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THERMOELECTRIC MONITORING OF THERMAL RESISTANCE IN ELECTRONIC SYSTEMS

Abouellail A.A.[1], Chang J.[2], Soldatov A.I.[3,4], Soldatov A.A.[3,4], Kostina M.A.[3,4], Vasiliev I.M.[5]

[1] Sphinx University, New Asyut, Egypt
[2] Institute for Advanced Study of Shenzhen University, Shenzhen, China
[3] National Research Tomsk Polytechnical University, Tomsk, Russian Federation, mariyakostina91@mail.ru
[4] Tomsk State University of Control Systems and Radioelectronics, Tomsk, Russian Federation
[5] Scientific and production center LLC "LEMZ-T", Tomsk, Russian Federation

The article proposes to apply the method of thermoelectric testing to determine the thermophysical parameters of the thermal interface. A thermal interface is located between metal surfaces, between which, thermoelectromotive force occurs during heating at any stage of the device operation. The obtained graphs of the temperature difference dependence on the heating time, measured by thermocouples, and measured using thermoelectromotive force confirm the accuracy of the thermoelectric method of testing. Graphs visualize the heat transfer process with thermal resistance variation, temperature fluctuations and the resulting thermoelectromotive force. The proposed method makes it possible to monitor thermal resistance with an error of less than 8 %.

Keywords: thermal interface, thermal resistance, thermoEMF, Seebeck effect, thermoelectric monitoring.

1. Introduction

In modern electronic technology, heat-conducting paste is widely used to ensure good thermal contact (low thermal resistance) between the body of a powerful semiconductor element and a heat sink. It functions as a thermal interface, which improves the quality of heat transfer from a heating element to a heat sink [1-5]. Defects that appear after applying the heat-conducting paste to the heat sink can lead to negative consequences, such as reduced performance and service life of the conductor element, false operation of overheating protection circuits, etc. Therefore, well-timed monitoring of thermal contact makes it possible to avoid a decrease in the reliability of the device and the system as a whole, as well as its premature failure.

At present, monitoring of the thermophysical parameters of a thermal interface after its application to a heat sink surface is carried out manually [6] or by indirect methods [7], and available methods only offer casual inspection or random testing. Inspection of the thermophysical parameters of the thermal interface is possible in some cases, but for its implementation, the device under study must have a temperature-dependent parameter, however, it should be borne in mind that the data obtained also depend on the indirect parameters of the product, for example, on the heat capacity of the product. Available monitoring methods do not provide ability to inspect thermal contact after installing a heat-generating element on a heat sink with a thermal interface in automatic mode, and neither do they provide ability to exclude the influence of other factors of the thermal circuit of the device under study.

As widely used thermal interfaces, heat-conducting gaskets, pastes, and adhesives can be distinguished [8-10]. The silicone heat-conducting paste (SHCP-8) is a particular example of a thermal interface material, which is widely used in Russia to improve thermal conductivity between thermocoductive elements and is locally produced in accordance with the requirements of standard technological regulations GOST 19783-74 [11] and typically recommended for use in in the temperature range from - 60 ºC to + 180 ºC. Among foreign modeling systems, we can specify HK-part HY880, ARCTIC MX-4, etc.

In modern industries, attempts are made to minimize the volume of electronic devices as much as possible, while maintaining its specific power; therefore, heat sinks for cooling transistors are in such a size that the temperature of the transistor chip at rated load does not exceed the normal operating conditions specified in the technical specifications, i.e. about 150°C.

2. Problem statement

The main thermophysical characteristic of a thermal interface, which characterizes its quality, is thermal resistance. The contribution of thermal resistance of the thermal interface to the total thermal resistance of the device thermal circuit R_{thcs} is from 20 % to 65 %, therefore the thermal interface must completely fill the air gap between the heat element body and the heat sink, and the thickness of the thermal interface layer must be at an optimal value, because a very thin layer may not provide high-quality heat transfer due to incomplete filling of air cavities (Figure 1) [12-18].

