)$, where x is the coordinate directed along the height of the leg.
2. The Seebeck coefficient $\alpha_{n,p}$, resistivity $\rho_{n,p}$ and thermal conductivity $\kappa_{n,p}$ of the materials of n- and p-type legs are temperature independent.
3. The influence of electrical contact resistance r_c, electrical resistance r_{com} of interconnects and thermal resistance R_t of interconnect and insulating plates is taken into account.

With such approximations, the cooling capacity Q_c and the heat productivity Q_h are determined from the system of heat balance equations for a thermoelement, which is given by

$$Q_c = \frac{1}{R_t}(T_c - T_{cj}), \tag{2}$$

$$Q_c = \alpha I T_{cj} - \left(\frac{1}{2}\rho\frac{L}{s} + \frac{2r_c}{s} + r_{com}\right)I^2 - \kappa\frac{s}{L}\left(T_{hj} - T_{cj}\right), \tag{3}$$

$$Q_h = \alpha I T_{hj} + \left(\frac{1}{2}\rho\frac{L}{s} + \frac{2r_c}{s} + r_{com}\right)I^2 - \kappa\frac{s}{L}\left(T_{hj} - T_{cj}\right), \tag{4}$$

$$Q_h = \frac{1}{R_t}(T_{hj} - T_h), \tag{5}$$

where $\alpha = |\alpha_n| + \alpha_p$, $\rho = \rho_n + \rho_p$, $\kappa = \kappa_n + \kappa_p$, L is the height of the leg, s is the cross-section of the leg, T_{cj} and T_{hj} are temperatures of the heat-absorbing and heat-releasing thermoelement junctions. The resistance of the interconnect plate is calculated by the formula $r_{com} = \frac{\rho_{com}}{l_{com}\sqrt{s}}\left(\frac{2}{3}\sqrt{s} + a\right)$ [33], and thermal resistance of the interconnect and insulating plates is determined as follows: $R_t = \frac{l_{com}}{\kappa_{com} s_{com}} + \frac{l_{ins}}{\kappa_{ins} s_{ins}}$, where ρ_{com} is resistivity of interconnect plate, κ_{com}, κ_{ins} is thermal conductivity of interconnect and insulating plates, respectively, l_{com}, l_{ins} is their height, $s_{com} = (2\sqrt{s} + a)\sqrt{s}$ is the area of interconnect plate, $s_{ins} = 2(\sqrt{s} + a)^2$ is the area of insulating plate, a is the distance between thermoelectric legs.

The temperatures T_{cj}, T_{hj} are found from Eqs. (2), (5) and are substituted into Eqs. (3), (4), the solution of which is the following expressions for Q_c, Q_h:

$$Q_c = \frac{Q_{c0} - \kappa \frac{s}{L} R_t Q_{ho}}{F_2}, \tag{6}$$

$$Q_h = \frac{Q_{h0} - Q_c \kappa \frac{s}{L} R_t}{F_1}, \tag{7}$$

where $F_1 = 1 - (\alpha I - \kappa \frac{s}{L}) R_t$, $F_2 = 1 + 2\kappa \frac{s}{L} R_t - (\alpha I R_t)^2$,

$$Q_{c0} = \alpha I T_c - \left(\frac{1}{2} \rho \frac{L}{s} + \frac{2r_c}{s} + r_{com} \right) I^2 - \kappa \frac{s}{L} \left(T_h - T_c \right), \tag{8}$$

$$Q_{h0} = \alpha I T_h + \left(\frac{1}{2} \rho \frac{L}{s} + \frac{2r_c}{s} + r_{com} \right) I^2 - \kappa \frac{s}{L} \left(T_h - T_c \right). \tag{9}$$

Cooling capacity Q_c and heat productivity Q_h depend on the value of current I in thermoelement legs. Computer methods are used to calculate the optimal value of current I_{opt}, whereby the maximum coefficient of performance is achieved which is found by the formula (1).

Note that for an ideal model of module in which the influence of the electrical and thermal resistances of contacts, interconnect and insulating plates is neglected, that is $r_c \to 0$, $r_{com} \to 0$, $R_t \to 0$, formulae (6), (7) for Q_c, Q_h acquire a classical form [33]

$$Q_c = \alpha I T_c - \frac{1}{2} \rho \frac{L}{s} I^2 - \kappa \frac{s}{L} \left(T_h - T_c \right),$$

$$Q_h = \alpha I T_h + \frac{1}{2} \rho \frac{L}{s} I^2 - \kappa \frac{s}{L} \left(T_h - T_c \right),$$

which makes it possible to calculate maximum coefficient of performance by the classical formula [33]

$$\varepsilon_{\max} = \frac{MT_c - T_h}{\Delta T(M+1)}, \tag{10}$$

where $\Delta T = T_h - T_c$, $M = \sqrt{1 + 0.5Z(T_h + T_c)}$, $Z = \frac{\alpha^2}{\rho\kappa}$.

Results of calculating maximum coefficient of performance and their analysis

For the theoretical study of the influence of electrical and thermal resistance of contacts, interconnect and insulating plates on the energy efficiency of thermoelectric coolers, the maximum coefficient of performance was calculated for modules made of Bi_2Te_3 based materials. The thermoelectric parameters of the materials of n- and p-type legs were considered to be the same. Calculations are made for modules with copper interconnects of legs and with insulating plates made of aluminum oxide Al_2O_3 and aluminum nitride AlN, the thermal conductivity of which is 5 times better than that of Al_2O_3.

To analyze the impact of electrical contact resistance r_c on the maximum coefficient of performance, calculations were made for two values of r_c, namely, for the value $r_c = 5\cdot10^{-6}$ Ohm·cm^2, which is considered typical for mass production modules [34], and for the minimum value $r_c = 10^{-7}$ Ohm·cm^2 of contact resistance due to the potential barrier at the boundary between the thermoelectric material and the nickel anti-diffusion layer [35].

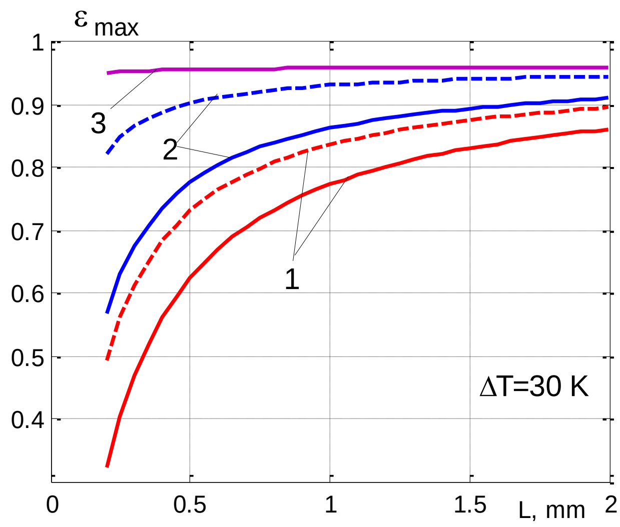
The initial data for the calculation of $\varepsilon_{\max}$ are given in Table 1.

<u>*Table 1*</u>

The values used for calculating maximum coefficient of performance

Quantity	Value
Seebeck coefficient α, μV/K	210
Resistivity ρ, Ohm·cm	10^{-3}
Thermal conductivity κ, W/cm·K	0.015
Height of legs L, cm	0.02 – 0.2
Cross-section of legs s, cm^2	0.1×0.1
Distance between legs a, cm	0.05
Height of interconnect plate l_{com}, cm	0.025
Height of insulating plate l_{ins}, cm	0.063

The dependences of $\varepsilon_{\max}$ on the height of thermoelement legs, calculated for the temperature differences on the module 30 K and 60 K, are shown in Fig. 2.



a)

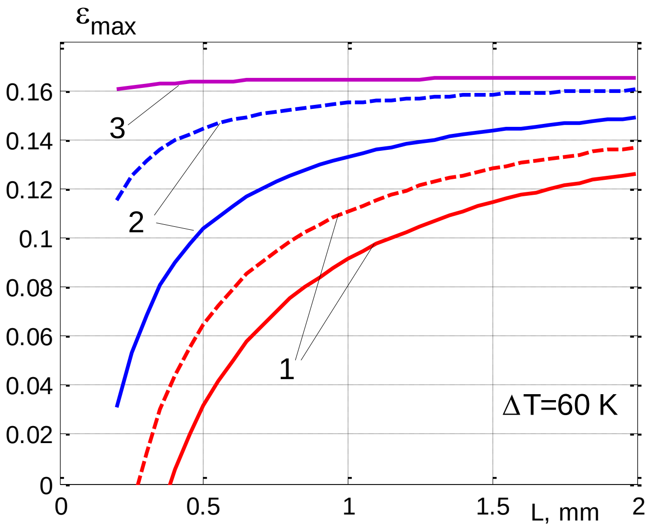


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Fig. 2. Dependences of maximum coefficient of performance ε_{max} on the height L of thermoelement legs. 1 and 2 – with account of electrical resistance of contacts and interconnect plates and thermal resistance of interconnect and insulating plates of Al_2O_3 (solid lines), of AlN (dashed lines). 1 – contact resistance $r_c=5\cdot10^{-6}$ Ohm·cm^2; 2 – $r_c=10^{-7}$ Ohm·cm^2; 3 – thermal resistance is not taken into account, $r_c=10^{-7}$ Ohm·cm^2. Temperature difference $\Delta T=30$ K (a), $\Delta T=60$ K (b), $T_h=30$ °C.

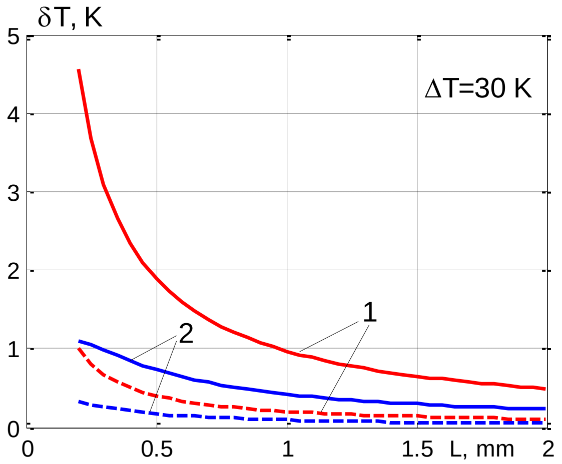
If the contact resistance is low, and the heat losses due to the thermal resistance of interconnect and insulating plates are not taken into account, then the coefficient of performance does not depend on the height of the thermoelement legs (dependence 3 in Fig. 2). These conditions correspond to the ideal model of the cooling module, and the maximum coefficient of performance can be calculated using the classical formula (10).

Note that the results of calculations of ε_{max} have shown that the electrical resistance of interconnect plates practically does not affect ε_{max}.

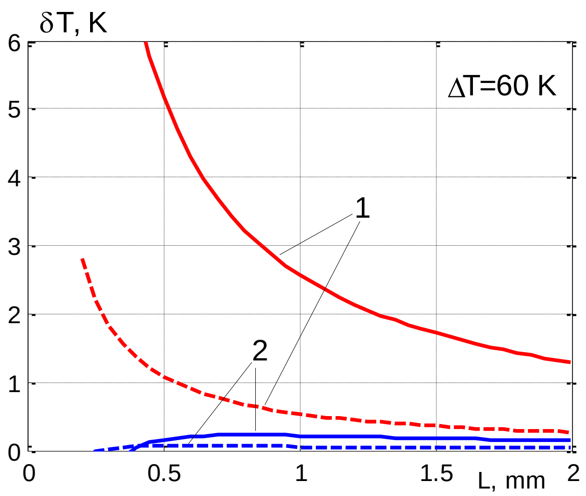
The influence of the thermal resistance of interconnect and insulating plates under the condition of both minimal (dependences 2 in Fig. 2) and real (dependences 1 in Fig. 2) contact resistance determines the dependence of ε_{max} on the height of the thermoelement legs.

A decrease in the height of the legs leads to a decrease in the coefficient of performance, which is especially noticeable during the miniaturization of thermoelements, when the height of the legs is less than 0.1 cm.

Thermal resistance is the reason for the temperature difference ΔT on interconnect and insulating plates (Fig. 3), which for miniature legs is the greater, the smaller their height. It is obvious that $\delta T_h = T_{hj} - T_h$ on the heat-releasing insulating plate will be significantly greater than $\delta T_c = T_c - T_{cj}$ on the heat-absorbing one. For modules with leg height L = 0.05 cm and Al_2O_3 insulating plates, δT_h reaches 5 degrees (Fig. 3*b*) and, accordingly, the temperature of the heat-generating junctions of thermoelements increases, which leads to a decrease in the coefficient of performance.



a)



b)

Fig.3. Dependences of temperature difference δT on interconnect and insulating plates of Al_2O_3 (solid lines), of AlN (dashed lines) on the height of thermoelement legs L. 1 – δT_h on the heat-releasing surface of thermoelements in the module, 2 – δT_c on the heat-absorbing surface. Temperature difference on the module ΔT = 30 K (a), ΔT = 60 K (b), T_h = 30 °C.

The loss of cooling efficiency can be reduced by reducing the thermal resistance of the insulating plates by using thinner plates made of materials with higher thermal conductivity, such as AlN. For insulation with AlN at L=0.05 cm, δT_h instead of 5 K will reach a value of less than 1 K (Fig. 3).

The dependence of ε_{max} on the temperature difference on the module is shown in Fig. 4. Here are the results of calculations for the modules with the height of legs L=0.2 cm and for the miniature legs with L=0.02 cm. If the legs are high, then ε_{max} of a real model of module (dependence 3, Fig. 4), which takes into account the electrical and thermal resistances of contacts, interconnect and insulating plates, is nor essentially different from ε_{max} of an ideal model (dependence 4, Fig. 4). For miniature legs this difference will be insignificant only on condition of minimum contact resistance and the use of insulating plates with high thermal conductivity (dependence 2 for AlN plates, Fig. 4). Otherwise, ε_{max} of a real micromodule will be 2–5 times less as compared to ε_0, calculated with the use of ideal model approximation. This conclusion follows from the results of calculation of the ratio $\varepsilon_0/\varepsilon_{max}$ of the coefficients of performance of the ideal and real models presented in Table 2.

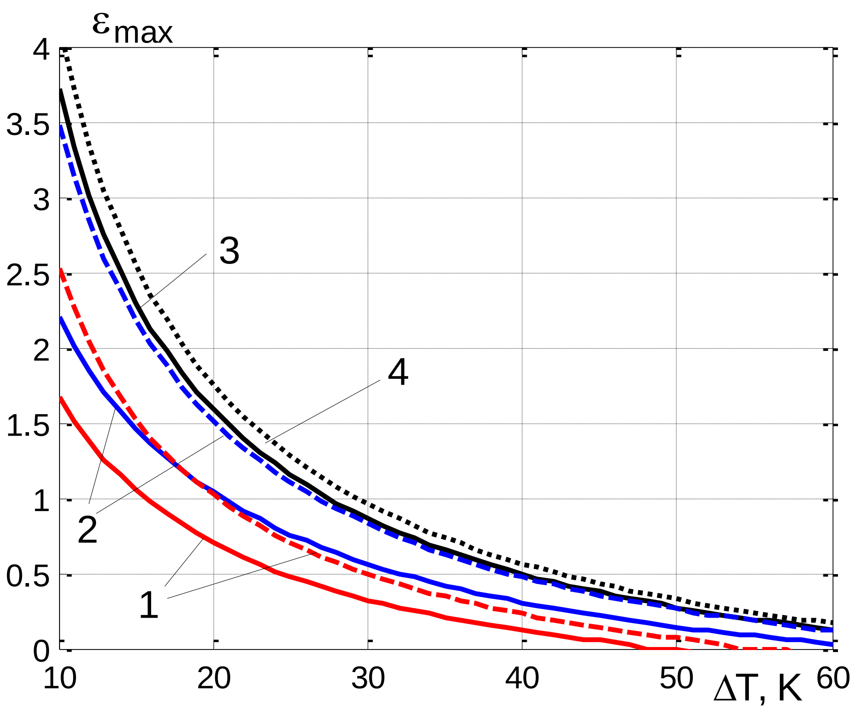


Fig.4. Dependences of maximum coefficient of performance ε_{max} on temperature difference ΔT, T_h=30 °C. 1, 2, 3 – with account of thermal losses in interconnect and insulating plates of Al_2O_3 (solid lines), of AlN (dashed lines). 1 – height of legs L=0.02 cm, contact resistance r_c=5·10^{-6} Ohm·cm^2; 2 – L=0.02 cm, r_c=10^{-7} Ohm·cm^2; 3 – L=0.2 cm, r_c=5·10^{-6} Ohm·cm^2; 4 – thermal losses are not taken into account, L=0.2 cm, r_c=10^{-7} Ohm·cm^2.

Table 2

Dependence of the ratio $\varepsilon_0/\varepsilon_{max}$ on the height of thermoelement legs.
ε_{max} – the value of coefficient of performance with account of electrical and thermal losses in the contacts with resistance r_c and in copper interconnect and insulating plates of Al_2O_3, ε_0 – the value of coefficient of performance for an ideal model of module with no account of the losses.

Height of legs L, cm	$\varepsilon_0/\varepsilon_{max}$ With account of only electrical losses in the contacts r_c=10^{-7} Ohm·cm^2	$\varepsilon_0/\varepsilon_{max}$ With account of electrical and thermal losses r_c=10^{-7} Ohm·cm^2	$\varepsilon_0/\varepsilon_{max}$ With account of only electrical losses in the contacts r_c=5·10^{-6} Ohm·cm^2	$\varepsilon_0/\varepsilon_{max}$ With account of electrical and thermal losses r_c=5·10^{-6} Ohm·cm^2
Temperature difference on the module ΔT=10 K, ε_0=4.15				
0.2	1.0	1.08	1.04	1.12
0.15	1.0	1.10	1.06	1.16
0.1	1.002	1.16	1.08	1.24
0.05	1.003	1.32	1.17	1.51
0.02	1.008	1.89	1.43	2.48
Temperature difference on the module ΔT=30 K, ε_0=0.96				
0.2	1.00	1.06	1.06	1.12
0.15	1.001	1.08	1.08	1.16
0.1	1.002	1.12	1.12	1.24
0.05	1.004	1.24	1.24	1.54
0.02	1.01	1.71	1.69	2.99
Temperature difference on the module ΔT=60 K, ε_0=0.17				
0.2	1.00	1.11	1.17	1.31
0.15	1.004	1.15	1.24	1.45
0.1	1.006	1.25	1.39	1.81
0.05	1.01	1.60	2.08	5.24
0.02	1.03	5.37	-	-

Here are the calculation data of the ratio $\varepsilon_0/\varepsilon_{max}$, the analysis of which also shows that the module efficiency losses with a decrease in the height of the thermoelement legs, which are caused by the thermal resistance of interconnect and insulating plates, are commensurate with the losses caused by the electrical contact resistance.

Thus, for the design of cooling modules with legs less than 1 mm high, it is important to take into account both the electrical contact resistance and the thermal resistance of interconnect and insulating plates. For modules with legs larger than 0.15 cm, an ideal model can be used that does not take into account the influence of electrical and thermal losses in energy efficiency.

Conclusions

1. The calculation and analysis of the maximum coefficient of performance, carried out on the basis of a real model of the cooling module, taking into account the influence of the electrical contact resistance and the electrical and thermal resistances of interconnect and insulating plates, allow us to draw the following conclusions:
2. The coefficient of performance depends on the height of thermoelement legs. The lower the height of the legs, the lower is coefficient of performance. For temperature differences less than 40 K, the coefficient of performance of modules with insulating plates made of Al_2O_3 and legs made of Bi_2Te_3 based materials with the height of 0.05 cm reaches only 65 % of its “ideal” values, which does not take into account the influence of electrical and thermal resistances, and for ΔT = 60 K this will be only 19 %. At the same time, for modules with a leg height 0.2 cm this figure is 90 %.
3. The greater the electrical contact resistance and thermal resistance of interconnect and insulating plates, the more significantly the coefficient of performance decreases with a decrease in the height of the legs. In so doing, the decrease in the coefficient of performance due to thermal resistance is commensurate with its decrease as a result of the impact of electrical contact resistance.
4. The energy efficiency of the modules can be improved by applying manufacturing technologies that minimize contact resistance [35] and by using insulating plates made of highly thermally conductive materials, such as AlN instead of Al_2O_3. The coefficient of performance of such modules will not significantly depend on the height of the legs and will approach its "ideal" value.