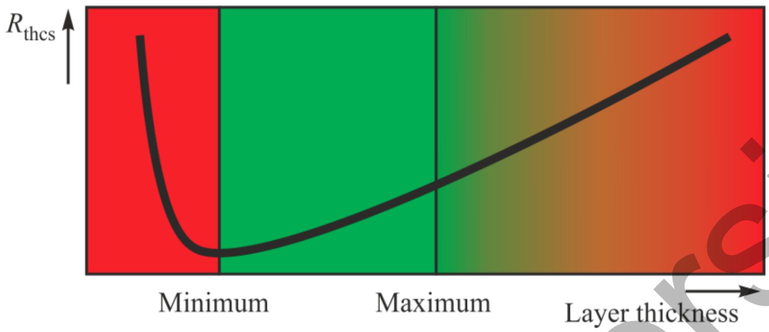

Fig.1. The dependence of the thermal resistance between the heat generating element and the heat sink on the thickness of the thermal interface layer [6]

The presence of air cavities in the gap between the body of the heating element and the cooling heat sink or poor thermophysical characteristics of the thermal interface due to improper application of the thermal interface, with prolonged use of the device, can lead to overheating of the device and ultimately a failure or, at best, reduction in the service life of the product. Therefore, manufacturers of semiconductor devices give recommendations on choosing a heat sink and choosing the right heat-conducting compound. This is especially important for field effect transistors. the open state resistance directly depends on the temperature of the chip, and the open state resistance, in turn, affects the efficiency of voltage converters.

Some companies supply their devices to consumers with a thermal interface already applied, which increases the cost of the device compared to other alternatives. However, this measure does not exclude the possibility of integrity violation of the thermal interface during transportation or installation of the heat-generating device on a heat sink without additional visual inspection before installation. Currently, there are several methods for providing the thermal resistance when installing a heating unit on a heat sink.

Weighing on precision scales is a method that does not guarantee the required thermal resistance, since it depends not only on the amount of heat-conducting compound, but also on its distribution between the heat sink and the body of the device. With uneven distribution of the thermal interface, local overheating of the element is possible [6].

Using a stencil is another method, where the required thermal resistance is provided by using the optimal amount of thermal interface. Its amount depends on the thickness of the stencil, the area of the holes and the distance between the holes and is calculated by the formula [7]:

$$V_{TIS} = S_{hol.} \cdot h_{st.}, \quad (1)$$

where V_{TIS} is the volume of the thermal interface, $S_{hol.}$ is the total area of all holes in the stencil, and $h_{st.}$ is the stencil thickness.

This method does not allow for monitoring the thermal resistance of the system (heat element - thermal interface – heat sink) after the system is assembled.

Simple comb-type Mechanical Thickness Gauges are widely used to provide the required thermal resistance (Figure 2). The thickness gauge is installed on the surface to be checked with a thermal interface with base teeth, and moves parallel to the surface under study, leaning on the base teeth. Because the measuring teeth are at a known distance from the base teeth, the mark left by them on the thermal interface layer indicates the thickness of the thermal interface.

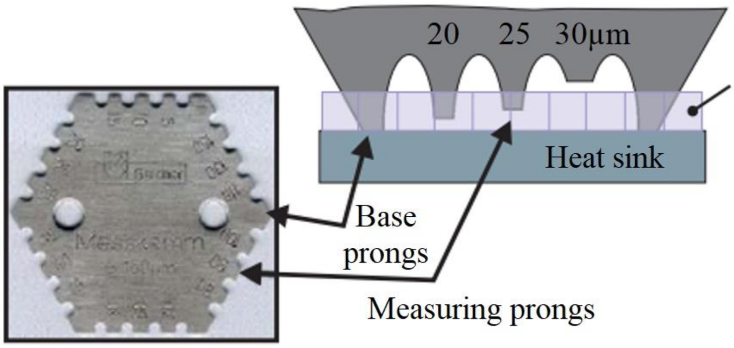

Fig.2. Comb Type Mechanical Thickness Gauge [6]

The disadvantage of this method is the damage to the layer in the inspection zone and the mandatory visual check after each measurement.

Monitoring the thermophysical characteristics of a thermal interface using a transfer circuit is a method that is implemented in many manufactured devices, which have a so-called temperature-dependent parameter. The total thermal resistance "chip-to-case" or "chip-to-environment" R_{Tjx} of semiconductor devices is given by:

$$R_{Tjx} = \frac{T_{j.} - T_x}{P_{pn}}, \tag{2}$$

where T_j – semiconductor chip temperature; T_x – housing or ambient temperature; P_{pn} – heat dissipation power of the device [19].

The method of monitoring standard thermal resistance requires the thermal resistance of the system (heat-generating element body - thermal interface - cooling heat sink) to be determined through the values of previously known thermal resistances and capacitances of the thermal circuit elements:

$$C_{th\Sigma} = \frac{P_{heat} \cdot t}{T_{SC.}(t) - T_{SC.}(0)}, \qquad R_{th\Sigma} = \frac{T_{SC.}(t) - T_{SC.}(0)}{P_{heat}}, \tag{3}$$

where P_{heat} – device power dissipation value; $T_{SC}(t)$ – initial temperature of the device chip, $C_{th\Sigma}$ – heat capacity, $R_{th\Sigma}$ – thermal resistance [20].

When determining the transfer function, it is necessary to maintain the temperature of the body of the object constant, which complicates the control process and the scheme of the measuring installation as a whole.

The modulation method for monitoring the thermophysical parameters of a thermal interface [21] has a sequence of current pulses with a duration t_{imp}, which is applied to the object under study, and can be expressed by the formula:

$$t_{imp} = t_{av}(1 + k \cdot \sin 2\pi f t), \tag{4}$$

where t_{av} – average pulse duration; k – modulation factor; f – pulse frequency [22].

In this case, the average heating power $P_{heat}(t)$ will be determined by the expression:

$$P_{heat}(t) = P_{av} + P_{\text{var}} \cdot k \cdot \sin 2\pi f t, \tag{5}$$

where P_{av} – average delivered power; P_{var}– peak-to-peak amplitude of the variable component of the supplied power [23].

A non-linear change in the heating power affects the change in the chip temperature with some time shift (temperature phase shift). The temperature phase shift is determined:

$$\varphi = arctg \frac{B(f)}{A(f)}, \tag{6}$$

where $A(f)$ – imaginary component and $B(f)$ – material component.

Functions $A(f)$ and $B(f)$ are defined through the discrete Fourier transform by the expressions:

$$A(f) = \frac{2}{N}\sum_{i=1}^{N} T_{SC}(t)\cdot\cos 2\pi(\frac{i}{N}),$$
$$B(f) = \frac{2}{N}\sum_{i=1}^{N} T_{SC}(t)\cdot\sin 2\pi(\frac{i}{N}). \quad (7)$$

Thermal impedance module $|Z_T(f)|$ defined as:

$$|Z_T(f)| = \sqrt{\frac{A^2(f)+B^2(f)}{P_{\text{var}}}}\ . \quad (8)$$

The analysis performed showed that, at present, there is no non-destructive method for monitoring the thermal resistance of the system with a heat-generating unit - thermal interface - heat sink in the assembled state.

3. Mathematical Modeling

The main thermophysical characteristic of a thermal interface is its thermal resistance, which in the steady state is determined by the formula:

$$R_S = \frac{\Delta T}{P}, \quad (9)$$

where ΔT – temperature difference; P – thermal power flow passing through the thermal interface.

To measure the temperature difference at the boundaries of the thermal interface layer, it is necessary to install two temperature sensors so that one of them has thermal contact only with the body of the semiconductor element as close as possible to the thermal interface and does not have thermal contact with the heat sink, and the second has thermal contact with the heat sink and does not have thermal contact with the body of the semiconductor element. Installing temperature sensors in this way complicates the verification process and introduces an error in determining the thermal resistance, because part of the heat is dissipated in the body of the semiconductor device up to the temperature sensor [24].

When two metals of different chemical nature come into contact, due to the difference in charge carriers at the external level, thermoEMF appears between dissimilar metals [25-28]. Due to the influence of temperature on the concentration of charge carriers at the external level, the value of the electromotive force in this case will directly depend on temperature:

$$E = (T_2 - T_1)\frac{k}{e}\ln\frac{n_2}{n_1}, \quad (10)$$

where T_2 – hot junction temperature; T_1 – cold junction temperature; k - Boltzmann's constant; e – electron charge; n_2 – carrier concentration of heatsink material (alloys of WCu or MoCu); n_1 – body material carrier concentration (alloys of Al or Cu).