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ВПЛИВ ЕЛЕКТРИЧНИХ ТА ТЕПЛОВИХ ОПОРІВ КОНТАКТІВ І КОМУТАЦІЙ НА ХОЛОДИЛЬНИЙ КОЕФІЦІЄНТ ТЕРМОЕЛЕКТРИЧНОГО МОДУЛЯ

В роботі описаний метод розрахунку максимального холодильного коефіцієнта для реальної моделі термоелектричного модуля, яка враховує вплив електричного опору контактів та комутацій і теплового опору комутаційних та ізоляційних пластин. Розраховані залежності максимального холодильного коефіцієнта модуля від висоти його віток і перепаду температур. Проведено порівняльний аналіз холодильного коефіцієнта реальної моделі модуля з його “ідеальним” значенням, яке не враховує вплив електричних і теплових опорів контактів, комутаційних та ізоляційних пластин. Бібл. 7, рис. 4, табл. 2.

Ключові слова: термоелектричний охолодний модуль, холодильний коефіцієнт, електричний контактний опір, тепловий опір комутаційної та ізоляційної пластин

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ВОЗДЕЙСТВИЕ ЭЛЕКТРИЧЕСКИХ И ТЕПЛОВЫХ СОПРОТИВЛЕНИЙ КОНТАКТОВ И КОММУТАЦИЙ НА ХОЛОДИЛЬНЫЙ КОЭФФИЦИЕНТ ТЕРМОЭЛЕКТРИЧЕСКОГО МОДУЛЯ

В работе описан метод расчета максимального холодильного коэффициента для реальной модели термоэлектрического модуля, учитывающей влияние электрического сопротивления контактов и коммутаций и теплового сопротивления коммутационных и изоляционных пластин. Рассчитаны зависимости максимального холодильного коэффициента модуля от высоты его ветвей и перепада температур. Проведен сравнительный анализ холодильного коэффициента реальной модели модуля с его "идеальным" значением, не учитывающим влияние электрических и тепловых сопротивлений контактов, коммутационных и изоляционных пластин. Библ. 7, рис. 4, табл. 2.

Ключевые слова: термоэлектрический охлаждающий модуль, холодильный коэффициент, электрическое контактное сопротивление, тепловое сопротивление коммутационной и изоляционной пластин

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THERMOELECTRIC FIGURE OF MERIT OF SEMICONDUCTOR SUPERLATTICES

The thermoelectric figure of merit of semiconductor superlattices has been studied in the quasi-classical one-miniband approximation. The change in the relaxation time of current carriers in 2D structures compared to their 3D analogs is taken into account when current carriers are scattered by acoustic phonons, point defects, and nonpolar optical phonons with arbitrary statistics. An analytical dependence of the figure of merit on the thermoelectric quality factor of the material and the width of the conduction miniband along the superlattice axis is established. It is shown that the figure of merit of semiconductor superlattices increases with increasing these parameters. Bibl. 14, Fig. 4.

Key words: superlattices, *conduction miniband,* relaxation time, thermopower, phonon thermal conductivity, thermoelectric figure of merit.

Introduction

Formulation of the problem. The efficiency of thermoelectric generators, as well as coefficient of performance of thermoelectric coolers is determined by the parameter of dimensionless thermoelectric figure of merit

$$zT = \frac{\alpha^2\sigma}{\kappa_e + \kappa_{ph}} T \ , \tag{1}$$

where α, σ, κ_e, κ_{ph} are the Seebeck coefficient, electric conductivity, electron and phonon thermal conductivity of thermoelectric material, T is average absolute temperature which characterizes the conditions of application of the thermoelectric device [1].

In [2], it is shown that for the bulk crystalline semiconductor materials, even with perfect combination of their parameters, $zT < 1.5$. In fact, the value of zT of modern thermoelectrics based on Bi_2Te_3 has approached the limit value of $zT < 1$.

Analysis of recent research and publications

In recent decades, intensive search for ways to increase the thermoelectric figure of merit has continued. In this case, the increase in thermoelectric figure of merit was mainly associated with a decrease in phonon thermal conductivity while maintaining electrical conductivity at least at the level of degenerate wide-gap semiconductors. The use of low-dimensional semiconductor structures has been proposed: thin films [3, 4], superlattices, [5, 6], nanoscale structures [7]. Analysis of the experimental data confirms the promise of creating highly efficient thermoelectric materials based on nanotechnologies [8].

However, a decrease in the phonon component of the lattice thermal conductivity is not the only consequence of the influence of low-dimensional structures on the properties of a thermoelectric material: in nanostructured materials, the processes of transport and scattering of not only phonons, but also electrons can change [9, 10].

The purpose of the work is to study the thermoelectric figure of merit of semiconductor superlattices in quasi-classical one-miniband approximation with regard to a change in relaxation time in 2D structures as compared to their 3D analogs at scattering of current carriers by acoustic phonons, point defects and nonpolar optical phonons with arbitrary statistics.

Formulation of the task

Finding the distribution function

The physical properties of semiconductor materials are determined by their electronic spectrum, which has a strong anisotropy in superlattices. While the movement of current carriers in the direction perpendicular to the SL axis is almost free and corresponds to movement along a wide conduction band, the movement along the superlattice axis is limited.

In this direction, the electronic spectrum is miniband. In the case of sufficiently narrow layers, which are quantum wells for electrons, all electrons will be located near the bottom of the lower size quantization miniband. In the framework of quasi-classical approximation $2\varepsilon_0 >> \hbar / \tau_{2D}$, eE_0, $a\nabla_z k_0 T$ the law of electron dispersion in the lower miniband of SL is given by [11]

$$\varepsilon(\vec{k}) = \frac{\hbar^2 k_\perp^2}{2m_\perp} + 2\varepsilon_0 (1 - \cos k_z a) \tag{3}$$

where $k_\perp = (k_x^2 + k_y^2)^{1/2}$, and k_z is transverse and longitudinal to SL axis components of quasi-wave vector, $m_\perp$ is transverse effective mass, which is close in size to the effective mass m^* of semiconductor electrons forming SL, a is SL period, $2\varepsilon_0$ is the width of SL conduction miniband in the direction k_z.

The calculation of kinetic coefficients will be carried out in the quasi-classical one-miniband approximation taking into account the change in the relaxation time in 2D structures in comparison with their three-dimensional 3D analogues. The nonequilibrium function of electron distribution f will be found from the kinetic Boltzmann equation

$$\vec{\upsilon} \frac{\partial f}{\partial \vec{r}} - e\vec{E_0} \frac{\partial f}{\hbar \partial \vec{k}} = -\frac{f_1}{\tau_{2D}}, \tag{2}$$

where $\vec{\upsilon} = \hbar^{-1}\partial\varepsilon(\vec{k})/\partial\vec{k}$ is electron velocity, $\vec{E_0} = -\partial\varphi/\partial\vec{r}$ is electric field strength, φ is electric potential, $f_1 = f - f_0$, $f_0 = [1 + \exp(\varepsilon - \varsigma)/k_0 T]$ is equilibrium Fermi-Dirac distribution function with space-variable absolute temperature T and chemical potential ς, τ_{2D} is relaxation time, k_0 is Boltzmann constant.

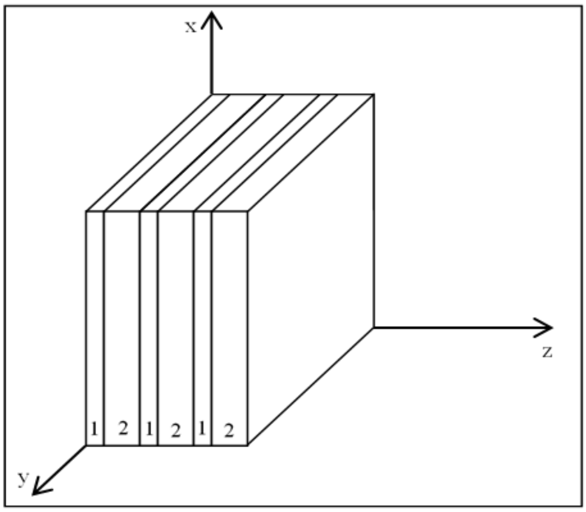

Fig.1 Schematic structure of semiconductor superlattice GaAs/AlAs. 1 – GaAs layer, 2 – AlAs layer.

The longitudinal component of the relaxation time tensor of the SL electron gas is written as follows [12]

$$\tau_{2D} = a\frac{2\sqrt{2m_\perp k_0 T}}{3\pi\hbar}\tau_{3D}\left(\frac{\varepsilon}{k_0 T}\right)^{1/2}, \tag{3}$$

where

$$\tau_{3D} = \tau_0\left(\frac{\varepsilon}{k_0 T}\right)^{r-1/2}, \tag{4}$$

– relaxation time in the bulk sample, τ_0 – electron energy-independent constant, r – scattering parameter are given by:

on point defects (short-term potential)

$$\tau_0 = \frac{\pi\hbar^4}{m_n(2m_n k_0 T)^{1/2} U_0^2 N_g}, \tag{5}$$

on acoustic phonons

$$\tau_0 = \frac{2\pi\hbar^4\rho\upsilon_0^2}{E_1^2(2m_n k_0 T)^{3/2}}, \tag{6}$$

on nonpolar optical phonons ($k_0 T >> \hbar\omega_0$)

$$\tau_0 = \frac{2}{\pi}\left(\frac{\hbar\omega_0}{E_0}\right)^2 \frac{\hbar^2 a^2 \rho}{m_n\left(2m_n k_0 T\right)^{3/2}}, \tag{7}$$

It is obvious that the differences in the power dependence of the relaxation time of the bulk sample and the superlattice are due to the different energy dependence of the density of states.

Solving equation (2) in the relaxation time approximation, for the nonequilibrium additive to the Fermi-Dirac distribution function we obtain

$$f_1 = -\tau_{2D}\left(\frac{\partial f_0}{\partial \varepsilon}\right)\left[\frac{\varepsilon(\vec{k})-\varsigma}{T}\;\vec{\upsilon}\nabla T - e\vec{\upsilon}\nabla\left(\varphi - \frac{\varsigma}{e}\right)\right]. \tag{8}$$

It is obvious that the first component of the nonequilibrium additive is caused by the sample temperature gradient, and the second one is caused by the current carrier energy gradient.

Calculation of kinetic coefficients

The current density and energy flux density are found from the known relations [12]

$$\vec{j} = -\frac{2e}{(2\pi)^3}\int \vec{\upsilon}(\vec{k}) f_1(\vec{k},\vec{r})\; d\vec{k}, \tag{9}$$

$$\vec{w} = \frac{2}{(2\pi)^3}\int \left[\varepsilon(\vec{k})-\varsigma\right]\; \vec{\upsilon}(\vec{k}) f_1(\vec{k},\vec{r})\; d\vec{k} \tag{10}$$

We assume that the vectors $\overrightarrow{E_0}$ and ∇T are directed along the superlattice axis, which is compatible with the axis of the cylindrical coordinate system *0z*. Given (8) and integrating in the cylindrical coordinate system for current and energy density, we obtain

$$j = j_z = \sigma(\eta,\beta)\;\nabla_z\left(\frac{\varsigma}{e} - \varphi\right) - \alpha(\eta,\beta)\;\sigma(\eta,\beta)\;\nabla_z T \tag{11}$$

$$w = w_z = -\kappa_e(\eta,\beta)\;\nabla_z T \tag{12}$$

where $\alpha(\eta, \beta)$, $\tau(\eta, \beta)$, $\kappa_e(\eta, \beta)$ are the Seebeck coefficient, electric conductivity and electron component of thermal conductivity along the SL axis.

Taking into account the form of the distribution function, from (11) and (12) we find the kinetic coefficients.

The Seebeck coefficient

$$\alpha(\eta,\beta)=\frac{\nabla_z\left(\frac{\varsigma}{e}-\varphi\right)}{\nabla_z T}=-\frac{k_0}{e}\left[\frac{I_{1,2,0}(\eta,\beta)+\beta\ I_{0,2,2}(\eta,\beta)}{I_{0,2,0}(\eta,\beta)}-\eta\right], \tag{13}$$

electric conductivity

$$\sigma(\eta,\beta)=\sigma_0\beta^2 I_{0,2,0}(\eta,\beta), \tag{14}$$

electron component of thermal conductivity

$$\kappa_e(\eta,\beta)=L_{2D}(\eta,\beta)\ \sigma(\eta,\beta)T\ , \tag{15}$$

where

$$L_{2D}(\eta,\beta)=\left(\frac{k_0}{e}\right)^2\left\{\begin{array}{l}\frac{I_{2,2,0}(\eta,\beta)+2\beta\ I_{1,2,2}(\eta,\beta)+\beta^2 I_{0,2,4}(\eta,\beta)}{I_{0,2,0}(\eta,\beta)}- \\ -\left[\frac{I_{1,2,0}(\eta,\beta)}{I_{0,2,0}(\eta,\beta)}+\beta\frac{I_{0,2,2}(\eta,\beta)}{I_{0,2,0}(\eta,\beta)}\right]^2\end{array}\right\} \tag{16}$$

the Lorentz number,

$$I_{k,l,m}(\eta,\beta)=\int_0^{\pi}F_k(\eta,z,\beta)(\sin z)^l\left(\sin\frac{z}{2}\right)^m dz, \tag{17}$$

$$F_k(\eta,z,\beta)=\int_0^{\infty}\frac{\exp\left(x-\eta+\beta\ \sin^2\frac{z}{2}\right)}{\left[1+\exp\left(x-\eta+\beta\ \sin^2\frac{z}{2}\right)\right]^2}x^k dx, \tag{18}$$

three-parameter Fermi integrals [12], $\varepsilon_\perp=\hbar^2 k_\perp^2/2m_\perp$, $x=\varepsilon_\perp/k_0T$, $\eta=\varsigma/k_0T$, $z=ak_z$, $\beta=2\varepsilon_0/k_0T$ is reduced width of conduction miniband in the direction of superlattice axis.

Calculation of thermoelectric figure of merit

Using the found kinetic coefficients, we calculate the thermoelectric figure of merit of *2D*-structure

$$z_{2D}(\eta,\beta)T=\frac{\alpha^2(\eta,\beta)\ \sigma(\eta,\beta)}{\kappa_e(\eta,\beta)+\kappa_{ph}}T=\frac{\alpha_0^2(\eta,\beta)}{L_0(\eta,\beta)+B^{-1}\left[\beta^2 I_{0,2,0}(\eta,\beta)\right]^{-1}}, \tag{19}$$

where $L_0(\eta,\beta) = L_{2D}(\eta,\beta)/(k_0/e)^2$ is the reduced Lorentz number, $\alpha_0(\eta,\beta) = \alpha(\eta,\beta)/(-k_0/e)$ is the reduced Seebeck coefficient,

$B = \left(\frac{k_0}{e}\right)^2 \frac{\sigma_0 T}{\kappa_{ph}}$ is coefficient of thermoelectric quality which contains material parameters of 2D lattice: coefficient of phonon thermal conductivity, SL period, effective mass and mobility of current carriers in the direction of SL axis and has a significant impact on the value of thermoelectric figure of merit. A similar parameter was introduced for the bulk semiconductor samples in [2].

Analysis of the results

At fixed values of current carrier parameters B and β, the thermoelectric figure of merit is a function of only η, and the dependence $z(\eta)$ has an extremum. That is, there is an optimal concentration of doping impurities, which leads to maximum figure of merit values. After maximization of $z(\eta)$ by chemical potential, the effect of parameters B and β on the thermoelectric figure of merit was investigated. Estimation of the most realistic range of changes in thermoelectric quality factor gives $B = 0.075\text{-}0.125$.

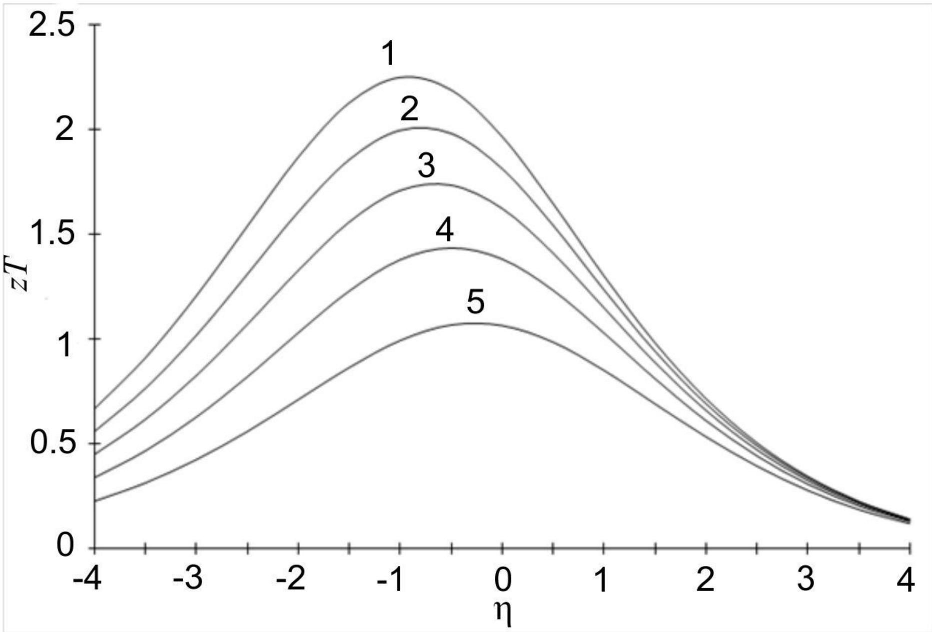

Fig. 2 Dependence of thermoelectric figure of merit on the reduced chemical potential at the width of the conduction miniband β=5 and at different values of quality factor. Curve 1 at B =0.15, 2- B =0.125, 3 - B =0.1, 4 - B =0.075, 5 - B =0.05.

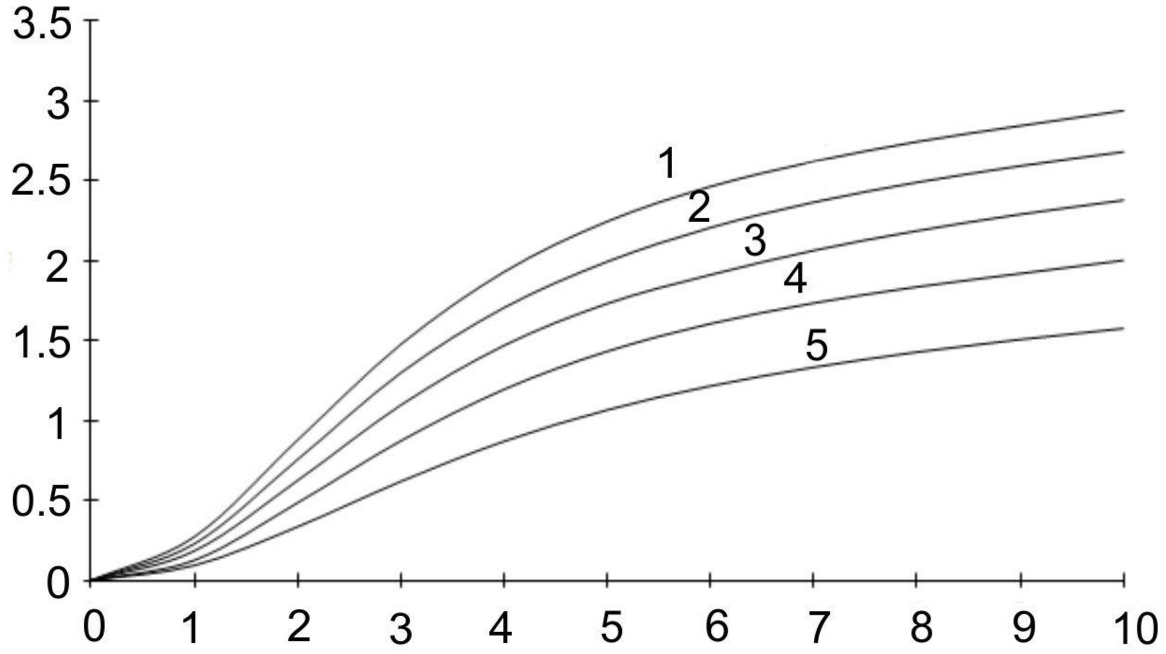

Fig. 3. Dependence of maximum thermoelectric figure of merit on the width of conduction miniband at different values of quality factor. Curve 1 at B =0.15, 2- at B =0.125, 3 – at B =0.1, 4 at - B =0.075, 5 at- B =0.05.