Value:

$$\frac{k}{e}\ln\frac{n_2}{n_1}, \quad (11)$$

is a constant for two metals and is called the thermopower coefficient or the Seebeck coefficient and is denoted by α. Formula (10) is shortened to the form:

$$E = (T_2 - T_1)\cdot\alpha. \quad (12)$$

Expressing ΔT from the formula (11) ($\Delta T = T_2 – T_1$) and substituting into the formula (9), we get:

$$R_S = \frac{E}{\alpha\cdot P}. \quad (13)$$

To determine the dependence of heat distribution in the object under study over time, as well as on thermal resistance, we will build a mathematical model in which two cylinders with a radius R and a height L_1 and L_2 are interconnected (Figure 3.a). The lower part of the cylinder with height L_1 at points A and D heats up instantly to 100°C, which corresponds to placing the cylinder in boiling water. Heat is transferred to

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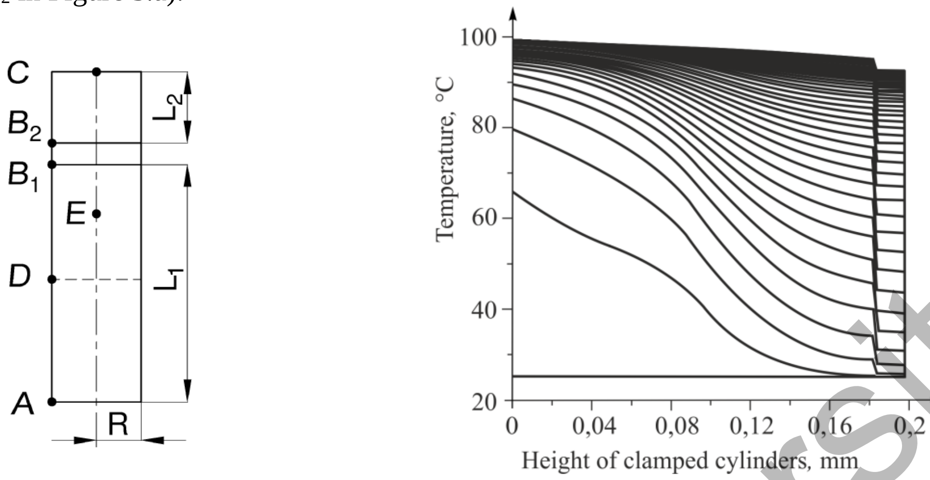
a cylinder with a height L_2, and its upper part is cooled by air with a temperature corresponding to normal climatic conditions. At the contact point of the cylinders, there is a heat-conducting layer with a thickness of l_s (distance B_1B_2 in Figure 3.a).



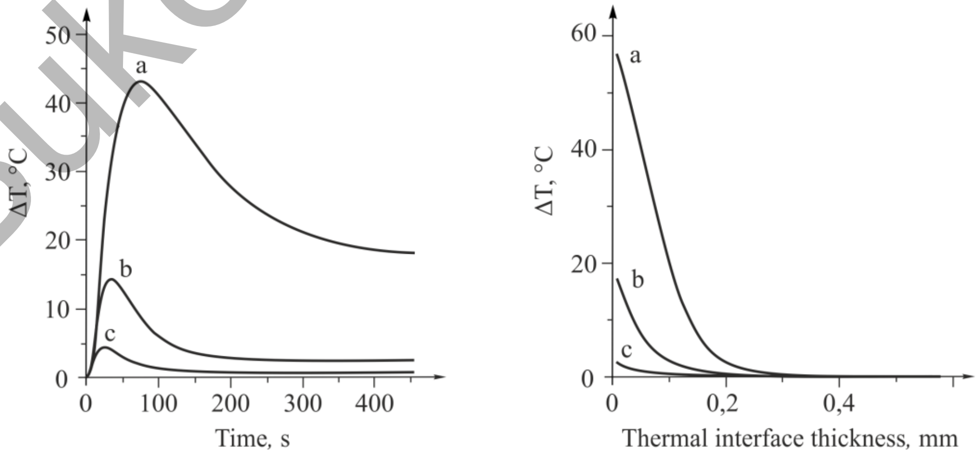
(a) (b)

Fig.3. Object under study; (a) Schematic representation, (b) temperature-time dependence of heat distribution in the cylinder

The mathematical model assumes that the contact between the cylinders is ideal, the thermal conductivity coefficients of substances are constant and do not depend on temperature, the temperature of boiling water is constant and equal to 100°C, and the thermal resistance in the contact zone of two cylinders is completely described by the effective thermal resistance of the contact layer.

By setting the parameters of the cylinders R=25 mm, AC=20 cm, AB_1=19.5 cm, AE=19 cm, AD=9.5 cm, the properties of the material of the cylinders correspond to the properties of the aluminum alloy material (for example: AMg6, AW-5056, AW-AI, Mg5Cr, etc.), the properties of the material of the heat-conducting layer correspond to the properties of the silicone heat-conducting paste SHCP-8 with a thickness of 0.05 mm, according to the results of calculations, we obtain a temperature slice (Fig. 3.b) of heat propagation in cylinders with lengths L_1 and L_2 connected through a thermal interface layer.

As can be seen from the obtained temperature distribution, the effective heat distribution in the region of 0.18 mm (Fig. 3.b) is deteriorated due to the low thermal resistance of the thermal interface compared to the thermal resistance of the cylinders. This picture clearly shows the effect of thermal resistance of the thermal interface on heat dissipation. When the specific thermal conductivity of the thermal interface and its thickness change, the transition process establishment time and the maximum temperature change (Fig. 4).



(a) (b)

Fig.4. Dependence of the temperature difference between two cylinders on: (a) time and on (b) the thickness of the thermal paste, curve a - thermal conductivity of the thermal paste is 10 times less than the nomin value; curve b - nominal specific thermal conductivity; curve c - thermal conductivity of thermal paste is 10 times higher than the nominal

Comparing the curves in Fig. 4, we can conclude that after the rapid heating of the first cylinder, the heating of the second cylinder occurs with some delay due to the finite value of the heat flux through the contact boundary of the two cylinders. Due to the different heating rates of the cylinders, an extremum appears on the graph. As the temperature of the second cylinder rises, the difference between the temperatures of the first and second cylinders decreases and tends to a steady value. For different thermal conductivity of the thermal interface, the steady-state value will be different, the higher the thermal conductivity, the smaller the temperature difference between the cylinders. The value of the extremum also depends on the thermal conductivity, the higher the thermal conductivity, the lower the value of the extremum. The graphs in Fig. 5 show the results of a theoretical study of the influence of the thermal interface thickness on the thermoEMF, whose value depends on temperature difference of the cylinders.

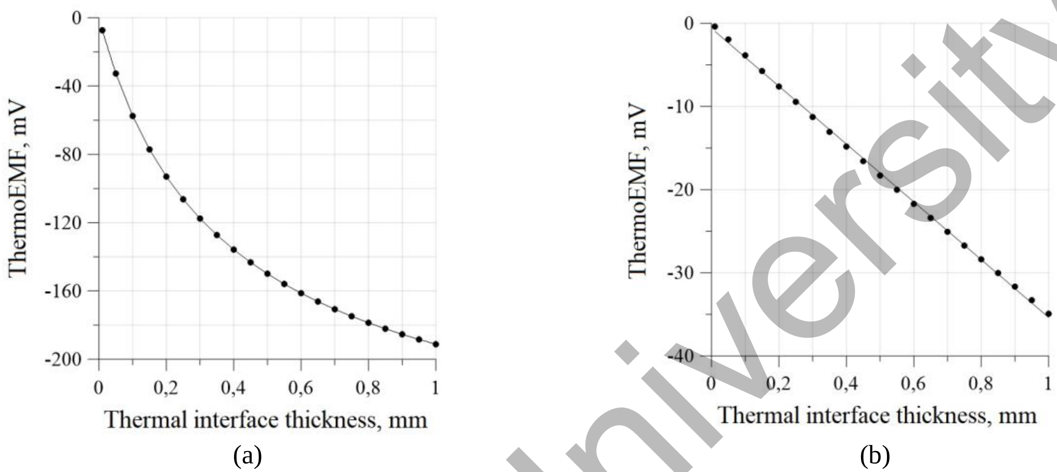


Fig.5. Dependence of thermoEMF on the thickness of the thermal interface layer; (a) transient mode, (b) steady state

The change in thermoEMF in the transient mode is almost 4 times greater than in the steady state, however, the nature of the dependence in the transient mode is nonlinear, and in the steady state it is linear, which makes this mode more preferable for monitoring conditions.