Taking into account the finiteness of the width of the conduction miniband leads to the dependence of the Lorentz number on its width. In particular, as the width of the miniband decreases in the direction of the SL axis, the Lorentz number and the electrical conductivity and electronic component of thermal conductivity decrease. And, despite the decrease in phonon thermal conductivity, this process leads to an overall decrease in thermoelectric figure of merit.

On the contrary, increasing the width of the conduction miniband increases the conductivity. However, this increases the electronic component of thermal conductivity, which can compensate for the decrease in phonon thermal conductivity. This process can lead to an overall reduction in thermoelectric figure of merit. It is obvious that there is an optimal width of the conduction miniband, which for the GaAs /AlAs superlattices is in the range $\beta = 5\text{-}9$.

In two-dimensional structures for the statistics of degenerate gas of current carriers, the reduced Lorentz number reaches the maximum value $L_0\ (\infty,\ \beta)=\pi^2/3$, and for nondegenerate electron gas and ultra-narrow minimum band of minimum conductivity - $L_0(\eta,\ 0)=1$.

To verify the correctness of the obtained relations, a boundary transition was performed at $\beta \rightarrow \infty$. The increase in β should be considered as the approximation of the width of the conduction band in the direction parallel to the SL axis to the width of the wide conduction band in the direction $k_\perp$.

In the boundary case $\beta = \infty$, the analytical relations for the kinetic coefficients are transferred to the known formulae for the bulk semiconductors with a parabolic dispersion law [12].

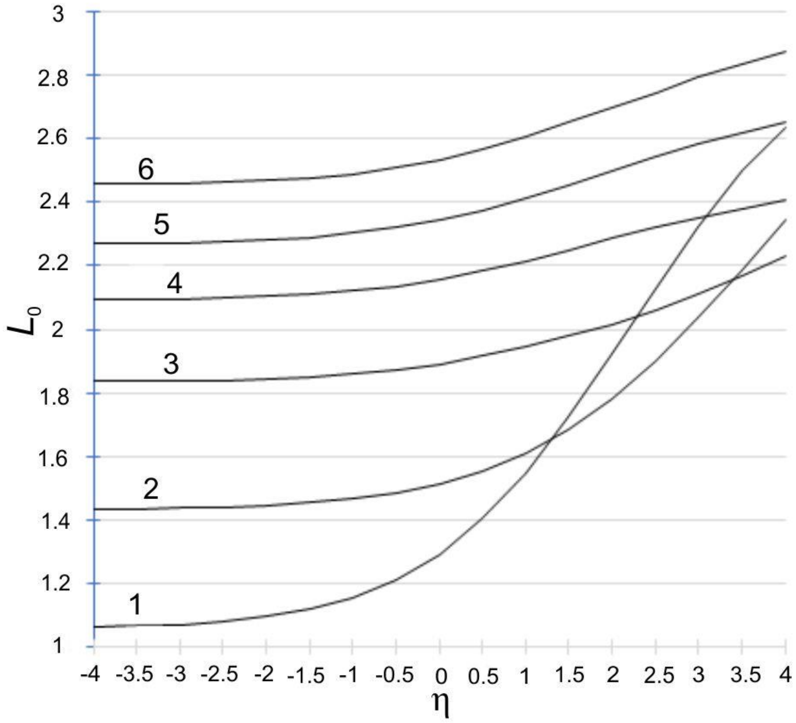

Fig. 4. Dependence of reduced Lorentz number on chemical potential at different width of conduction miniband. Curves: 1 - at β=1, 2 – at β =3, 3 at β =5, 4 at β =7, 5 at β =10, 6 - at β =∞.

One of the most important results of the creation of low-dimensional heterostructures, leading to an increase in thermoelectric figure of merit, is a decrease in the thermal conductivity of the lattice as a result of phonon scattering on surfaces and heterointerfaces.

However, the decrease in lattice thermal conductivity is not the only consequence of the impact of low-dimensional structures on the properties of thermoelectric material: in nanostructured materials, the scattering processes of not only phonons but also of electrons change. In particular, the relaxation time of current carriers in 2D structures changes in comparison with their 3D analogues.

Conclusions

The thermoelectric figure of merit of superlattices depends on the chemical potential η, the width of conduction miniband β and thermoelectric quality factor *B*. The dimensionless parameter of thermoelectric material quality is determined by the value: phonon thermal conductivity, superlattice period, effective mass of current carriers in the direction of superlattice axis, etc. The most realistic range of change in *B* for two-dimensional structures based on GaAs/AlAs is *0.050-0.125*.

At fixed values of parameters *B* and β, the thermoelectric figure of merit is a function of only η, and the dependence $z(\eta)$ has an extremum which, when *B* increases, shifts toward smaller values of chemical potential. In the region of room temperatures, under the condition of the optimal concentration of dopants, with the width of the conduction miniband $\beta=10$ and with the most favorable value of thermoelectric quality factor $B=0.125$, the thermoelectric figure of merit of superlattices based on *AlGaAs* can reach the values $zT=3$. The resulting limit value of SL thermoelectric figure of merit is sufficient for thermoelectric devices to compete in efficiency with electric generators and refrigerators operating on other principles.

Naturally, the effect of electron-phonon drag can make significant adjustments to the value of thermoelectric figure of merit [13, 14].

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ТЕРМОЕЛЕКТРИЧНА ДОБРОТНІСТЬ НАПІВПРОВІДНИКОВИХ НАДҐРАТОК

В квазікласичному одномінізонному наближені досліджена термоелектрична добротність напівпровідникових надґраток. Врахована зміна часу релаксації носіїв струму 2D структурах в порівнянні з їх 3D аналогами при розсіюванні носіїв струму на акустичних фононах, точкових дефектах і неполярних оптичних фононах при довільній статистиці. Встановлена аналітична залежність добротності від коефіцієнта термоелектричної якості матеріалу та ширини мінізони провідності в напрямку осі надґратки. Показано, що добротність напівпровідникових надґраток збільшується із збільшенням цих параметрів. Бібл. 14, рис. 4

Ключові слова: надґратки, *мінізона провідності,* час релаксації, термоЕРС, фононна теплопровідність, термоелектрична добротність.

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ТЕРМОЭЛЕКТРИЧЕСКАЯ ДОБРОТНОСТЬ ПОЛУПРОВОДНИКОВЫХ СВЕРХРЕШЕТОК

В квазиклассическом одноминизонном приближении исследована термоэлектрическая добротность полупроводниковых сверхрешеток. Учтено изменение времени релаксации носителей тока в 2D структурах по сравнению с их 3D аналогами при рассеивании носителей тока на акустических фононах, точечных дефектах и неполярных оптических фононах при произвольной статистике. Установлена аналитическая зависимость добротности от коэффициента термоэлектрического качества материала и ширины минизоны проводимости по оси сверхрешётки. Показано, что добротность полупроводниковых сверхрешеток увеличивается с увеличением этих параметров. Библ. 14, рис. 4.

Ключевые слова: сверхрешетки, минизона проводимости, время релаксации, термоЭДС, фононная теплопроводность, термоэлектрическая добротность, .

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COMPUTER METHOD OF DESCRIPTION OF THE TECHNOLOGIES AND PROPERTIES OF Bi_2-Te_3 -BASED THERMOELECTRIC MATERIALS OBTAINED BY THE BRIDGMAN METHOD

This paper presents the results of the study of literary sources describing the technologies and properties of thermoelectric materials obtained by the Bridgman method. The results of one of the stages of creating a software product for the description of the production technologies and properties of a thermoelectric material based on Bi-Te compounds are given.Bibl.8, Fig.2, Table 1.

Key words: Bridgman method, interpolation, bismuth telluride.

Introduction

Thermoelectric materials are in high demand due to their use in power generation and refrigeration applications. They are an excellent solution in active cooling devices in military, telecommunication equipment and temperature control systems.

Bismuth telluride (Bi_2Te_3) is one of the best thermoelectric materials with the highest thermoelectric figure of merit (Z), which in turn is related to thermal conductivity (κ) and electric conductivity (σ), as represented in formula 1

$$Z = \frac{\alpha^2\sigma}{\kappa}, \quad (1)$$

where α is the Seebeck coefficient.

Traditional methods of manufacturing bismuth telluride compounds include the Bridgman, Czochralski, and zone melting methods, as well as powder metallurgy methods such as hot pressing and hot extrusion [1].

The purpose of this work is to study the thermoelectric characteristics of solid solutions based on bismuth telluride obtained by the Bridgman method, as well as application of a modified computer program with the study of Bridgman's method and characteristics of thermoelectric materials based on *Bi-Te* compounds.

Dependence of the thermoelectric characteristics of Bi_2-Te_3-based materials obtained by the Bridgman method

When obtaining samples of Bi_2Te_3 and its solid solutions by the Bridgman method, the material is synthesized by fusing the initial components in the same ampoule in which the material will be grown later [2]. The Bridgman method consists in the fact that an ampoule with a crystallizing substance moves in the furnace from the upper part with a temperature exceeding the melting temperature to the lower part, the temperature of which is lower than the melting temperature. Bridgman-produced ingots of Bi_2Te_3 consist of one or more crystalline grains large enough to be cut into single-crystal samples.

Table 1 shows the thermoelectric characteristics of *Bi-Te*-based materials obtained by the Bridgman method.

Table 1

Thermoelectric characteristics of Bi-Te-based materials obtained by the Bridgman method.

Working temperature, K	Z, 10^{-3},K^{-1}	α, mV/K	σ, $Ohm^{-1}cm^{-1}$	κ, W/m·K	Material type:	Material composition	Ingot length, mm	Melt temperature, K	Annealing temperature, K	Annealing duration, h	Literary source:
308	4.57	-	-	1.21	P	$(Bi_{0,25}Sb_{0,75})_2Te_3$	15	686	473-673	2-5	[3]
308	3.67	-	-	-	N	$Bi_2(Te_{0,94}Se_{0,06})_3$	15				[3]
298	1.27	-	-	1.38	P	$(Bi_{0.25}Sb_{0.75})_2Te_3$	-	-	-	-	[4]
298	1.25	-	-	1.36	N	$Bi_2(Te_{0.94}Se_{0.06})_3$	-	-	-	-	[4]
298	0.91	221	-	1.36	P	$(Bi_{0,25}Sb_{0,75})_2Te_3$	15	-	673	5	[5]
298	1.09	223	-	1.65	N	$Bi_2(Te_{0,94}Se_{0,06})_3$	15	-	673	5	[5]
473	-	-	-	-	P	$Bi_{0,5}Sb_{1,5}Te_{3,0}$	-	923	-	-	[6]
300	2.8	171	1910	10.2	N	$Bi_2Te_{1.5}Se_{1.5}$	-	-	600	1200	[7]
300	2.7	161	2120	9.5	N	$Bi_{1.9998}Sn_{0.0002}Te_{1.5}Se_{1.5}$	-	-	600	1200	[7]
300	3	163	2320	8.9	N	$Bi_{1.9996}Sn_{0.0004}Te_{1.5}Se_{1.5}$	-	-	600	1200	[7]

All the data in the table were implemented in the software product to describe the technologies and properties of *Bi-Te* -based thermoelectric material. Updating the software product database will be described in future papers.

Theory of linear interpolation

Interpolation in the general sense is a method of calculating certain intermediate values of any studied quantity based on a set of known values.

If the investigated process can be described by a linear function, the procedure for calculating unknown parameters can be significantly simplified compared to other calculation cases. Mathematical modeling of various production situations of engineering and scientific practicality by methods of linear interpolation suggests the possibility of mathematical forecasting by identifying the value of the interpolated coordinate *Y* by a given parameter of the *X* coordinate with known coordinates of two points of a linear function [8].

For successful management, it is necessary to foresee how this or that system will behave within the framework of the existing process described by the corresponding linear function. The first point of the linear function has coordinates X0,Y0, the second - X1,Y1, the resulting interpolated Y coordinate, which is calculated, based on the given value of the X coordinate, is calculated according to formula 2:

$$Y = \left(\left(X - X_0\right)\times\left(Y_1 - Y_0\right)\div\left(X_1 - X_0\right)\right) + Y_0 , \qquad (2)$$

Further development of the software product for describing the technologies and properties of *Bi-Te* – based thermoelectric material.

The function of theoretical calculation of unknown values of α and δ using interpolation was introduced into the software product for describing the production technologies and characteristics of thermoelectric material based on *Bi-Te* compounds. The general algorithm of this function is as follows.

- Calling the interpolation function by the user.
- Creation of a dynamic form and all its components for interpolation.
- After the user enters the required working temperature, the program searches the database for a material whose performance range may include the desired value. To do this, the following algorithm is implemented (Fig.1).
- After selecting the optimal material, the program calculates the value of the coefficient α using a linear interpolation formula.
- Based on the result obtained, the program plots the dependence of α on temperature.
- After receiving the results of α, the program calculates the value of δ using a linear interpolation formula.
- Based on the result obtained, the program plots the dependence of δ on temperature.
- The results are also displayed in Label.
- After the user terminates, the program deletes all form components and the form itself. The general view of the value interpolation window is shown in Fig.1.

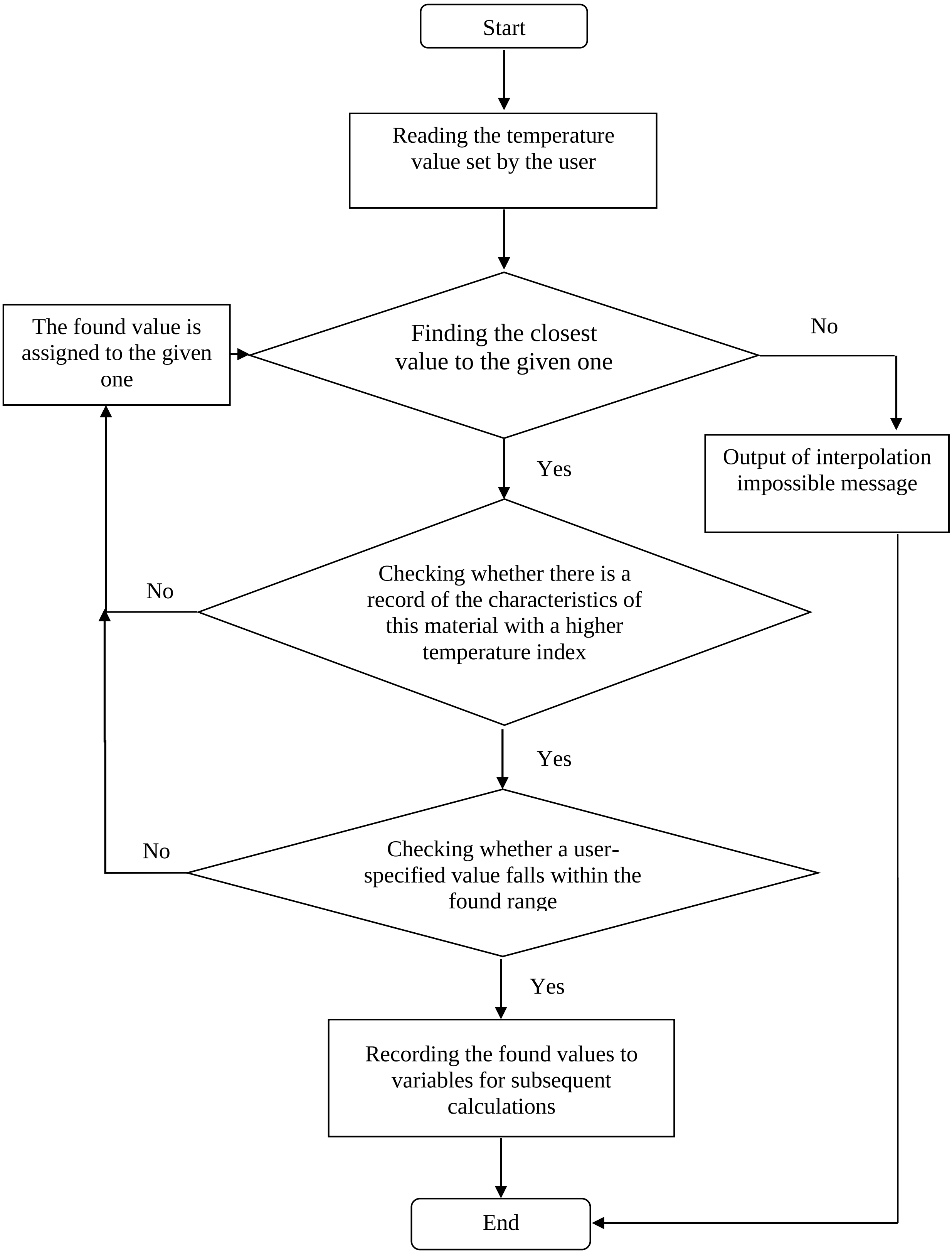

Fig. 1. Algorithm of finding optimal material for interpolation

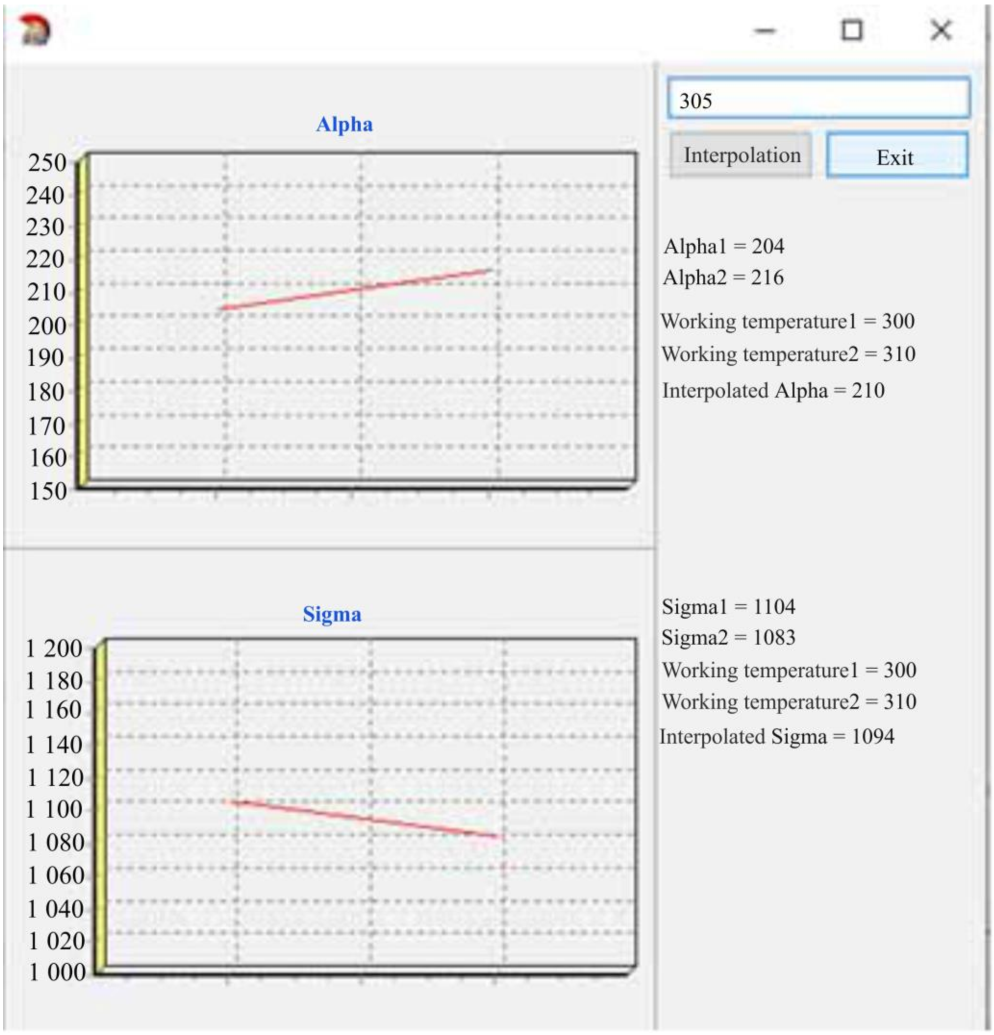

Fig. 2. General view of the value interpolation window
Interpolation; output; working temperature; interpolated Alpha; interpolated Sigma

Further development of the software product will be described in future papers.

Conclusions

A study of literary sources describing *Bi-Te*-based thermoelectric materials obtained by the Bridgman method was carried out.

1. The research data were added to the database of the software product to describe the technologies and properties of obtaining *Bi-Te*-based thermoelectric material.
2. The interpolation function is implemented in the software product to describe the technologies and properties of obtaining *Bi-Te*-based thermoelectric material.
3. Further versions of the software product will be described in subsequent papers.

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КОМП'ЮТЕРНИЙ МЕТОД ОПИСУ ТЕХНОЛОГІЙ ТА ВЛАСТИВОСТЕЙ ТЕРМОЕЛЕКТРИЧНИХ МАТЕРІАЛІВ НА ОСНОВІ Bi_2-Te_3, ОТРИМАНИХ МЕТОДОМ БРІДЖМЕНА

У даній роботі наводяться результати дослідження літературних джерел в яких описуються технології та властивості термоелектричних матеріалів отриманих методом Бріджмена. Наводяться результати одного з етапів створення програмного продукту для опису технологій отримання та властивостей термоелектричного матеріалу на основі сполук Bi-Te. Бібл. 8. рис. 2. табл. 1.

Ключові слова: метод Бріджмена, інтерполяція, телурид вісмуту.

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КОМПЬЮТЕРНЫЙ МЕТОД ОПИСАНИЯ ТЕХНОЛОГИЙ И СВОЙСТВ ТЕРМОЭЛЕКТРИЧЕСКИХ МАТЕРИАЛОВ НА ОСНОВЕ Bi_2-Te_3, ПОЛУЧЕННЫХ МЕТОДОМ БРИДЖМЕНА

В данной работе приводятся результаты анализа литературных источников, в которых описываются технологии и свойства термоэлектрических материалов, полученных методом Бриджмена. Приводятся результаты одного из этапов создания программного продукта для описания технологий производства и свойств термоэлектрического материала на основе соединения Bi-Te. Библ. 8. рис. 2. табл. 1.

Ключевые слова: метод Бриджмена, интерполяция, теллурид висмута.

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ON THE ISSUE OF CHOOSING THERMOCOUPLE MATERIAL FOR THERMAL CONVERTERS OF METROLOGICAL PURPOSE

In this paper, we consider ways to increase the sensitivity of a thermoelectric converter for metrological purposes due to design improvements in the thermoelectric converter and optimization of thermal operating modes. The features of the requirements for thermoelectric material intended for designing thermoelectric converters as measuring instruments are shown. Bibl. 11, Fig. 1.

Key words*: thermoelectric converter, heater, thermocouple, sensitivity, thermoelectric material*

Introduction

The creation of high-precision devices for measuring alternating current values is a fundamental task of modern thermoelectric instrumentation. An increase in the sensitivity of such devices is directly related to an increase in the sensitivity of a thermoelectric converter (TC) for metrological purposes.

Increasing the sensitivity of TC is mainly achieved by improving the parameters of thermoelectric material (TEM). However, along with the search for new TEMs and improving the quality of known materials, the possibilities of increasing the figure of merit (z) of which are practically exhausted at this stage, there are opportunities to increase the parameters of the TC due to their design improvements, optimize thermal operating modes in order to increase the efficiency of using the heat generated by the TC heater. The task of optimal application of TEM specifically for TC remains relevant, because in this case there is a significant difference from the use of TEM for other thermoelectric devices – thermal generators (TEG), radiation receivers, coolers, etc.

Therefore, an important task and purpose of this work is to establish the features of the application of TEM in the development of TC.

Differences in the choice of TEM for different types of thermoelectric devices

It is known [2] that the use of a semiconductor material for thermal into electrical energy converters has led to a sharp improvement in their coefficient of performance (COP) and created good prerequisites for the widespread use of such converters. The possibilities of improving the parameters of TC for metrological purposes have been studied to a much lesser extent. Often, attempts to use thermoelectric materials (TEMs) developed for energy applications have not met with the expected success. This is due to the fact that TEMs intended for measurement technology and metrology must satisfy a number of additional requirements that are not taken into account when developing TEMs for other applications, such as TEG, thermoelectric coolers (TEC) and thermoelectric heating devices.

When choosing a TEM for TC thermocouples, the TEM optimization criteria are modified. In TEG, TEC and thermoelectric heating devices, the main parameter that determines their quality is the efficiency. For TEG, the efficiency ($\eta_{\text{мах}}$) in the maximum power mode is determined by the expression [3]:

$$\eta_{\max} = \frac{1}{2}\frac{T_1 - T_2}{T_1 + \frac{2}{z} - \frac{1}{4}(T_1 - T_2)} , \tag{1}$$

where T_1 and T_2 are the temperatures of the hot and cold junctions, respectively, z is the thermoelectric figure of merit of TEM which is determined by the formula:

$$z = \frac{\alpha^2 \sigma}{x}, \tag{2}$$

where α is the Seebeck coefficient, σ is electric conductivity, x is thermal conductivity.

To characterize the TEC, the coefficient of performance $\varepsilon_{\text{мах}}$ is used, which is determined from Eq.[4]:

$$\varepsilon_{\max} = \frac{T_2}{T_1 - \mathrm{T}_2} \cdot \frac{\sqrt{1 + 0{,}5z(T_1 + T_2)} - T_1/T_2}{\sqrt{1 + 0{,}5z(T_1 + T_2)} + T_1/T_2}. \tag{3}$$

The heating coefficient K_{T} for thermoelectric heating devices is determined as [5]:

$$K_T = \frac{1}{4}\left(\frac{T_2}{2} - \frac{T_1 - T_2}{zT_2}\right). \tag{4}$$

Formulae (1), (2), (3), (4) remain correct regardless of which type of device is considered. In these formulae, the main parameter that characterizes the efficiency of the device is z. Therefore, the main requirement for the TEM is to achieve the maximum possible value of z.

Another, no less important, requirement is to maintain the figure of merit of the TEM in a wide range of temperatures.

Only for a small group of measuring devices – radiation receivers, microcalorimeters, thermocouples - a relation has been found from which the relationship between the parameters of the TEM and the main characteristics of the device is determined, taking into account the possibility of reaching their boundary values, limited only by thermal and temperature noises [5].

The main parameters describing radiation receivers are signal detection capability and volt-watt sensitivity. Similar parameters are introduced for microcalorimeters. These parameters have long been studied and described in [3,4]. Mathematical expressions to determine these parameters do not take into account a number of additional factors inherent in various thermoelectric devices. Expressions for real structures are much more complicated [5]. They include TEM parameters in different combinations: α, σ, x. In addition to the requirements for achieving maximum sensitivity, a number of additional conditions are imposed on TEM and TC: stability in a given temperature range, high temporal stability, etc.

From the above it can be seen that the requirements for TEM, designed for TEG, TEC and heat pumps, differ significantly from the requirements for TEM, designed for the design of TC as measuring instruments. For example, the figure of merit of a TEM is decisive for a TEG, and its efficiency at small values of *ZT* depends on the figure of merit according to a law close to linear. Whereas for measuring instruments, the expressions that include *z* are determined by the power dependence [6] and other coefficients. For this reason, the conditions for optimizing the TEM to achieve the maximum value of sensitivity, speed, etc., will differ. In addition, there are differences in the requirements for TEM and for different measuring instruments [7]. Due to this, a universal TEM suitable for various thermoelectric products cannot be created.

However, the requirements for TEM to achieve the extremely important parameters of the TC are either not fully investigated and defined, or are chosen from considerations that do not always follow from the physical principles of the TC operation, but are determined by operational approaches. As a result, it is often difficult to choose the best TEM for TC.

The relationship of the main parameters of TC with the properties of TEM

To determine the method of selection and optimization of TEM for TC, consider the main parameters of TC.

The most influential parameters describing the properties of TC are those that determine the relationship between the initial values (current, voltage) and the output values (thermoEMF of thermocouples, thermoelectric current, power in the thermocouple circuit). To describe this connection, the following is accepted in the literature [5]:

a) sensitivity $S_I = \frac{\partial E_T}{\partial I_H}$, as the ratio of the increase in thermoEMF of the thermocouple E_T to the increase in current I_H through the heater;

b) sensitivity $S_U = \dfrac{\partial E_T}{\partial U_H}$, as the ratio of the increase in thermoEMF of the thermocouple E_T to the increase in voltage U_H;

c) sensitivity $S_W = \dfrac{E_T}{P_H}$, as the ratio of E_T to power P_H dissipated by the heater.

To determine S_I and S_U, use formulae [10, 11]:

$$S_I = 2K_1 I_H\,, \tag{5}$$

$$S_U = 2K_2 U_H\,. \tag{6}$$

Conversion factors K_I and K_2 are related by the ratio:

$$K_I = K_2 R_H^2\,, \tag{7}$$

where R_H is the resistance of the heater.

Conversion factor K_I can approximately written as [10]:

$$K_I = \frac{\alpha R_H}{S\lambda}\,, \tag{8}$$

where S is heat exchange surface, λ is heat transfer coefficient.

Expressions (5) and (6) for sensitivity S_I and S_U include only one parameter of TEM – α. Formulae (5) and (7) are valid only for some types of TC in which heat dissipation by the heater is much greater than heat dissipation by the thermocouple.

In most TC designs, the thermocouple and the heater are similar in both geometric dimensions and thermophysical parameters of the materials. In this case, as shown in [8], the thermal conductivity of the thermocouple affects the temperature distribution along the heater. Therefore, expressions (5) and (6) do not fully take into account the physical processes that take place in the TC.

The volt-watt sensitivity [9] for small temperature differences is equal to

$$S_W = \frac{\alpha r_T}{S\lambda}\,, \tag{9}$$

where r_T is thermal resistance of thermocouple which is determined by the formula:

$$r_T = \frac{l_T}{x S_T}\,, \tag{10}$$

Where l_T and S_T are the length and cross-section of thermocouple leg.

The volt-watt sensitivity is related to conversion factor K_I by the ratio:

$$S_W = \frac{K_1}{R_H}. \tag{11}$$

With regard to (11), the general expression for TC sensitivity can be written as:

$$S_I = \frac{r_\alpha r_T R_H I_H}{S\lambda}. \tag{12}$$

Thus, E_q.(12) determines the relationship between the main parameters of the thermocouple. It can be seen from formula (12) that S_I makes it possible to establish with greater certainty the dependence of the properties of the TC on the parameters of the TEM, however, the sensitivity S_I does not fully characterize them either.

To most fully determine the dependence of TC parameters on the properties of TEM, we introduce the sensitivity parameter

$$S_\eta = \frac{P}{P_H}, \tag{13}$$

which is the ratio of the power obtained on the electric load of the thermoelement to the AC electric power supplied to the TC. To find S_η, consider the equivalent schematic of a contactless TC with the load r_H, Fig. 1.

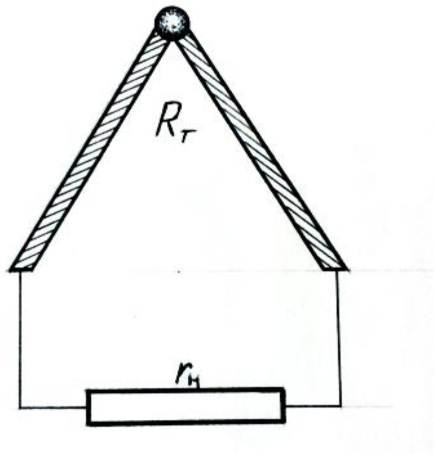

Fig. 1. Schematic of a contactless TC with the load

If the load resistance is matched with the thermocouple resistance ($r_H = R_T$), then TC works in a mode close to maximum efficiency mode, and then

$$S_\eta = \frac{E_T^2}{4R_T R_H I_H^2}. \tag{14}$$

On the other hand, the watt-watt sensitivity S_η can be recorded through the thermophysical parameters of the thermocouple TEM in the form:

$$S_\eta = \frac{z(T_1 - T_2)}{4F_p}, \tag{15}$$

where F_P is coefficient that characterizes the rationality of using heat dissipated by the heater in TC. In so doing,

$$F_p = \frac{2P_H r_T}{T_1 - T_2}. \quad (16)$$

Formula (15) according to [3] corresponds to the expression for TEG efficiency under the condition of small temperature differences in the thermocouple and under the condition that the TEM parameters for the thermocouple do not depend on temperature. Moreover, the expression for can be written [5] in the form:

$$S_\eta = \eta = \frac{(T_1 - T_2)\sqrt{1 + zT} - 1}{(T_1\sqrt{1 + zT} - T/T_1)F_P}. \quad (17)$$

From the analysis of (15) and (17) it follows that the main operational characteristics of the TC are set by the thermoelectric figure of merit of the TEM *z*, the operating drop $\Delta T = T_1 - T_2$ and the coefficient F_P dependent on the concentration of the TC.

Therefore, an increase in the sensitivity of the TC can be achieved by increasing *z* and ΔT and decreasing the coefficient F_P. However, an increase in ΔT unambiguously worsens the TC parameters: the squareness of the conversion (the K_I coefficient in formula (5) becomes temperature dependent), the ability to overcurrent, the stability over time due to the aging of the heater metal and the acceleration of diffusion processes at the thermocouple junctions. Therefore, a significant increase in ΔT is impractical.

Evaluation of the rationality of the TC design, taking into account the possibility of reducing heat losses due to the evacuation of the TC body or filling it with inert gases with low thermal conductivity (for example, xenon) [10], the optimal ratio of the geometric dimensions of the heater and thermocouple, the use of a heater with a variable cross section [11], which optimizes the use of heat from the heater, etc., significantly improve the parameters of the TC. But the main increase in sensitivity is still provided by using TEM with the maximum value of z and the Seebeck coefficient α.

Conclusion

The combination of various options for increasing the TC parameters using effective materials based on Bi_2Te_3 creates favorable opportunities for the development of TC with boundary sensitivity values.

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ДО ПИТАННЯ ВИБОРУ МАТЕРІАЛУ ТЕРМОПАРИ ДЛЯ ТЕРМОПЕРЕТВОРЮВАЧІВ МЕТРОЛОГІЧНОГО ПРИЗНАЧЕННЯ

У даній роботі розглянуто способи збільшення чутливості термоелектричного перетворювача метрологічного призначення за рахунок конструктивних удосконалень термоелектричного перетворювача та оптимізації теплових режимів роботи. Показано особливості вимог до термоелектричного матеріалу, призначеного для конструювання термоелектричних перетворювачів як вимірювальних приладів. Бібл. 11, рис. 1.
Ключові слова: термоелектричний перетворювач, нагрівник, термопара, чутливість, термоелектричний матеріал

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К ВОПРОСУ ВЫБОРА МАТЕРИАЛА ТЕРМОПАРЫ ДЛЯ ТЕРМОПРЕОБРАЗОВАТЕЛЕЙ МЕТРОЛОГИЧЕСКОГО НАЗНАЧЕНИЯ

В данной работе рассмотрены способы увеличения чувствительности термоэлектрического преобразователя метрологического назначения за счет конструктивных усовершенствований термоэлектрического преобразователя и оптимизации тепловых режимов работы. Показаны особенности требований к термоэлектрическому материалу, предназначенному для конструирования термоэлектрических преобразователей как измерительных приборов. Библ. 11, рис. 1.
Ключевые слова: термоэлектрический преобразователь, нагреватель, термопара, чувствительность, термоэлектрический материал

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AUTOMATION AND COMPUTERIZATION OF PROCESSES OF MEASURING THERMOELECTRIC PARAMETERS OF MATERIALS FORMING PART OF GENERATOR AND COOLING THERMOELECTRIC MODULES

The results of development of automation system for measuring thermoelectric parameters of materials forming part of thermoelectric modules by the absolute method are presented. The measurement control unit is built on the basis of a multi-channel analog-to-digital converter. Processing and display of measurement results is carried out using a computer to which the measurement unit is connected via a standard USB channel. The results are displayed in the form of graphs and tables.

The developed automation system is universal and makes it possible to measure the thermoelectric properties of materials both as part of generator and as part of cooling thermoelectric modules. Bibl. 9, Fig. 3.

Key words: electrical conductivity, thermoEMF, thermal conductivity, thermoelectric material, automation, computerization.

Introduction

General characterization of the problem.

It is known that the quality control of thermoelectric power converters (modules) plays an important role both in the development and in the creation on the basis of these modules of thermoelectric devices for cooling and generation of electric energy. This control is carried out by measuring the parameters of thermoelectric modules, namely cooling capacity, coefficient of performance and temperature difference on the module for thermoelectric coolers; efficiency, electric power - for thermoelectric generators. One of the best measurement methods is the absolute method [1, 2]. The main advantages of this method are the determination of the parameters of the modules in the real conditions of their operation and the possibility of instrumental minimization of the main sources of measurement errors [3].

Moreover, the absolute method makes it possible to additionally obtain information about the properties of the material forming part of the module, namely thermoEMF, electrical conductivity and thermal conductivity of a pair of thermoelectric legs. This information is useful both for optimizing the thermoelectric material for its specific applications and for improving the design of modules [4 - 6].

The implementation of these methods requires complete automation of the measurement process. In addition, this will eliminate possible subjective errors of operators when measuring electrical signals, processing them to determine σ, α, κ, Z, when plotting graphs and tables.

Therefore, *the purpose of the work* was to create a computerized measurement control system to automate the processes of determining the thermoelectric properties of materials forming part of thermoelectric power converters, processing and displaying their results.

Requirements for automation of measurements

The diagrams of the absolute method taken as a basis for creation of automated equipment for determining the parameters of generator and cooling thermoelectric modules are given in Fig.1 and Fig.2, respectively.

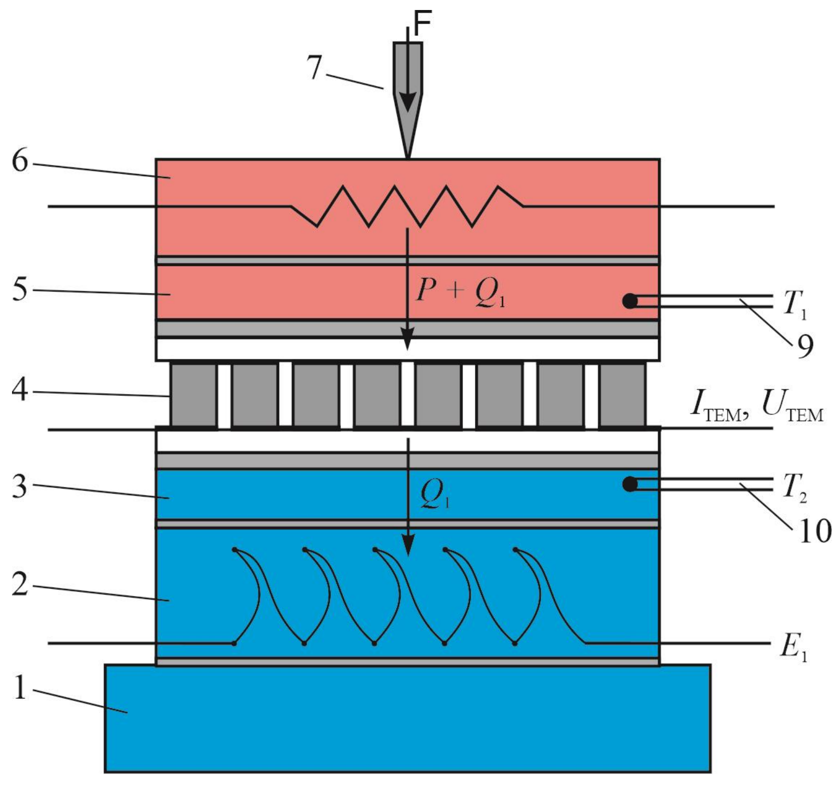

Fig. 1. Absolute method for measuring parameters of thermoelectric generator modules: 1 – thermostat; 2 – heat meter, 3, 5 – heat equalizing plates; 4 – module under study; 6 – heater; 7 – clamp; 9, 10 – thermocouples.