The housings of power semiconductor devices are made of different materials (alloys of WCu or MoCu), and in addition, they can be coated with nickel, tin, silver or gold, which have different Seebeck coefficients. The influence of various coatings of the heat-generating unit on the thermoEMF is shown in Fig.6.

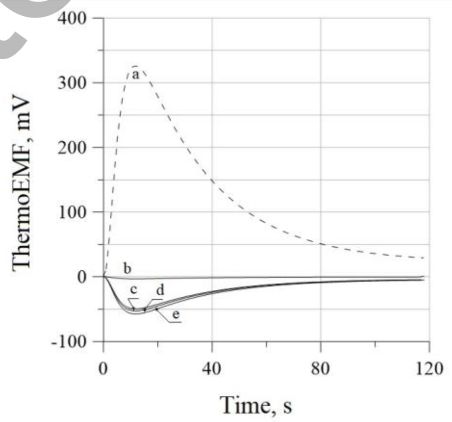


Fig.6. Dependence of thermoEMF on time with a thermal interface of 0.1 mm thickness between aluminum and copper coated with: a) nickel, b) tin, c) silver, d) gold, e) uncoated

Figure 6 shows that with respect to copper, nickel has the highest thermoEMF. This is due to its large value of the Seebeck coefficient compared to other materials [29]. Tin coating relative to copper gives the smallest value of thermoEMF due to its small Seebeck coefficient, with a maximum value was 3.2 mV. The remaining coatings give similar results due to the similar value of the Seebeck coefficient.

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4. Model Verification

To verify the proposed model, experimental studies were carried out, and samples similar to the mathematical model were used as the object of study. The scheme of the experimental setup is shown in Figure 7 [30-32].

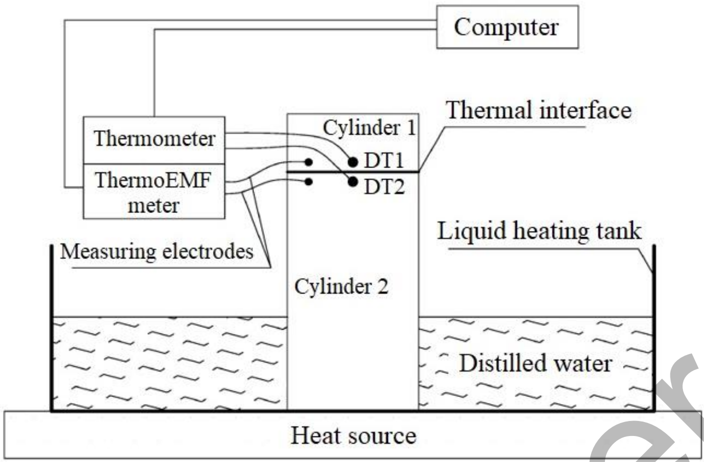

Fig.7. Schematic of the experimental setup

To measure the temperature difference at the boundaries of the thermal interface layer, two platinum rhodium-platinum rhodium thermocouples DT1 and DT2 (manufactured by Elemer R&D company, Russia) connected according to a differential circuit were used [33, 34]. The connection was carried out in such a way that the distance from the thermocouple to the boundary of contact between the body of the power semiconductor device and the heat sink was minimal. In addition, a high-accuracy millivoltmeter was connected to both cylinders to measure thermoEMF. The silicone heat-conducting paste was placed in the gap between the cylinders. The recalculated value of the temperature difference from thermoEMF and the value of the temperature difference measured using thermocouples is shown in Figure 8. Figure 8 shows that the deviation of the two dependences does not exceed 6 %, and the temperature difference caused by the high thermal resistance of the thermal interface, even in steady state, exceeds the heat loss in the environment.