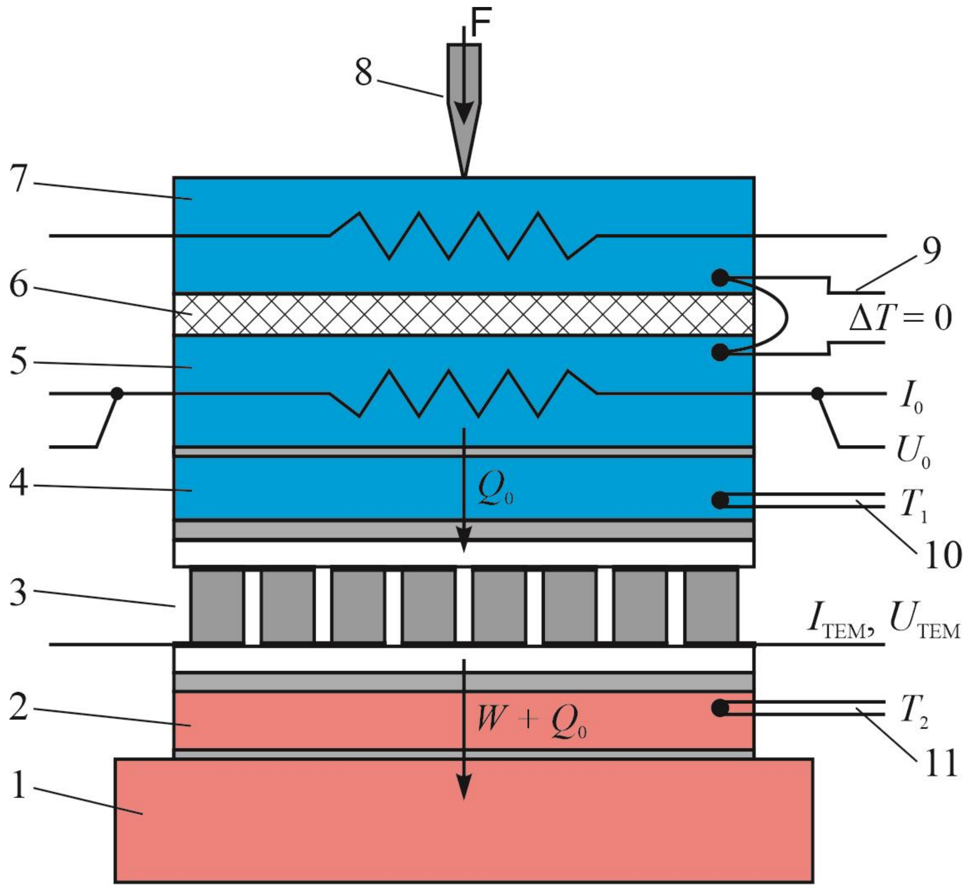

Fig. 2. Absolute method for measuring parameters of thermoelectric cooling modules:
1 – thermostat; 2, 4 – heat equalizing plates; 3 – module under study;
5 – reference heater; 6 – thermal insulation; 7 – protective heater;
8 – clamp; 9 – zero thermocouple; 10, 11 – thermocouples.

To determine the parameters of the generator thermoelectric module, the latter is placed between two heat equalizing plates, which in turn are located between the electric heater and the heat meter (Fig. 1). The other side of the heat meter is in contact with the thermostat. By means of the electric heater a given temperature difference is created on the module and the thermoEMF E_{TEM} that occurs on the module wires is measured. After that, the matched electrical load is connected to the module wires, whereby the voltage at the module wires will be equal to half of the EMF. The values of the electric current I_{TEM} passing through the module, the voltage on its wires U_{TEM} are measured, and with the help of a heat meter, the value of the heat flux Q_1, removed from the cold side of the module to the thermostat, is determined. The electrical power of the module P and the efficiency η are determined by the formulae

$$P = I_{TEM} \cdot U_{TEM}\,, \tag{1}$$

$$\eta = \frac{P}{Q_1 + P_{TEM}}. \quad (2)$$

where I_{TEM} and U_{TEM} are current and voltage of module, Q_1 is heat flux which is removed from the cold side of the module and determined by means of the heat meter, F is clamp.

When determining the parameters of cooling modules, a protective heater is additionally used to prevent heat loss from the heater through the clamping mechanism (Fig. 2). The values of cooling capacity Q_0, temperature difference ΔT and coefficient of performance ε are determined by the formulae

$$Q_0 = I_0 \cdot U_0, \quad (3)$$

$$\Delta T = T_1 - T_2, \quad (4)$$

$$\varepsilon = \frac{Q_0}{W}, \quad (5)$$

where I_0 and U_0 are current through the heater and voltage drop thereon, T_1 is the temperature of the "cold" side of module, T_2 is the temperature of the "hot" side of module, W is electrical power consumed by the module.

To find the properties of the thermoelectric material forming part of the modules, the method described in detail in [4, 6] was used.

The average values of electrical conductivity, thermoEMF, thermal conductivity and figure of merit of thermoelectric module legs are determined by the formulae

$$\sigma = \frac{1}{R_M / 2N} \frac{h_1}{a_1 \cdot b_1} \cdot K_1, \quad (6)$$

$$\alpha = \frac{E / 2N}{\Delta T} \cdot K_2, \quad (7)$$

$$\kappa = \frac{Q / 2N}{\Delta T} \frac{h_1}{a_1 \cdot b_1} \cdot K_3, \quad (8)$$

$$Z = \frac{\alpha^2 \sigma}{\kappa}, \quad (9)$$

where R_M is the AC module resistance; a_1 x b_1 is the cross-section of legs; h_1 is the height of legs; N is the number of pairs; E is the EMF of module; ΔT is the temperature difference between thermocouples arranged on the heat equalizing plates between which a module under study is located; Q is the thermal flux through the module; K_1 - K_3 are correction factors to reduce the value of measurement errors calculated for given module design and measuring equipment or determined experimentally.

To implement this method, the measurement control system must have:

- means for setting and maintaining the temperature of the measuring thermostat in a wide temperature range (temperature controller, power supply, control thermocouple, etc.);
- adjustable power supply for passing current through the module, current switch;
- adjustable power supply of the reference heater;
- means for maintaining zero temperature difference between the reference heater and the protective shield (temperature controller, power supply, control zero-thermocouple, etc.);
- high-precision voltage meter with a resolution of at least 1 μV;
- the ability to work out the necessary cyclogram for switching on / off power supplies and recording the measurement results of all measuring channels (temperatures of "hot" and "cold" thermocouples, voltage drop between modules, current and voltage values through the module, current and voltage supply of the reference heater, etc.);
- the possibility of transferring the measurement results to a computer for further processing, plotting graphs and tables, generating a module passport.

Description of measurement control system

Universal units with discrete control inputs and corresponding analog outputs have been developed. By combining these units and controlling them according to the required cyclograms with the help of a programmable controller, one can create different installations that make it possible to implement any method of measuring the parameters of thermoelectric modules.

The block diagram of the automation system for measuring the parameters of thermoelectric modules is shown in Fig. 3. It is based on a 4 - channel analog-to-digital converter (ADC) with differential inputs, the measured voltage range of which is ± (5 μV - 2.5 V). ADC differential inputs allow high-precision voltage measurements in electrical circuits of different units, which can have different power supplies.

The system also includes electronic load 18, which utilizes a range of state-of-the-art MOSFETs with low on-resistance to reduce heat generation and eliminate the need for heat sinks.

The holder of the thermoelectric module 1 uses an interchangeable heating heat exchanger, which includes a reference heater 15, with a temperature sensor in the heat equalizing plate 14, a shield heater and a differential zero-thermocouple. The heat exchanger through the block 19 is connected to the power supply units of the reference 27 and shield 24 heaters, as well as to the current / voltage meters of the reference heater 26 and the zero node 25. All these elements are included in the power unit 2.

To perform the measurement algorithm, a control unit 3 is used, containing a 4-channel precision ADC 20 and an electronic load 18, as well as control systems for the electronic load and a cooling thermostat. The electronic load control system includes a control unit 22 and a current/voltage converter of the electronic load 21. The thermostat control system includes power supplies 23 for thermostat elements and circuits of the control unit itself. The central processor 29 controls all elements of the control unit and also provides the output of the received information to the digital indicator 28. The control unit contains a power key 30 for the reference heater 15.

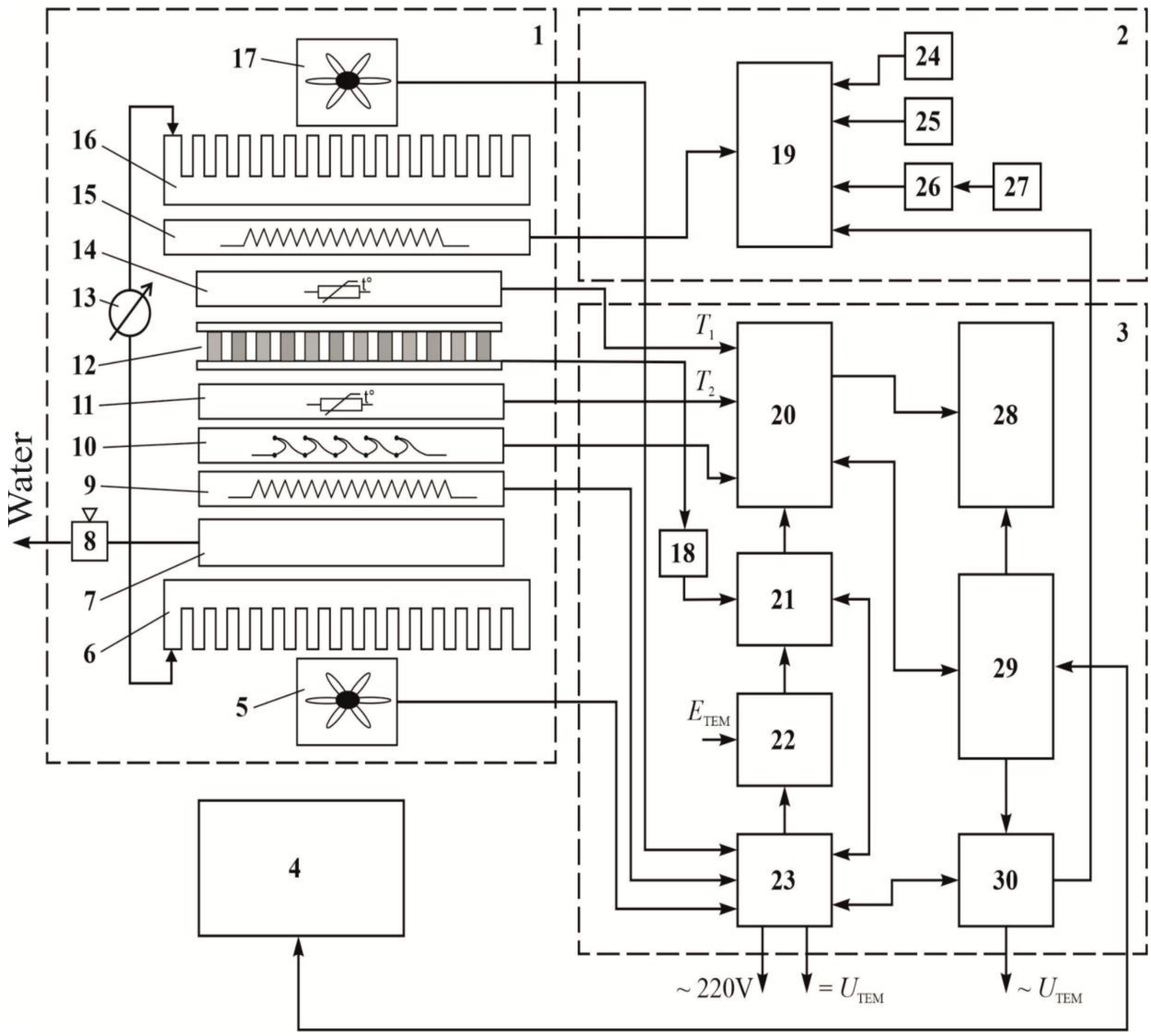

Fig. 3. Block-diagram of automation system for measuring parameters of thermoelectric modules by the absolute method: 1 – thermoelectric module holder; 2 – power unit; 3 – control unit; 4 – personal computer; 5, 17 – fans; 6, 16 – air heat exchangers; 7 – water heat exchanger; 8 –tap; 9 –thermostat electric heater; 10 – heat meter; 11, 14 – heat equalizing plates with embedded temperature sensors; 12 – thermoelectric module under study; 13 –dynamometer; 15 – module heater; 18 – electronic load; 19 – heater connection block; 20 – 4 – channel precision ADC; 21 – electronic load current / voltage converter; 22 – electronic load control unit; 23 – thermostat power supply; 24 –shield heater power unit; 25 – zero node; 26 – reference heater current/voltage meter; 27 – reference heater power unit; 28 – digital indicator; 29 – control processor; 30 – triac heater control key

The thermostat of the device contains a base-radiator 6 with a fan 5, a water heat exchanger 7 with a control water tap 8 and an additional heater 9. A heat meter 10 is placed above the thermostat to determine the heat flux. The thermoelectric module 12 under study is placed between the heat meter and the heater. The thermostat elements 7–11 can also be changeable, depending on the type of the module under study and different measurement conditions. Fans 5 and 7, as well as heater 9, are auxiliary and are used if necessary. The heating heat exchanger, the module and the thermostat in the holder are pressed against each other during measurement by the clamping unit, the force of which is controlled and determined by the dynamometer 13.

The measuring unit via the USB channel is connected to the personal computer 4, where the cyclograms of measurements are set, the necessary calculations are performed, the corresponding graphs are built, measurement protocols are formed.

To measure the parameters of the thermoelectric module, the required temperature is set on the thermostat, which is maintained on the heat equalizing plate 11. The temperature is maintained at a given level by regulating water consumption in the heat exchanger 7 and adjusting it with an additional heater 8 using a PID-PWM controller. The temperature is also set on the hot side of the thermoelectric module, which will be determined by the readings of the sensor in the plate 14 of the heating heat exchanger. The reference heater 15, through the key 30, is energized to heat the hot side of the module to the required temperature. By monitoring the zero-thermocouple signal, the shield heater automatically heats up to the temperature of the hot side of the module, thus compensating as much as possible for heat losses from the reference heater. The error in maintaining temperatures is not more than ± 0.1 °C. The heat flux passing through the module also passes through the heat meter, the signal of which is measured by the ADC. Moreover, the ADC measures the current and voltage of the reference heater through unit 26.

Depending on the chosen measurement algorithm, the heat flux can be determined both by the heat meter and by the power of the reference heater, provided that heat losses are compensated by the shield heater. This makes it possible to implement various algorithms for measuring the parameters of both generator modules and cooling modules. For example, when determining the parameters of generator modules, the thermal power from an electric heater passing through the module generates an electrical voltage at its wires. Until the temperature on the heat equalizing plates reaches the set levels, the electronic load is switched off and the thermoEMF of the module is measured with the help of an ADC. After the specified temperature difference is reached, the processor turns on the electronic load and measures the module current. In so doing, the temperature controllers of the thermostat and the heating heat exchanger automatically compensate for the thermal disturbance caused by the Peltier effect due to the action of the module current. All measured signals are fed to the controller, where they are normalized to specific physical quantities. The values of electrical voltages, currents and temperatures are displayed on a digital indicator 28, and are also sent to a personal computer 4 for calculations and plotting in a given temperature range. The sequence of measurements and the time between them are set in the cyclogram, which is formed by the operator before the start of measurements.

The appearance of measurement automation system is given in Fig. 4.

The developed system is universal. The number and characteristics of control and measuring channels allows it to be applied to other measurement methods, such as the Harman method.

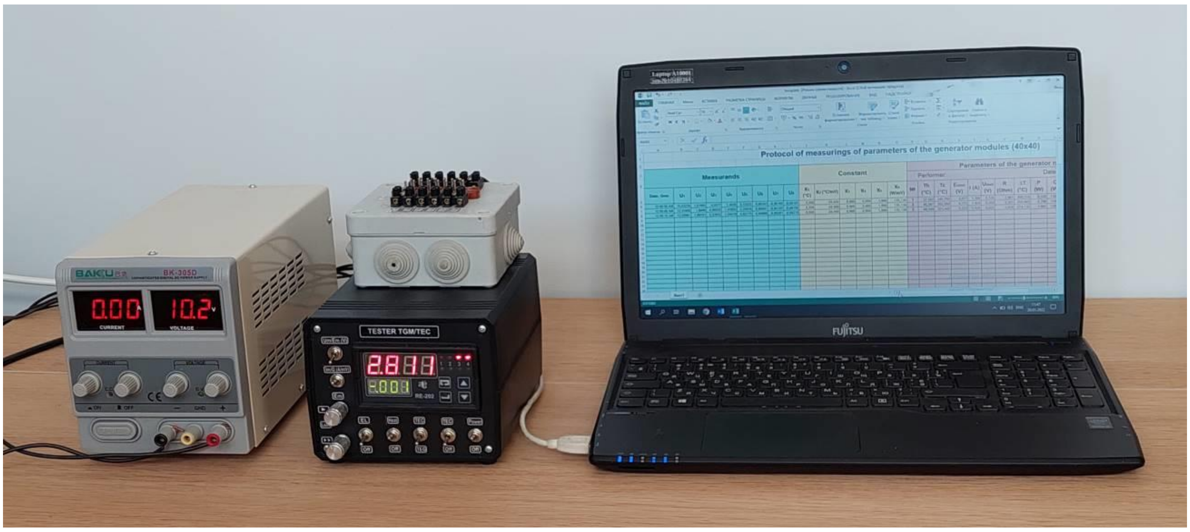

Fig. 4. Appearance of automation system for measuring parameters of thermoelectric modules.

Based on the developed control system, automation of equipment was carried out for measuring the parameters of thermoelectric generator modules with dimensions from 10×10 to 72×72 mm in the temperature range from 30 to 600 °C and cooling modules of similar sizes – from -50 to 100 °C, as well as determining the properties of thermoelectric materials within these modules.

Conclusions

1. A universal electronic control system has been developed that makes it possible to measure the parameters of thermoelectric generator and cooling modules by the absolute method, as well as to determine the properties of thermoelectric materials forming part of these modules. Automated measuring equipment based on such a system allows measurements in a wide range of operating temperatures: from -50 to 100 °C – for cooling modules and from 30 to 600 °C – for generator modules.
2. The computerization of the measurement process has been carried out. The equipment created on the basis of the developed control system makes it possible to perform real time measurements, process their results, display the measurement results in the form of graphs and tables, save them in a computer, and print out the passport of the studied module.

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АВТОМАТИЗАЦІЯ ТА КОМП'ЮТЕРИЗАЦІЯ ПРОЦЕСІВ ВИМІРЮВАНЬ ТЕРМОЕЛЕКТРИЧНИХ ПАРАМЕТРІВ МАТЕРІАЛІВ У СКЛАДІ ГЕНЕРАТОРНИХ ТА ХОЛОДИЛЬНИХ ТЕРМОЕЛЕКТРИЧНИХ МОДУЛІВ

Представлено результати розробки системи автоматизації процесу вимірювань термоелектричних параметрів матеріалів у складі термоелектричних модулів абсолютним методом. Блок керування вимірюваннями побудовано на основі багатоканального аналогово-цифрового перетворювача. Обробка та відображення результатів вимірювань проводяться за допомогою комп'ютера, до якого блок вимірювань підключається по стандартному каналу USB. Результати відображаються у вигляді графіків і таблиць. Розроблена система автоматизації є універсальною та дозволяє реалізовувати вимірювання термоелектричних властивостей матеріалів як у складі генераторних, так і у складі холодильних термоелектричних модулів. Бібл. 6, рис. 4.

Ключові слова: електропровідність, термоЕРС, теплопровідність, термоелектричний матеріал, автоматизація, комп'ютеризація.

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АВТОМАТИЗАЦИЯ И КОМПЬЮТЕРИЗАЦИЯ ПРОЦЕССОВ ИЗМЕРЕНИЙ ТЕРМОЭЛЕКТРИЧЕСКИХ ПАРАМЕТРОВ МАТЕРИАЛОВ В СОСТАВЕ ГЕНЕРАТОРНЫХ И ХОЛОДИЛЬНЫХ ТЕРМОЭЛЕКТРИЧЕСКИХ МОДУЛЕЙ

Представлены результаты разработки системы автоматизации процесса измерений термоэлектрических параметров материалов в составе термоэлектрических модулей абсолютным методом. Блок управления измерениями построен на основе многоканального аналогово-цифрового преобразователя. Обработка и отображение результатов измерений производятся с помощью компьютера, к которому блок измерений подключается через стандартный канал USB. Результаты отображаются посредством графиков и таблиц. Разработанная система автоматизации универсальна и позволяет реализовывать измерения термоэлектрических свойств материалов как в составе генераторных, так и в составе холодильных термоэлектрических модулей. Библ. 6, рис.4.

Ключевые слова: электропроводность, термоЭДС, теплопроводность, термоэлектрический материал, автоматизация, компьютеризация.

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METHOD FOR DETERMINING THE THERMOELECTRIC PARAMETERS OF MATERIALS FORMING PART OF THERMOELECTRIC COOLING MODULES

A method for determining the thermoelectric parameters of materials forming part of thermoelectric cooling modules is proposed. A detailed physical model of this method is considered and the results of estimation of possible error values are given. The efficiency of application of various methods of error reduction is investigated. Bibl. 6, Figs. 2, Table 1.

Key words: measurement, electrical conductivity, thermoEMF, thermal conductivity, figure of merit, thermoelectric module.

Introduction

When developing thermoelectric power converters, including thermoelectric cooling modules, and when creating thermoelectric devices on their basis, module metrology plays an important role. At the same time, the accuracy of determining the parameters must be high in order to reliably record the impact of new technologies and designs on the quality of modules.

Among the existing methods for determining the parameters of thermoelectric cooling modules, the most common is the Harman method [1 – 3]. However, in this method, the parameters of the cooling module under study (cooling capacity, coefficient of performance, maximum temperature difference) are not measured, but calculated from the obtained figure of merit of the module. In this case, the temperature dependences of the material parameters are not taken into account. And since the requirement of the method is a small temperature difference on the module, the obtained figure of merit values will differ from those that will actually be in the operating mode, especially in the mode close to ΔT_{max}. The total influence of factors leading to errors in the Harman method for measuring micromodules can reach 60-70 %. Even taking them into account by introducing corrections makes it possible to reduce the errors only to 10-15 %. In so doing, it is necessary to know a lot of additional information about the properties of thermoelectric material, interconnect material, current and potential wires, ceramics, etc.

The absolute method has no such shortcomings [5]. Measurement errors by the absolute method, as well as by the Harman method, can also be high (up to 25 %). However, the peculiarity and advantage of the absolute method is that these errors can be instrumentally minimized and taken into account in the form of corrections [6].

However, such equipment is designed to determine the parameters of finished products - cooling capacity, coefficient of performance and temperature difference on the module. It can be improved to obtain information about the properties of the material in the module - thermoelectric power, electrical conductivity and thermal conductivity of a pair of thermoelectric legs. This information is useful both for optimizing the thermoelectric material for specific applications and for improving the design of the modules.

The purpose of this work is to develop a method for determining the thermoelectric parameters of materials forming part of thermoelectric cooling modules, to evaluate possible errors of this method and to determine the conditions for their minimization.

Description of method for determining the σ, α, κ, *Z* of legs material when measuring the parameters of thermoelectric cooling module

When using the absolute method to determine the parameters of a thermoelectric cooling module, the module under study is placed between a thermostatically controlled base and a heat source - an electric heater (Fig. 1). It is assumed that the side and top surfaces of the heat source, as well as the side surface of the module, are adiabatically insulated.

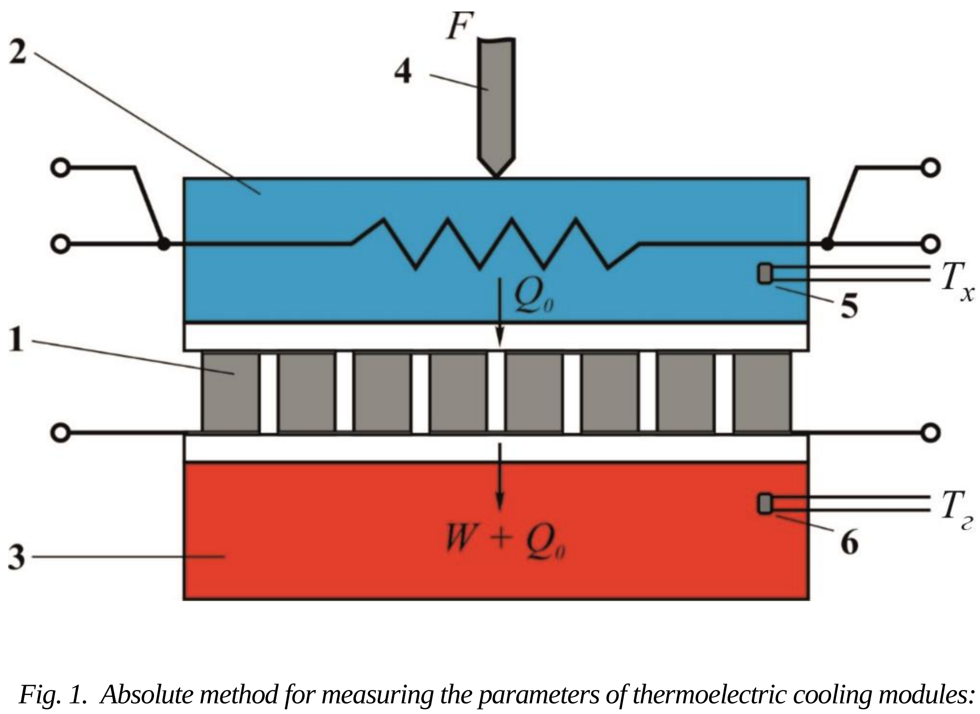

Fig. 1. Absolute method for measuring the parameters of thermoelectric cooling modules:
1 – thermoelectric module, 2 – reference heater, 3 – thermostat,
4 – clamping mechanism, 5, 6 – thermocouples.

The values of cooling capacity Q_0, temperature difference ΔT and coefficient of performance ε are determined by the formulae

$$Q_0 = I_0 \cdot U_0 , \tag{1}$$

$$\Delta T = T_{г} - T_{x} , \tag{2}$$

$$\varepsilon = \frac{Q_0}{W} , \tag{3}$$

where I_0 and U_0 is current through the heater and voltage drop thereupon, T_c is "cold" side temperature of module, T_h is "hot" side temperature of module, W is electric power consumed by the module, F is clamp.

The method for determining the average values σ, α, κ, Z of the material of legs forming part of the module is as follows:

- determination of electrical conductivity σ by the measured value of the AC resistance of the module and the known design of the module;
- creation on the module of temperature difference by means of electrical heater (with the current switched off through the module);
- determination of the Seebeck coefficient α by the measured values of module EMF and temperature difference on the module;
- determination of thermal conductivity κ by the measured values of heat flux through the module (electric heater power) and temperature difference on the module.

The average values of electrical conductivity, thermoEMF, thermal conductivity and figure of merit of the material of thermoelectric module legs are determined by the formulae

$$\sigma = \frac{1}{R_M/2N} \frac{h_1}{a_1 \cdot b_1} , \tag{4}$$

$$\alpha = \frac{E/2N}{\Delta T} , \tag{5}$$

$$\kappa = \frac{Q/2N}{\Delta T} \frac{h_1}{a_1 \cdot b_1} , \tag{6}$$

$$Z = \frac{\alpha^2 \sigma}{\kappa} , \tag{7}$$

where R_M is module resistance measured on alternating current; a_1 x b_1 is the cross-section of legs; h_1 is the height of legs; N is the number of pairs; E is the EMF of module; ΔT is temperature difference between thermocouples arranged on the heat equalizing plates between which a module under study is located; Tc_0

is the temperature on heat meter located on the cold side of module; Q is heat flow through the module which is considered equal to the power of electric heater.

However, the values of σ, α, κ, Z obtained by formulae (4 – 7) will be inaccurate, since these formulae do not take into account temperature differences between the heater (cooler) and the module, temperature differences on ceramic plates and interconnect, contact and interconnect electrical resistances, heat exchange with the environment by convection, radiation through thermocouple wires and module wires.

Estimation of possible errors of the proposed method

To estimate possible values of errors, it is necessary to consider a detailed physical model of measurement, shown in Fig. 2. It contains the thermoelectric module under study, on both sides of which copper heat equalizing plates are located. On the "cold" side of the module, above the heat equalizing plate, there is an electric heater. The module, heater and plates are pressed to the base of the thermostat by means of a clamping mechanism consisting of a screw and a bar, the ends of which are fixed to the wall of the thermostat. The clamping screw has a pointed end to reduce heat leakage. The entire system is placed under the hood of a vacuum unit that provides a vacuum of 10^{-4} Pa.

Current to electrical heater is supplied through the wires, voltage drop on it is measured by additional potential wires. To determine the properties of thermoelectric material of which the module is made, by means of electrical heater a small temperature difference, about 10K, is created on the module.

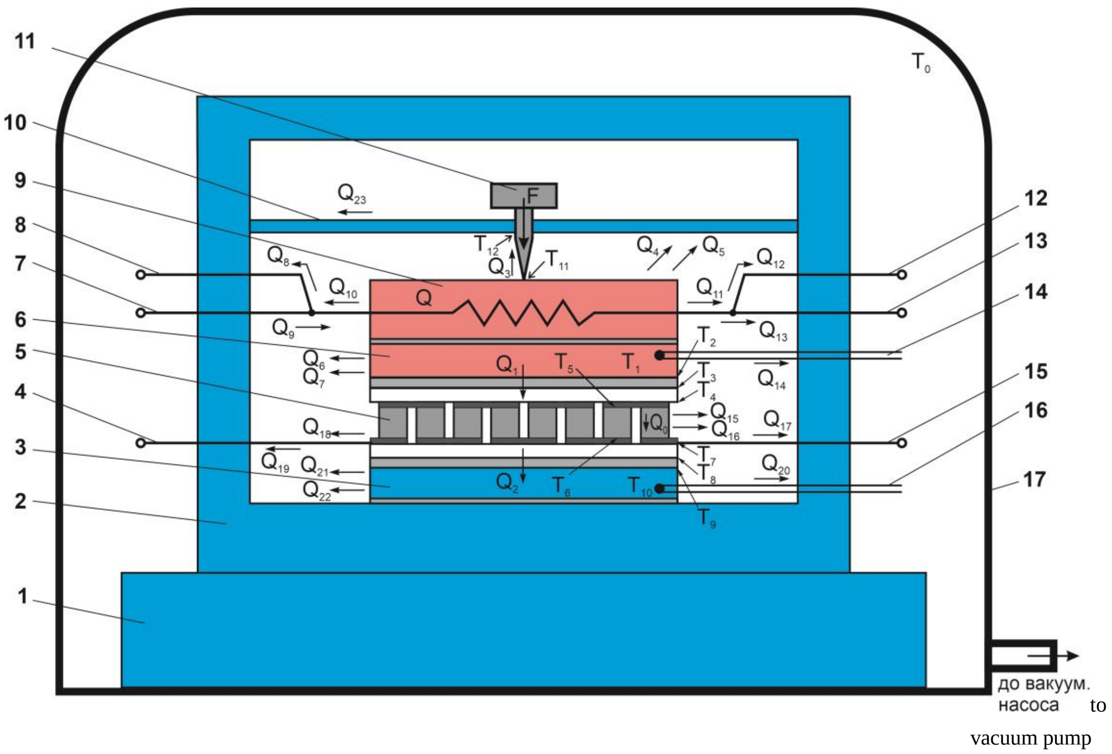

Fig. 2. Schematic of absolute method for measuring the parameters of thermoelectric cooling modules: 1 – thermostat; 2 – isothermal shield; 3, 6 – heat equalizing plates; 4, 15 – wires of module under study; 5 – module under study; 7, 13 – current heater wires; 8, 12 – potential heater wires; 9 – heater; 10 – clamping bar; 11 – clamping screw; 14, 16 – thermocouples; 17 – bell jar.

In Fig. 2: Q_1 is heat transferred from electric heater 9 to module under study 5 through heat equalizing plate 6; Q_2 is heat transferred from module 5 to heat equalizing plate 3; Q_3 is heat transferred from electric heater 9 to clamping bar 10; Q_4 is heat transferred from heater 9 to the inner surface of isothermal shield 2 by radiation; Q_5 is heat transferred from heater 9 to the inner surface of isothermal shield 2 by convection; Q_6 is heat transferred from heat equalizing plate 6 to the inner surface of isothermal shield 2 by radiation; Q_7 is heat transferred from heat equalizing plate 6 to the inner surface of isothermal shield 2 by convection; Q_8 – Q_{13} is heat transferred from heater 9 to isothermal shield 2 through current (7 and13) and potential (8 and 12) heater wires; Q_{14}, Q_{20} is heat transferred from heat equalizing plate 6 to isothermal shield 2 through thermocouple wires (14 and 16); Q_{15} is heat transferred from the lateral surface of module 5 to the inner surface of isothermal shield 2 by radiation; Q_{16} is heat transferred from the lateral surface of module 5 to the inner surface of isothermal shield 2 by convection; Q_{17}, Q_{18}, Q_{19} is heat transferred from module 5 to isothermal shield 2 through module wires (4 i 15); Q_{21} is heat transferred from heat equalizing plate 3 to the inner surface of isothermal shield 2 by radiation; Q_{22} is heat transferred from heat equalizing plate 3 to the inner surface of isothermal shield 2 by convection; Q_{23} is heat transferred from heater 9 to isothermal shield 2 through clamping bar 10, Q_0 is heat flow through module legs.

Errors in determining electrical conductivity

When determining the average value of the electrical conductivity of thermoelectric module legs, determined by formula (1), the total AC resistance of the module R_M is used, which, in addition to the resistance of the legs R_1, also includes the interconnect resistance R_2, the contact resistance R_3 and the resistance of the wires R_4

$$R_M = R_1 + R_2 + R_3 + R_4 . \qquad (11)$$

To estimate possible errors, the parameters of the thermoelectric cooling module of the type Altec-CM-1-S-SQ-27-1.8x1.8-2.0 were used as an example:

- number of pairs – N = 127;
- height of legs h_1 = 2 mm;
- cross-section of legs a_1 x b_1 = 1.8 mm x 1.8 mm;
- ceramics thickness h_2 = 0.65 mm;
- ceramics area a_2 x b_2 = 40 mm x 40 mm;
- interconnect thickness h_3 = 0.5 mm;
- electrical conductivity of legs material $\sigma = 1000$ $Ohm^{-1}\cdot cm^{-1}$.

For the above values of module geometry and material properties: R_1 = 1.568 Ohm; $R_2 \approx 0.011$ Ohm; R_3 = 0.078 Ohm (with the value of specific electrical contact resistance $5\cdot10^{-6}$ $Ohm\cdot cm^2$); R_4 = 0.008 Ohm (for two wires of diameter 1 mm and length15 cm); $R_M \approx 1.665$ Ohm.

Therefore, the error in determining the electrical conductivity due to disregard for contact resistance will be ~ 4.7%; interconnect resistance ~ 0.7%; wires resistance ~ 0.5%. The errors associated with the accuracy of information about the geometric dimensions of the legs will be determined by the manufacturing technology of the legs and methods for their geometry control. These errors can be reduced by introducing appropriate corrections calculated for a given module design or determined experimentally.

Errors in determining thermoEMF

The errors in determining the Seebeck coefficient of the material of thermoelectric module legs will arise due to the fact that formula (5) should include not the temperature difference ($T_1 - T_{10}$) on the plates in contact with the module, but the temperature difference ($T_5 - T_6$) directly on the legs

$$\alpha = \frac{E/2N}{(T_5 - T_6)}. \tag{12}$$

Temperature difference on the legs ($T_5 - T_6$) can be found as

$$(T_5 - T_6) = (T_1 - T_{10}) - (T_1 - T_2) - (T_2 - T_3) - (T_3 - T_4) - (T_4 - T_5) - (T_6 - T_7) -$$
$$- (T_7 - T_8) - (T_8 - T_9) - (T_9 - T_{10}). \tag{13}$$

where ($T_1 - T_2$) and ($T_9 - T_{10}$) are temperature differences on the parts of heat equalizing plates between thermocouple and the surfaces of plates in contact with the "hot" and "cold" module sides; ($T_2 - T_3$) and ($T_8 - T_9$) are temperature differences on the thermal contact resistances of the "hot" and "cold" module sides; ($T_3 - T_4$) and ($T_7 - T_8$) are temperature differences on the ceramic plates of the "hot" and "cold" module sides; ($T_4 - T_5$) and ($T_6 - T_7$) are temperature differences on the interconnects of the "hot" and "cold" module sides.

To estimate the values of these differences, the value of the heat flux Q_1 passing through the module was initially estimated. Without taking into account heat losses from the module and when a temperature difference of 10 K is created on the legs, the heat flux through one leg will be 0.00324 W, and through the entire module - 0.823 W (with the thermal conductivity of the legs material κ = 2 W/(m·K). Then the temperature differences on each of the elements can be estimated as:

– $(T_1 - T_2) = \frac{Q_1}{\kappa_{Cu} \cdot \frac{a_2 \cdot b_2}{h_{Cu}}} = 0.0026K$ (with the distance between the thermocouple and the surface in contact with the module h_{Cu} = 2 mm);

– $(T_2 - T_3) = \frac{Q_1}{K_{конт.}} = 0.0412K$ (with the value of contact thermal resistance $K_{cont.}$ = 20 W/K);

– $(T_3 - T_4) = \frac{Q_1}{\kappa_{Al_2O_3} \cdot \frac{a_2 \cdot b_2}{h_2}} = 0.0223K$;

– $(T_4 - T_5) = \frac{Q_1}{\kappa_{Cu} \cdot \frac{2N \cdot a_1 \cdot b_1}{h_3}} = 0.0013K$ (on the assumption that heat flux Q_1 is uniformly distributed between *2N* interconnect areas with the cross-section equal to leg cross-section and the height equal to interconnect thickness);

– $(T_6 - T_7) = (T_4 - T_5) = 0.0013K$;

– $(T_7 - T_8) = (T_3 - T_4) = 0.0223K$;

– $(T_8 - T_9) = (T_2 - T_3) = 0.0412K$;

– $(T_9 - T_{10}) = (T_1 - T_2) = 0.0026K$.

Thus, the temperature difference measured by thermocouples will be ($Th_0 - Tc_0$) = 10.135 K, which is 9.1 % more than the difference on the legs. In this case, the greatest contribution to the error is made by contact thermal resistance (0.82 %) and thermal resistance of ceramic plates (0.45 %). These errors can be significantly reduced by introducing corrections determined experimentally.

Errors in determining thermal conductivity

The error in determining the thermal conductivity of the material according to formula (3) will consist of errors in determining the temperature difference on the legs (without introducing corrections ~ 1.35%, according to the calculations given in clause 2.2), errors in measuring the geometric dimensions of the legs and errors in determining the heat flux passed through the legs.

Heat fluxes from the module and the heat equalizing late ($Q_{17} - Q_{22}$) can be ignored, since they have no impact on determining the thermal conductivity of legs material by formula (6).

To reduce heat losses, all the wires and clamping mechanism must have the so-called thermal switches, which are elements of electrically insulating material, the temperature of which is maintained close to the temperature of the heater.

Transfer of heat in the gap between the legs by radiation (Q_{24})

$$Q_{24} \approx \varepsilon_1 \sigma_B S \left(T_4^4 - T_7^4\right), \tag{14}$$

where ε_1 is the emissivity of the inner ceramic surface; σ_B = 5.67·10^{-8} W/(m^2·K^4) is Stephan-Boltzmann constant; $S = (a_1 \cdot b_1 - 2N \cdot a_2 \cdot b_2)$ is the total area of gap between the legs.

Loss of heat Q_4 from the heater by convection

$$Q_4 = H_{conv}(h_4)(2a_2 + 2b_2)\left(T_{11} - T_{екр}\right), \tag{13}$$

where H_{conv} is coefficient of convective heat exchange, h_4 is the height of the heater.

Loss of heat Q_5 from the heater by radiation

$$Q_5 = \varepsilon_4 \sigma_B (h_4)(2a_2 + 2b_2)\left(T_{11}^4 - T_{екр}^4\right), \tag{14}$$

where ε_4 is the emissivity of the lateral surface of the heater.

Loss of heat Q_6 from the heat equalizing plate by convection

$$Q_6 = H_{conv}(h_5)(2a_2 + 2b_2)\left(T_1 - T_{екр}\right), \qquad (13)$$

where h_5 is the height of the heat equalizing plate.

Loss of heat Q_7 from the heat equalizing plate by radiation

$$Q_7 = \varepsilon_5 \sigma_B (h_5)(2a_2 + 2b_2)\left(T_1^4 - T_{екр}^4\right), \qquad (14)$$

where ε_5 is the emissivity of the lateral surface of the heat equalizing plate.