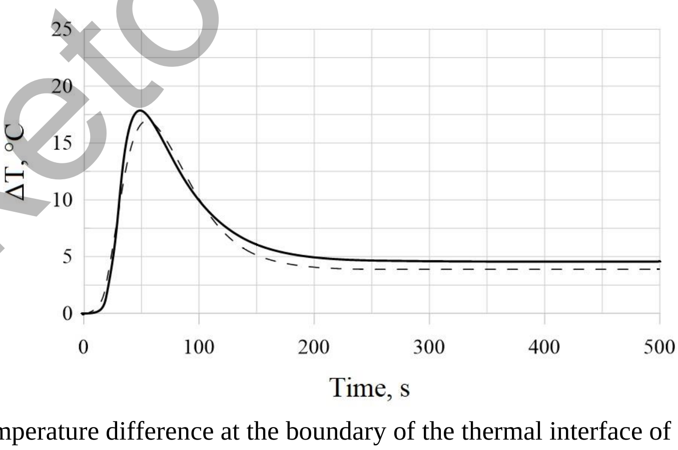

Fig.8. Dependence of the temperature difference at the boundary of the thermal interface of two samples on time, (solid line - measured by thermocouples, dotted line - measured using thermoEMF)

Further research was carried out using a cooling radiator made of AlSi12 silumin alloy, SHCP-8 thermal paste, and a KT808 semiconductor transistor in a TO-220 electronic package. The TO-220 package is widely used in the production of power semiconductor technology. Electronic package material is copper, while package coating material is tin. Platinum rhodium-platinum rhodium thermocouples DT1 and DT2 were attached to the body of the TO-220 power element and to the heat sink through a heat-conducting glue, connected in a differential circuit [35]. The connection was carried out in such a way that the distance from the thermocouple to the boundary of contact between the body of the power device and the cooling heat sink was minimal. The dependences of the temperature difference between the body of the power device and the heat sink, obtained by using thermocouples and by recalculating the thermoEMF are shown in Figure 9.

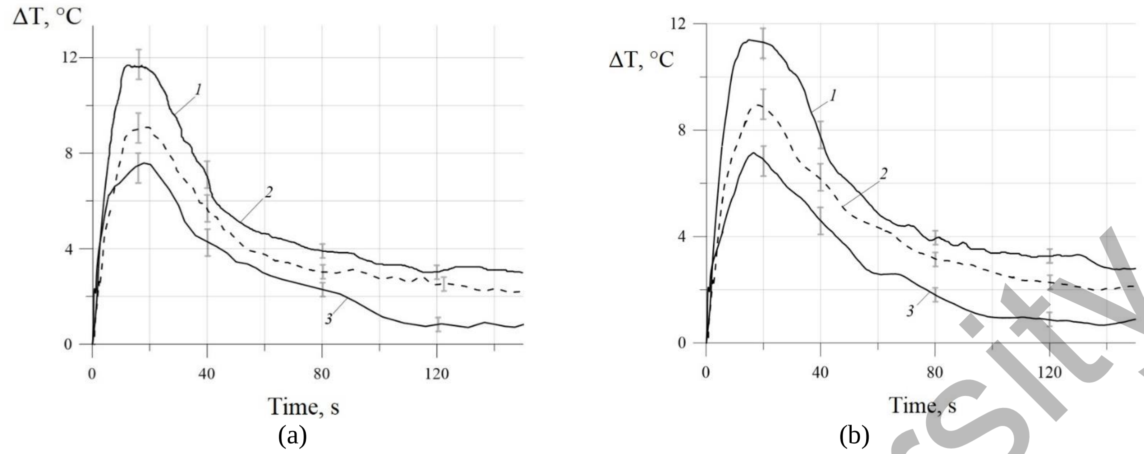

Fig.9. Dependences of the temperature difference between the body of the power device and the cooling heat sink on time; (a) obtained by using thermocouples, (b) obtained by recalculating thermos EMF, *curve 1* - without a thermal interface; *curve 2* - with partially applied thermal interface (50 %); *curve 3* - with applied thermal interface

The results of experimental studies of the dependence of thermoEMF on the area of coverage of the body of the power element with a thermal interface show an almost linear dependence; with an increase in the area of coverage, the thermoEMF linearly decreases (Fig. 10). Confidence interval does not exceed 8 %.