Loss of heat from the module through potential heater wires (Q_8 and Q_{12})

$$Q_8 = Q_{12} = \kappa_8 \frac{S_8}{L_8}\left(T_{11} - T_{ключа}\right), \qquad (11)$$

where: S_8 is cross-section of potential wire; L_8 is the length of potential wire; κ_8 is thermal conductivity of the potential wire material; T_{switch} is thermal switch temperature.

Loss of heat from the module through heater wires (Q_9 and Q_{13})

$$Q_9 = Q_{13} = \kappa_9 \frac{S_9}{L_9}\left(T_{11} - T_{ключа}\right), \qquad (11)$$

where: S_9 is cross-section of potential wire; L_9 is the length of potential wire; κ_9 is thermal conductivity of the potential wire material.

Loss of heat Q_{14} from thermocouple wires

$$Q_{14} = \kappa_{10} \frac{S_{10}}{L_{10}}\left(T_1 - T_0\right) + \kappa_{11} \frac{S_{11}}{L_{11}}\left(T_1 - T_{ключа}\right), \qquad (12)$$

where S_{10} and S_{11} are cross-sections of thermocouple wires; L_{10} and L_{11} are lengths of thermocouple wires; κ_{10} and κ_{11} are thermal conductivities of thermocouple wires.

Loss of heat Q_{15} from the module lateral surface by convection

$$Q_{15} \approx H_{conv}(h_1 + 2h_2 + 2h_3)(2a_2 + 2b_2)\left(\frac{T_3 + T_8}{2} - \bar{T}_{екр.}\right), \qquad (9)$$

where H_{conv} is coefficient of convective heat exchange, $\bar{T}_{екр.}$ is the average temperature of shield surface which opposite to the surface of module.

Loss of heat Q_{16} from the lateral surface of module by radiation

$$Q_{16} \approx \varepsilon_2 \sigma_B (h_1 + 2h_2 + 2h_3)(2a_2 + 2b_2)\left(\left(\frac{T_3 + T_8}{2}\right)^4 - \bar{T}_{екр.}^4\right), \qquad (10)$$

where ε_2 is the emissivity of the lateral surface of module.

The following parameters were used to calculate possible values of these heat losses: emissivity – 0.7; diameter of wires and potential heater wires – 0.2 mm; their length (before contact with the thermal switch) – 10 cm; diameter of thermocouple wires – 0.2 mm; their length (before contact with the thermal switch) – 10 cm; number of pairs – 127; legs height – 2 mm; legs cross section – 1.8 mm×1.8 mm; ceramics thickness – 0.65 mm; ceramics area – 40 mm×40 mm; interconnect thickness – 0.5 mm; heater height – 5 mm; heat equalizing plate height – 5 mm.

The results of estimating possible errors in determining the heat flux through the legs of the material, caused by heat losses through the wires of the heater and thermocouples, clamp, as well as heat losses by radiation from the surface of the heater, heat equalizing plate and module are given in Table 1. The results are obtained for the case when the temperature of the thermal switch is equal to the temperature of the heat equalizing plate T_{10}, and the temperature difference between the hot and cold plates ($T_1 - T_{10}$) is 10 K. The case of using a protective shield with a temperature that differs from the heater temperature by no more than 1K is also considered.

Table 1.

Results of estimating possible errors when determining heat flux through material legs.

№	**Name of losses**	**δ*Q*, % (the ratio of heat losses to heat flux through the legs)**	
		Without a protective shield	With a protective shield
1	Losses by radiation in the gap between the legs	3.85	3.85
2	Losses by radiation from the heater surface	11.9	1.25
3	Losses by radiation from the plate surface	3.96	0.42
4	Losses by radiation from the module surface	1.56	0.16
5	Losses in the clamp	2.77	0.28
6	Losses in heater wires	0.04	<0.01
7	Losses in thermocouple wires	<0.01	<0.01
Total:		24.08	5.96

Thus, the greatest losses are caused by radiation from the surface of the heater, module and heat plate, as well as radiation in the gap between the legs inside the thermoelectric module. In general, radiation losses account for almost 90 % of all heat losses. However, they can be drastically reduced when using a protective shield. For the case when the shield temperature differs from the heater temperature by no more than 1K, the total heat loss, hence the error in determining the heat flux through the legs of the module will not exceed 6 %. Taking into account the errors in determining the temperature difference on the legs (without introducing corrections ~ 1.35 %), the error in determining the thermal conductivity of the thermoelectric material from which the module legs are made will be up to 7.4 %.

The obtained results are the basis for the modernization of equipment for measuring the parameters of thermoelectric cooling modules.

Conclusions

1. A method is proposed for determining the thermoelectric parameters of the legs material of thermoelectric cooling module when measuring its parameters by the absolute method. A detailed physical model of this method is considered and the results of estimating possible values of errors are given by the example of a thermoelectric module of the type Altec-CM-1-S-SQ-127-1.8x1.8-2.0.
2. It is shown that, in determining the electrical conductivity, the decisive factor leading to errors of ~ 4.7 %, is failure to take into account the electrical contact resistance. The impact of the interconnect resistance will be ~ 0.7 %, the resistance of wires ~ 0.5 %. To reduce the value of these errors, appropriate corrections should be made, calculated for a given module design or determined experimentally.
3. In determining the thermoEMF, the largest contribution to the error is made by errors in determining the temperature difference on the legs caused by contact thermal resistance (0.82 %) and thermal resistance of ceramic plates (0.45 %). These errors can be also significantly reduced by making appropriate corrections.
4. When determining the thermal conductivity, apart from the errors in determining the temperature difference on the legs, an additional factor is the presence of heat losses, the total value of which, when using thermal switches and a protective shield, will be up to 7.4 %. The largest component here (up to 4 %) is heat loss by radiation in the gap between the legs. However, these losses for a known module design can be determined and taken into account in the form of corrections.

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МЕТОДИКА ВИЗНАЧЕННЯ ТЕРМОЕЛЕКТРИЧНИХ ПАРАМЕТРІВ МАТЕРІАЛІВ У СКЛАДІ ТЕРМОЕЛЕКТРИЧНИХ МОДУЛІВ ОХОЛОДЖЕННЯ

Запропоновано методику визначення термоелектричних параметрів матеріалів у складі термоелектричних модулів охолодження. Розглянуто детальну фізичну модель цієї методики та наведено результати оцінки можливих величин похибок. Досліджено ефективність застосування різних методів зниження похибок. Бібл. 6, рис. 2, табл. 1.
Ключові слова: вимірювання, електропровідність, термоЕРС, теплопровідність, добротність, термоелектричний модуль.

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МЕТОДИКА ОПРЕДЕЛЕНИЯ ТЕРМОЭЛЕКТРИЧЕСКИХ ПАРАМЕТРОВ МАТЕРИАЛОВ В СОСТАВЕ ТЕРМОЭЛЕКТРИЧЕСКИХ МОДУЛЕЙ ОХЛАЖДЕНИЯ

Предложена методика определения термоэлектрических параметров материалов в составе термоэлектрических модулей охлаждения. Рассмотрена подробная физическая модель этой методики и приведены результаты оценки возможных величин погрешностей. Исследована эффективность применения различных методов снижения погрешностей. Библ. 6, рис. 2, табл. 1.

Ключевые слова: измерение, электропроводность, термоЭДС, теплопроводность, добротность, термоэлектрический модуль.

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A BENCH FOR CALIBRATING HEAT METERS FOR DETERMINATION OF PARAMETERS OF GENERATOR THERMOELECTRIC MODULES

The results of the development of a bench for calibrating heat meters to determine the heat flux through the generator thermoelectric module when measuring its parameters by the absolute method are presented. The bench allows one to study the metrological characteristics of heat meters in the required temperature range and transfer the measurement results to a personal computer in real time. Bibl. 6, Fig. 6.

Key words: thermoelectric module, heat meter, calibration, accuracy.

Introduction

General characterization of the problem

Improving the quality and reducing the cost of thermoelectric generator modules requires their use in the development and manufacture of advanced technologies and high-performance materials. At the same time, increasing the accuracy in determining the thermal and electrical parameters of the modules makes it possible to more predictably adjust the module production technology, as well as to optimally approach the direct creation of final devices based on these generator modules. The accuracy of determining the parameters of modules should be such as to reliably record the impact of new technologies and designs on the quality of modules. No less important is the metrological support in the creation of thermoelectric generators. The identity and reliability of measurements of module parameters from suppliers and consumers of modules that use them in thermoelectric products, eliminates the problems that arise.

The most reliable and accurate among the existing methods of determining the parameters of thermoelectric generator modules is the absolute method [1 – 3], which allows measuring parameters of modules in real conditions of their operation and allows instrumental minimization of major sources of measurement errors [4]. In addition, the absolute method makes it possible to additionally obtain information about the properties of the material in the composition of the module – thermoEMF, electrical conductivity and thermal conductivity of a pair of thermoelectric legs [5, 6]. This information is useful both for optimizing thermoelectric material for its specific applications and for improving the design of modules. When using the absolute method, one of the main sources of errors is the inaccuracy in determining the heat flux passing through the module, associated with the presence of heat losses due to convection and radiation from the surface of the reference heater and the module, as well as heat losses through conductors and structural elements of the measuring equipment. An effective method of reducing these errors is the use of heat meters to determine the heat flow from the cold side of the module to the thermostat [3]. It is obvious that the accuracy of calibration of the heat meter will play a crucial role.

The purpose of this work is to create a bench for calibrating heat meters for high-precision determination of the heat flux through the investigated generator thermoelectric module when measuring its parameters by the absolute method.

Description of the absolute method of measuring the parameters of thermoelectric generator modules

To measure the parameters of the generator thermoelectric modules by the absolute method, a measuring cell is used, which includes hot and cold heat exchangers, between which the investigated module is placed. An electric heating resistive element is usually used as a hot heat exchanger. Cold heat exchanger can be liquid or air cooled. Heat exchangers have built-in temperature sensors, which are placed in heat-equalizing plates to reduce measurement errors. The heat exchangers and the module are pressed together with a given force. The thermal model of such a measuring cell is shown in Fig. 1

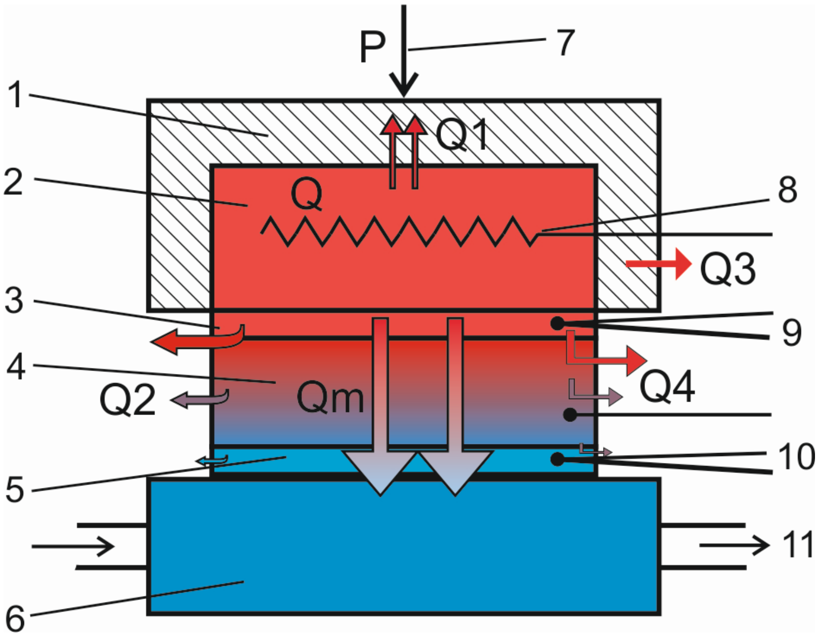

Fig. 1. The thermal model of a measuring cell to determine parameters of generator thermoelectric modules by the absolute method: 1 – hot heat exchanger; 2 – reference heater; 3 – "hot" heat-equalizing plate; 4 – generator thermoelectric module; 5 – "cold" heat-equalizing plate; 6 – cold liquid heat exchanger; 7 – clamping unit; 8 – electric wires of reference heater; 9 – thermocouple of "hot" heat exchanger; 10 – thermocouple of "cold" heat exchanger; 11 – heat carrier (liquid)

In Fig. 1, the arrows show the paths of heat generated in the reference heater. It passes through the module and is dissipated by the heat carrier in the cold heat exchanger. Schematically, the size of the arrows is proportional to the heat fluxes.

Under ideal conditions, all the heat output of the reference heater must pass through the module. But in real conditions, part of the heat capacity is dissipated into the environment. Thus, in Fig. 1: Q is heat released by the reference heater; Q_1 is heat losses on the structural elements of the hot heat exchanger housing; Q_2 is heat losses from the surface of module and heat-equalizing plates due to convection and radiation; Q_3 is heat losses in the electrical wires of the heater; Q_4 is heat losses in the electrical wires of the module and temperature sensors; Q_m is useful thermal power that passed through the module and created operating temperature difference thereupon.

Obviously,

$$Q_m = Q - Q_1 - Q_2 - Q_3 - Q_4.$$

The magnitude of heat loss depends on many factors and is usually difficult to take into account, so it is necessary to use special methods to accurately determine heat fluxes.

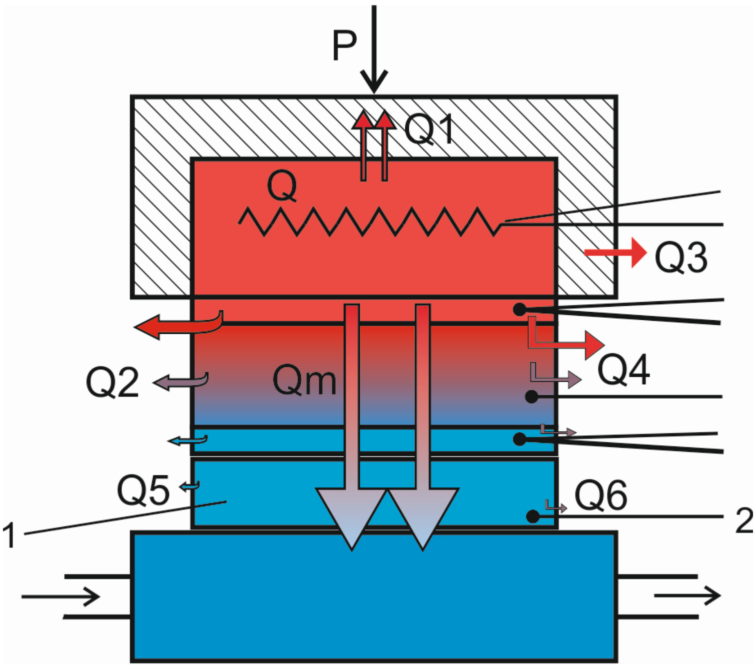

Fig. 2. Schematic of the measuring cell with a heat meter: 1 – heat meter; 2 – potential heat meter wires

The use of heat meters greatly simplifies the measurement process and increases the accuracy of determining the parameters of generator modules. The real thermal model of the measuring cell with a heat meter is shown in Fig. 2. Since the heat meter is sequentially added to the thermal circuit of the measuring cell, a temperature difference is also created on it, and heat (Q_5 and Q_6) will also be lost from the side surface of the heat meter and through the electrical wires, however, these heat losses will not be large, since the temperature the heat meter is close to the ambient temperature.

Description of the bench for calibrating heat meters

When used in equipment for determining the parameters of generator modules, a separate heat meter is produced for each of the standard sizes of modules that can be measured on this equipment. The appearance of heat meters of different sizes is shown in Fig. 3.

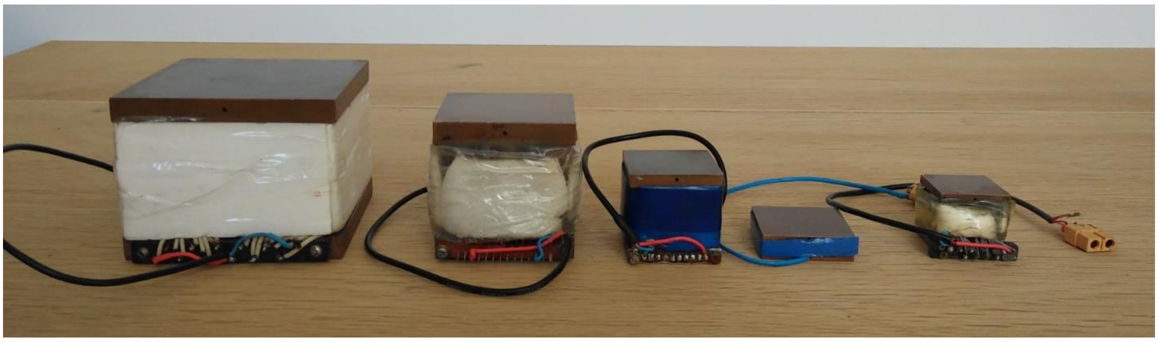

Fig. 3. Heat meters of different sizes for equipment for determining the parameters of thermoelectric generator modules by the absolute method

The heat meter consists of a monolithic body made of a material with high thermal conductivity, in which a thermopile is placed on the side surface (Fig. 4). The end surfaces of the body of the heat meter are its working surfaces, parallel to each other and made with high surface finish for high-quality thermal contact with the module and the cold heat exchanger. Junctions of thermopile thermocouples are placed on the side surface in two rows in height, each row being on its common plane, parallel to the base. The junctions are located on special pins that have good thermal contact with the body of the heat meter, but are electrically isolated from it.

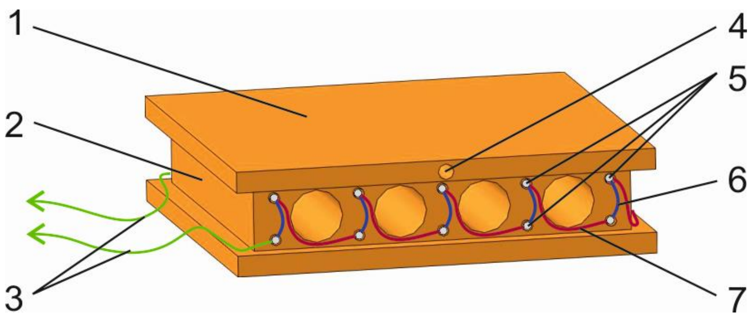

Fig. 4. Heat meter design:
1 – heat meter work area; 2 – heat meter body; 3 – heat meter electrical wires;
4 – opening for measuring thermocouple; 5 – junctions of differential thermocouples;
6 – n-legs of thermocouples; 7 – p-legs of thermocouples

General requirements for heat meters: the dimensions of the working area of the heat meter should be close to the dimensions of the working surfaces of the generator module; the height of the heat meter should be optimal to create a minimum temperature difference in the heat meter, but sufficient to ensure its high sensitivity. The conversion factor of the heat meter, its volt-watt sensitivity, must be stable over the operating temperature range.

To optimize the heat meter along the passage of the heat flux in the body, technological selections can be made (for example, in Fig. 4 it can be seen that holes are made in the body of the heat meter).

Differential thermocouples are combined into a thermopile to increase the sensitivity of the heat meter, which depends on the material of the thermocouples, the thermal conductivity of the heat meter body material and its design, the distance between the junctions, as well as the accuracy in determining the distance and quality of thermal contact between the thermocouple junction and the body. Obviously, such errors are difficult to take into account, so heat meters need to be calibrated.

The heat meter is calibrated by direct measurement of the thermopile signal from the action of the temperature difference caused by the heat flux created by the electric heater. At the same time, the electric power of this heater is determined. The voltage-watt sensitivity of the heat meter will be determined by the ratio:

$$k = \frac{E}{Q} \qquad \text{as} \qquad Q = W = Ih \cdot Uh, \qquad \text{then} \qquad k = \frac{E}{Ih \cdot Uh}$$

where k is heat meter volt-watt sensitivity, E is heat meter signal; Q is heat flux that passed through the heat meter, W is electrical power of the main heater; Ih is current of the main heater, Uh is voltage on the main heater.

The heat flux is directed only through the heat meter, and heat loss from the heater to the environment is eliminated with the help of protective and radiation shields.

The appearance of the developed bench is given in Fig. 5.

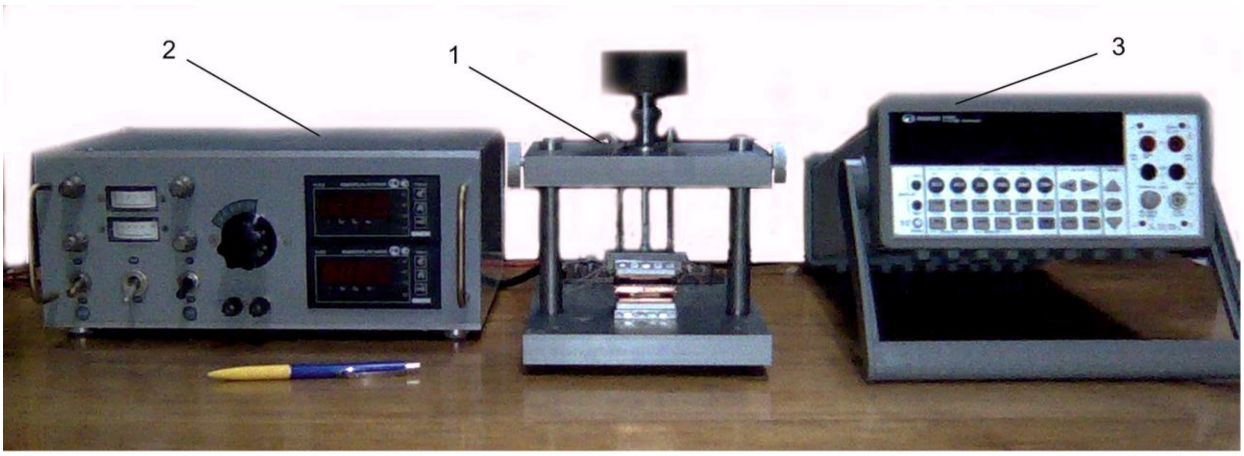

Fig. 5. Appearance of a bench for calibrating heat meters:
1 – measuring unit; 2 – control unit; 3 – high-precision digital multimeter

The bench consists of a measuring unit, a control unit and a measuring device (high-precision digital multimeter). In turn, the measuring block contains an aluminum platform on which liquid heat exchangers, a clamping device and a switching block are placed. The heat meter under study is placed between the hot and cold heat exchangers. The layout of the bench is shown in Fig. 6.

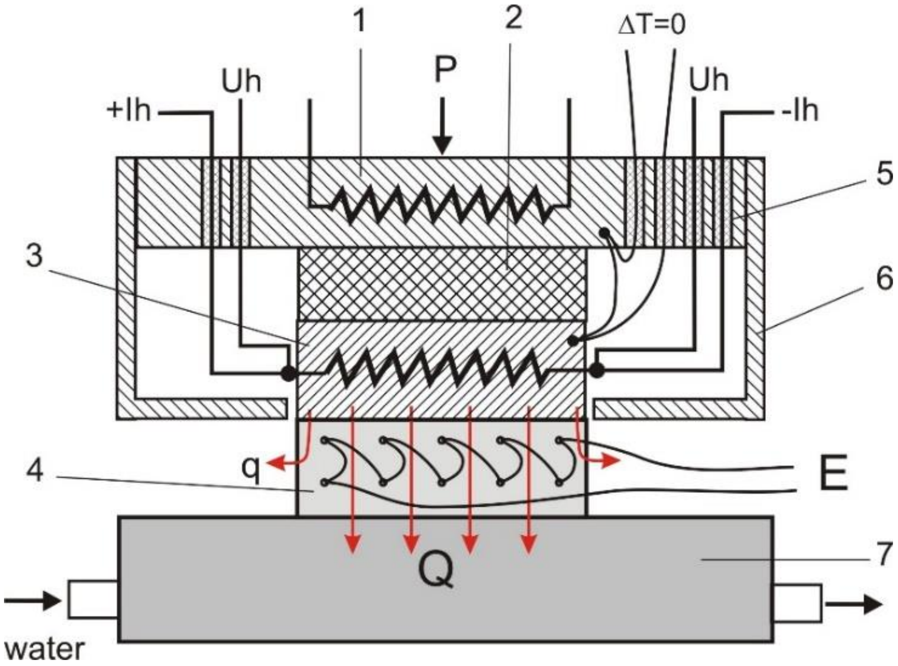

Fig. 6 – Heat meter calibration layout:
1 – protective heater; 2 – thermal insulation; 3 – main heater;
4 – heat meter; 5 – thermal locks; 6 – protective shield;
7 – heat removal unit

On the lower base of the aluminum platform and on the suspension of the upper base of the measuring unit, two identical heat exchange units are fixed, which are designed to remove heat, namely cold heat exchangers. These heat exchangers are reversible, since they are based on thermoelectric coolers (TEC) with liquid waste heat removal and can operate both in cooling and heating modes, depending on the direction of electric current flux. On the working side of the TEC, copper heat-equalizing plates with built-in temperature sensors – platinum resistance thermometers – are fixed. These plates in the central part have a flat surface polished with a high class of cleanliness – a working platform. The heat meter under study is placed on this area. The other side of the heat meter is in contact with a hot heat exchanger – a flat heater with two (upper and lower) polished working surfaces. The flat heater is made thin enough so that its side surface is as small as possible and it warms up well throughout its entire volume. A temperature sensor is also mounted in the body of this heater – a platinum resistance thermometer. The use of platinum temperature sensors makes it possible to measure and maintain the temperatures of the working areas of heat exchangers using thermostats with an accuracy of at least 0.1 ° C. During calibration, the heater is powered by a separate stabilized DC source. Measurement of the voltage on the heater is carried out by precision voltmeters with an error of 0.05 %. The current through the heater is also determined by the voltage drop across the reference resistance in the heater power circuit. The error in determining the current is about 0.1 %. In addition, there will be heat loss to the environment through electrical conductors. Therefore, measures should be taken to minimize these losses, in particular, the use of thermal locks. Thermal locks are insulators made of beryllium ceramics with high thermal conductivity, which provide local heating of the conductor section at the exit point from the heater's protective housing to the heater temperature. Thus, heat losses through underwater conductors are eliminated as much as possible. The measuring thermocouples are mounted in the same way.

Since a temperature difference is created on the heat meter along its height, the heat meter body material (usually metal – copper, aluminum, brass, etc.) has a temperature dependence of the thermal conductivity coefficient, and the thermocouple material has a temperature dependence of the Seebeck coefficient, then the heat meter must be calibrated over the entire range of operating cold temperatures of the investigated thermoelectric module.

In the developed bench, the process of thermostating all heat exchangers is controlled by a specially designed electronic unit containing adjustable power supplies for the TEC and heaters, two two-channel microprocessor-based temperature controllers RE-202, interconnect elements and measurement control terminals. All terminals of electrical components from the measuring unit converge on the terminal block and are connected to the control unit by means of a cable. A measuring device is also connected to the control unit - a high-precision digital multimeter M3500 with the ability to transfer measurement results to a personal computer in real time. Thus, the developed bench makes it possible to calibrate heat meters and study their metrological characteristics in dynamics.

An example of the temperature dependence of the volt-voltage sensitivity of a heat meter with dimensions of 40x40 mm is shown in Fig. 6.

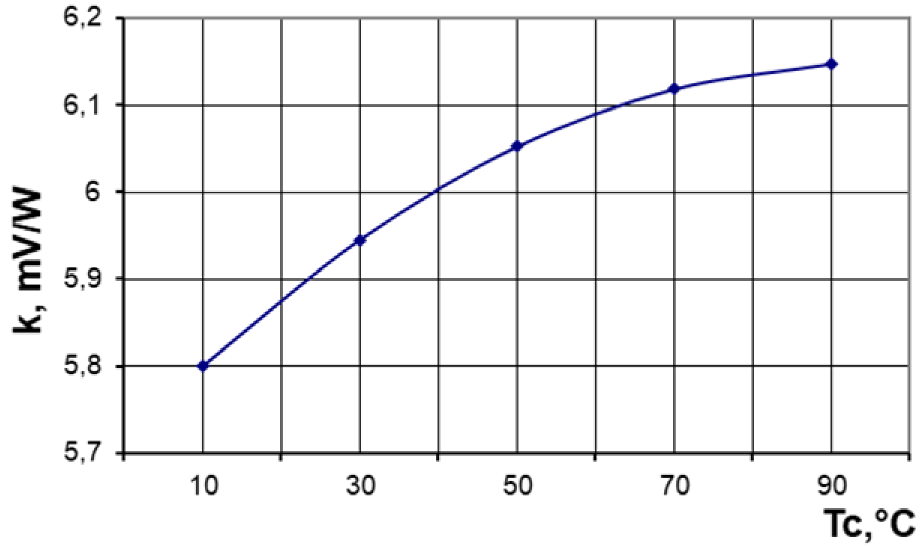

Fig. 6. The temperature dependence of the volt-watt sensitivity of heat meter with dimensions of 40x40

Conclusions

1. A bench for calibrating heat meters for determining heat flux through generator thermoelectric module when measuring its parameters by the absolute method has been developed and

manufactured. The bench allows one to study the metrological characteristics of heat meters and transfer the measurement results to a personal computer in real time.

2. An improved method for calibrating heat meters with the use of auxiliary highly sensitive heat flux converter has been implemented, which makes it possible to improve the accuracy of experimental determination of the volt-watt sensitivity of heat meters.

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СТЕНД ДЛЯ ГРАДУЮВАННЯ ТЕПЛОМІРІВ ДЛЯ ВИЗНАЧЕННЯ ПАРАМЕТРІВ ГЕНЕРАТОРНИХ ТЕРМОЕЛЕКТРИЧНИХ МОДУЛІВ

Представлено результати розробки стенду для градуювання тепломірів для визначення теплового потоку через генераторний термоелектричний модуль при вимірюваннях його параметрів абсолютним методом. Стенд дає можливість досліджувати метрологічні характеристики тепломірів у необхідному інтервалі температур та у реальному часі передавати результати вимірювань на персональний комп'ютер. Бібл. 6, рис. 6.
Ключові слова: термоелектричний модуль, тепломір, градуювання, точність.

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СТЕНД ДЛЯ ГРАДУИРОВКИ ТЕПЛОМЕРОВ ДЛЯ ОПРЕДЕЛЕНИЯ ПАРАМЕТРОВ ГЕНЕРАТОРНЫХ ТЕРМОЭЛЕКТРИЧЕСКИХ МОДУЛЕЙ

Представлены результаты разработки стенда для градуировки тепломеров для определения теплового потока через генераторный термоэлектрический модуль при измерениях его параметров абсолютным методом. Стенд позволяет исследовать метрологические характеристики тепломеров в необходимом интервале температур и в реальном времени передавать результаты измерений на персональный компьютер. Библ. 6, рис. 6.
Ключевые слова: термоэлектрический модуль, тепломер, градуировка, точность.

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ARTICLE SUBMISSION GUIDELINES

For publication in a specialized journal, scientific works are accepted that have never been printed before. The article should be written on an actual topic, contain the results of an in-depth scientific study, the novelty and justification of scientific conclusions for the purpose of the article (the task in view).

The materials published in the journal are subject to internal and external review which is carried out by members of the editorial board and international editorial board of the journal or experts of the relevant field. Reviewing is done on the basis of confidentiality. In the event of a negative review or substantial remarks, the article may be rejected or returned to the author(s) for revision. In the case when the author(s) disagrees with the opinion of the reviewer, an additional independent review may be done by the editorial board. After the author makes changes in accordance with the comments of the reviewer, the article is signed to print.

The editorial board has the right to refuse to publish manuscripts containing previously published data, as well as materials that do not fit the profile of the journal or materials of research pursued in violation of ethical norms (for instance, conflicts between authors or between authors and organization, plagiarism, etc.). The editorial board of the journal reserves the right to edit and reduce the manuscripts without violating the author's content. Rejected manuscripts are not returned to the authors.

Submission of manuscript to the journal

The manuscript is submitted to the editorial office of the journal in paper form in duplicate and in electronic form on an electronic medium (disc, memory stick). The electronic version of the article shall fully correspond to the paper version. The manuscript must be signed by all co-authors or a responsible representative.

In some cases it is allowed to send an article by e-mail instead of an electronic medium (disc, memory stick).

English-speaking authors submit their manuscripts in English. Russian-speaking and Ukrainian-speaking authors submit their manuscripts in English and in Russian or Ukrainian, respectively. Page format is A4. The number of pages shall not exceed 15 (together with References and extended abstracts). By agreement with the editorial board, the number of pages can be increased.

To the manuscript is added:

1. Official recommendation letter, signed by the head of the institution where the work was carried out.

2. License agreement on the transfer of copyright (the form of the agreement can be obtained from the editorial office of the journal or downloaded from the journal website – Dohovir.pdf). The license agreement comes into force after the acceptance of the article for publication. Signing of the license agreement by the author(s) means that they are acquainted and agree with the terms of the agreement.

3. Information about each of the authors – full name, position, place of work, academic title, academic degree, contact information (phone number, e-mail address), ORCID code (if available). Information about the authors is submitted as follows:

authors from Ukraine - in three languages, namely Ukrainian, Russian and English;
authors from the CIS countries - in two languages, namely Russian and English;
authors from foreign countries – in English.

4. Medium with the text of the article, figures, tables, information about the authors in electronic form.

5. Colored photo of the author(s). Black-and-white photos are not accepted by the editorial staff. With the number of authors more than two, their photos are not shown.

Requirements for article design

The article should be structured according to the following sections:

- *Introduction*. Contains the problem statement, relevance of the chosen topic, analysis of recent research and publications, purpose and objectives.
- *Presentation of the main research material* and the results obtained.
- *Conclusions* summing up the work and the prospects for further research in this direction.
- *References*.

The first page of the article contains information:

1) in the upper left corner – UDC identifier (for authors from Ukraine and the CIS countries);

2) surname(s) and initials, academic degree and scientific title of the author(s);

3) the name of the institution where the author(s) work, the postal address, telephone number, e-mail address of the author(s);

4) article title;

5) abstract to the article – not more than 1 800 characters. The abstract should reflect the consistent logic of describing the results and describe the main objectives of the study, summarize the most significant results;

6) key words – not more than 8 words.

The text of the article is printed in Times New Roman, font size 11 pt, line spacing 1.2 on A4 size paper, justified alignment. There should be no hyphenation in the article.

Page setup: “mirror margins” – top margin – 2.5 cm, bottom margin – 2.0 cm, inside – 2.0 cm, outside – 3.0 cm, from the edge to page header and page footer – 1.27 cm.

Graphic materials, pictures shall be submitted in color or, as an exception, black and white, in .opj or .cdr formats, .jpg or .tif formats being also permissible. According to author’s choice, the tables and partially the text can be also in color.

Figures are printed on separate pages. The text in the figures must be in the font size 10 pt. On the charts, the units of measure are separated by commas. Figures are numbered in the order of their arrangement in the text, parts of the figures are numbered with letters – a, b, .. On the back of the figure, the title of the article, the author (authors) and the figure number are written in pencil. Scanned images and graphs are not allowed to be inserted.

Tables are provided on separate pages and must be executed using the MSWord table editor. Using pseudo-graph characters to design tables is inadmissible.

Formulae shall be typed in Equation or MatType formula editors. Articles with formulae written by hand are not accepted for printing. It is necessary to give definitions of quantities that are first used in the text, and then use the appropriate term.

Captions to figures and tables are printed in the manuscript after the references.

Reference list shall appear at the end of the article. References are numbered consecutively in the order in which they are quoted in the text of the article. References to unpublished and unfinished works are inadmissible.

Attention! In connection with the inclusion of the journal in the international bibliographic abstract database, the reference list should consist of two blocks: CITED LITERATURE and REFERENCES (this requirement also applies to English articles):

CITED LITERATURE – sources in the original language, executed in accordance with the

Ukrainian standard of bibliographic description DSTU 8302:2015. With the aid of VAK.in.ua (http://vak.in.ua) you can automatically, quickly and easily execute your “Cited literature” list in conformity with the requirements of State Certification Commission of Ukraine and prepare references to scientific sources in Ukraine in understandable and unified manner. This portal facilitates the processing of scientific sources when writing your publications, dissertations and other scientific papers.

REFERENCES – the same cited literature list transliterated in Roman alphabet (recommendations according to international bibliographic standard APA-2010, guidelines for drawing up a transliterated reference list “References” are on the site http//www.dse.org.ua, section for authors).

To speed up the publication of the article, please adhere to the following rules:

- in the upper left corner of the first page of the article – the UDC identifier;
- family name and initials of the author(s);
- academic degree, scientific title;

begin a new line, Times New Roman font, size 12 pt, line spacing 1.2, center alignment;

- name of organization, address (street, city, zip code, country), e-mail of the author(s);

begin a new line 1 cm below the name and initials of the author(s), Times New Roman font, size 11 pt, line spacing 1.2, center alignment;

- the title of the article is arranged 1 cm below the name of organization, in capital letters, semi-bold, font Times New Roman, size 12 pt, line spacing 1.2, center alignment. The title of the article shall be concrete and possibly concise;
- the abstract is arranged 1 cm below the title of the article, font Times New Roman, size 10 pt, in italics, line spacing 1.2, justified alignment in Ukrainian or Russian (for Ukrainian-speaking and Russian-speaking authors, respectively);
- key words are arranged below the abstract, font Times New Roman, size 10 pt, line spacing 1.2, justified alignment. The language of the key words corresponds to that of the abstract. Heading “Key words” - font Times New Roman, size 10 pt, semi-bold;
- the main text of the article is arranged 1 cm below the abstract, indent 1 cm, font Times New Roman, size 11 pt, line space spacing 1.2, justified alignment;
- formulae are typed in formula editor, fonts Symbol, Times New Roman. Font size is “normal” – 12 pt, “large index” – 7 pt, “small index” – 5 pt, “large symbol” – 18 pt, “small symbol” – 12 pt. The formula is arranged in the text, center aligned and shall not occupy more than 5/6 of the line width, formulae are numbered in parentheses on the right;
- dimensions of all quantities used in the article are represented in the International System of

Units (SI) with the explication of the symbols employed;

- figures are arranged in the text. The figures and pictures shall be clear and contrast; the plot axes – parallel to sheet edges, thus eliminating possible displacement of angles in scaling; figures are submitted in color, black-and-white figures are not accepted by the editorial staff of the journal;
- tables are arranged in the text. The width of the table shall be 1 cm less than the line width. Above the table its ordinary number is indicated, right alignment. Continuous table numbering throughout the text. The title of the table is arranged below its number, center alignment;

• references should appear at the end of the article. References within the text should be enclosed in square brackets behind the text. References should be numbered in order of first appearance in the text. Examples of various reference types are given below.

Examples of LITERATURE CITED

Journal articles

Anatychuk L.I., Mykhailovsky V.Ya., Maksymuk M.V., Andrusiak I.S. Experimental research on thermoelectric automobile starting pre-heater operated with diesel fuel. *J.Thermoelectricity*. 2016. №4. P.84–94.

Books

Anatychuk L.I. *Thermoelements and thermoelectric devices. Handbook.* Kyiv, Naukova dumka, 1979. 768 p.

Patents

Patent of Ukraine № 85293. Anatychuk L.I., Luste O.J., Nitsovych O.V. Thermoelement.

Conference proceedings

Lysko V.V. *State of the art and expected progress in metrology of thermoelectric materials.* Proceedings of the XVII International Forum on Thermoelectricity (May 14-18, 2017, Belfast). Chernivtsi, 2017. 64 p.

Authors' abstracts

Kobylianskyi R.R. *Thermoelectric devices for treatment of skin diseases*: extended abstract of candidate's thesis. Chernivtsi, 2011. 20 p.

Examples of REFERENCES

Journal articles

Gorskiy P.V. (2015). Ob usloviakh vysokoi dobrotnosti i metodikakh poiska perspektivnykh sverhreshetochnykh termoelektricheskikh materialov [On the conditions of high figure of merit and methods of search for promising superlattice thermoelectric materials]. *Termoelektrichestvo - J.Thermoelectricity*, 3, 5 – 14 [in Russian].

Books

Anatychuk L.I. (2003). *Thermoelectricity. Vol.2. Thermoelectric power converters*. Kyiv, Chernivtsi: Institute of Thermoelectricity.

Patents

Patent of Ukraine № 85293. Anatychuk L. I., Luste O.Ya., Nitsovych O.V. Thermoelements [In Ukrainian].

Conference proceedings

Rifert V.G. Intensification of heat exchange at condensation and evaporation of liquid in 5 flowing-down films. In: *Proc. of the 9th International Conference Heat Transfer.* May 20-25, 1990, Israel.

Authors'abstracts

Mashukov A.O. *Efficiency hospital state of rehabilitation of patients with color carcer.* PhD (Med.) Odesa, 2011 [In Ukrainian].