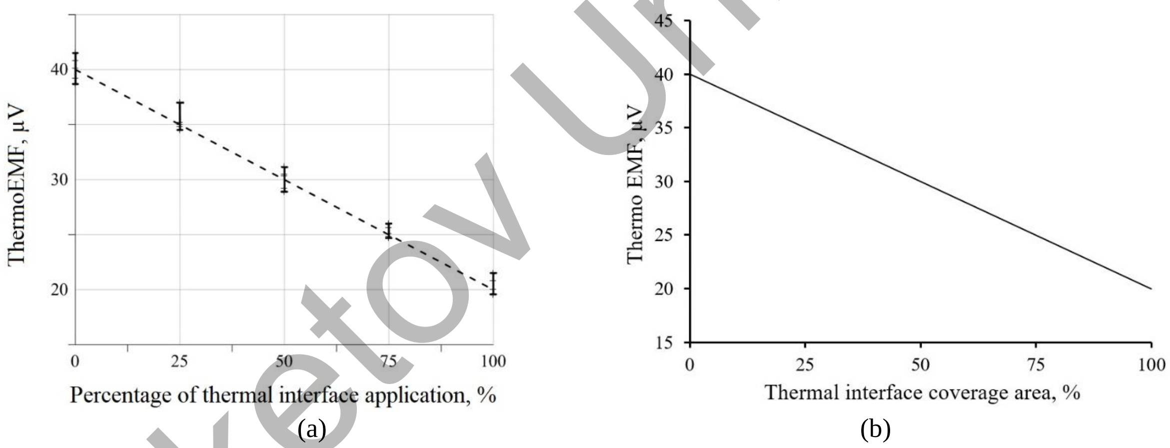

Fig.10. Dependence of thermoEMF on: (a) percentage of thermal interface application, and on (b) on the thermal interface coverage area of the body of the power semiconductor element

The obtained linear dependence of thermoEMF on the area of coverage of the body of the power element with a thermal interface makes it possible to use the thermoelectric method to monitor the thermal resistance of the system of the body of the power semiconductor element - thermal interface - cooling radiator. The result of the theoretical calculation of the thermal resistance Rs, using formula (13) is shown in Fig. 11, where the obtained values of the thermal resistance were obtained using linear filtering.

Variations in thermal resistance are characterized by a random error caused by temperature fluctuations during the experiment. The measured average thermal resistance of the thermal interface is (0.002721±0.0002) K/W, while the calculated value is 0.0025429 K/W, which implies that the difference between the calculated and experimental values does not exceed 8%.

When using heat sinks or devices in electronic housings made of other materials, it is necessary to first determine the calibration dependence of thermoEMF on the area covered by the thermal interface of the power element housing. It should be noted that the thermoelectric monitoring method can be used directly during the operation of electronic equipment.

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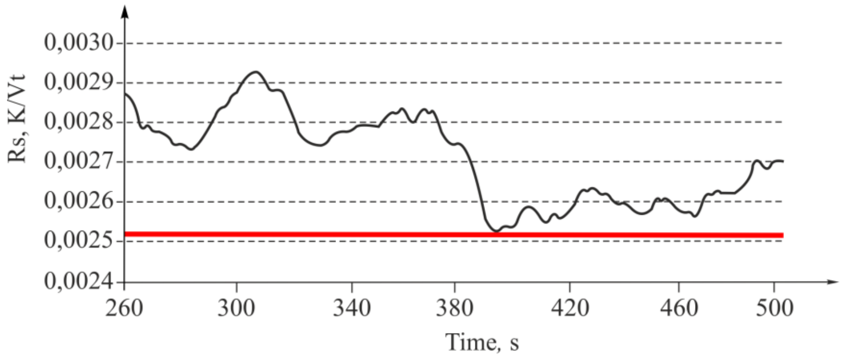

Fig.11. Thermal resistance of the thermal interface in steady state

5. Conclusion

The thermoelectric method is proposed, for the purpose of non-destructive testing of the thermal resistance of the system (electronic package of power semiconductor element - thermal interface - cooling radiator). This method, in comparison with the method of measuring the temperature difference using temperature sensors, gives a more reliable result due to the absence of the influence of the thermal resistance of thermal sensors when installed on the body of the power semiconductor device and the cooling heat sink, as well as the absence of thermal inertia of the temperature sensors. The proposed method makes it possible to monitor thermal resistance with an error of less than 8 %.

Laboratory tests in the application of the proposed method confirmed the correctness of the construction of the mathematical model and the theoretical justification of the method. The practical operation of the developed method for monitoring the thermophysical characteristics of the thermal interface showed that the developed monitoring system has high accuracy and repeatability.

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