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Modeling of thermoelectrical processes in a power MOSFET modules

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Abstract: **The paper represents thermal model of power MOSFET module based on a transistors mounted on copper-ceramic DBC (Direct Bond Copper) plate. The analysis of thermal processes in the module caused by pulse heating of particular transistors was performed by the finite elements method using COMSOL Multiphysics. The model performs estimation of the temperature field on the DBC plate and transistors overheat temperature. The modeling results was compared to the experiment – thermal impedance matrix measured by the modulation method using the heating power modulated by the harmonic law. Analysis of the data obtained allows to conclude that the calculated and experimental values of the dies overheating temperature are in good agreement with each other and confirms the correctness of the developed thermal power module model.**

Keywords: **power module, MOSFET, thermal model, temperature filed, thermal resistance**

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Contents

1. INTRODUCTION

Power modules are widely used in various industries, including transport, electric power, metallurgy, industrial electric drive, etc. They usually consist of several powerful MOSFETs or IGBTs mounted on a common heat-conducting substrate, enclosed in a sealed case. The main requirements for power modules are the ability to switch high currents at high frequency and withstand high voltages in the closed state. Unlike devices of similar purpose, implemented on discrete electronic components, power modules have a much higher power density. In them, due to the dense dies arrangement, active and parasitic connections between the module elements are sharply reduced, which increases the efficiency and reduces possible overloads and the level of electromagnetic interference when switching transistors [1].

A feature of power modules operation is that at any time only a part of the transistors are in the open state, the other transistors are closed. The result is inhomogeneous heating of the module dies and, as a consequence, inhomogeneous temperature distribution over the substrate surface. This can lead to the average temperature over the substrate within the normal range, some dies will have a temperature above the maximum allowable. To prevent this, it is necessary to control the temperature of each module chip. Such a problem can be solved either by analyzing the thermal model or by measuring the thermal impedance matrix, which takes into account thermal cross-links between the module transistors.

2. OBJECT AND RESEARCH METHOD

The object of research was the power module SK85MH10T manufactured by Semikron, consisting of four power MOSFETs mounted on a board made using DBC technology (Direct Bond Copper). The design of the module is shown in **Fig. 1***a*, where the numbers indicate: 1 – die; 2 – jumper; 3 – DBC board; 4 – radiator; 5 – dielectric; 6 – base of the module. The basis of the DBC board is an Al_2O_3 ceramic substrate, on both sides of which a copper foil is attached by sintering in an oxygen atmosphere. The copper foil provides high electrical and thermal conductivity to the mounting layer of the DBC board, and the ceramic base provides good insulating properties. The structure of the transistor formed in each module chip is shown in Fig. 1*b*.

To study the mutual influence of thermal connections between the transistors of the module, measurements of cross-coupled thermal resistances and determination of the elements of the thermal impedance matrix were carried out. In order to maintain the temperature of the base of the module constant due the measurements, the module was attached to the heatsink using thermal grease. After measuring cross thermal resistances, the module cover was dismantled in order to determine the exact dimensions of the chips and their location on the DBC board, which is necessary to simulate the thermal processes that occur when heating current pulses pass through the module transistors.

Fig. 1*b* shows only part of the power MOSFET structure, namely its base cell. In reality, a powerful MOSFET is made up of many such base cells, which can number in the thousands. A feature of the structure is the presence in each base cell of an antiparallel diode between the p^+ source region and the n^- drain region. When the transistor is open, when the current flows from the drain to the source, the anti-parallel diode does not affect the operation of the transistor in any way. However, the JEDEC standard [2] recommends using it to measure the die temperature. To do this, a small measuring current is passed through the diode (shown by arrows in Fig. 1*b*) and the voltage USD between the source and drain is measured, which decreases linearly with increasing die temperature. It should be taken into account that the voltage USD is measured for a plurality of diodes connected in parallel, while the value of USD depends on the local temperature of the die. In the case of a non-uniform temperature distribution across the die, the measured USD voltage will determine the highest local temperature of the die.

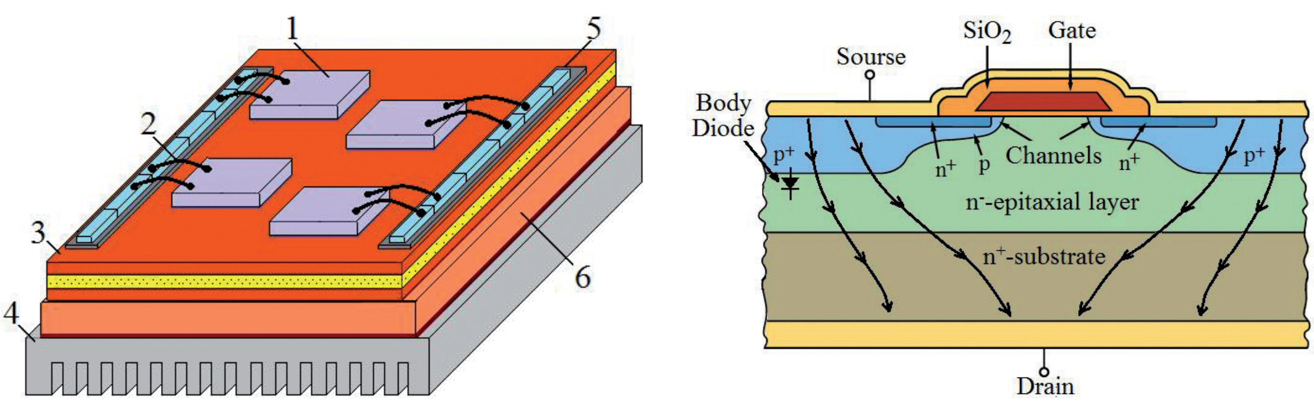

Fig. 1. *Power module SK85MH10T: a) design; b) MOSFET structure.*

The most widely used method for studying thermoelectric processes in power modules is the analysis of their thermal model. To build a model, the principle of thermoelectric analogy is often used [3], according to which thermal parameters (heat flux, temperature, thermal resistance, heat capacity, etc.) correspond to an electrical analogue (current strength, voltage, resistance, electric capacitance, etc.). In this case, the object is represented by an equivalent circuit consisting of RC-chains connected in a certain way according to its design. Usually, Cauer or Foster substitution circuits are used [4]. Thermal processes occurring in an object are mathematically described similarly to electrical processes in an equivalent circuit.

To determine the equivalent circuit parameters, either used information about the material and geometry of the structural elements of the object or experimental results. An illustration of the first approach is the work [5], in which the authors managed to calculate the parameters of all elements of the power module from six pairs of IGBTs and diodes located on a copper base that has thermal contact with an aluminum radiator. To experimentally determine the parameters of the equivalent circuit, measurements of transient responses are often used. A sequence of heating current pulses with a duration increasing according to a logarithmic law is passed through the object, and after each pulse, the response to this effect is measured – the change in the dies temperature until a steady state is reached. An analysis of the heating curve allows to determine the thermal resistance components used to build a model of a multi-chip system [6]. Modeling methods based on solving the heat equation are widely used. In this case, either the finite element method [7] or the differential difference method [8] is used to calculate heat fluxes in a multi-die system.

The processes of heat removal from heated dies through the substrate to the base of the module case, as well as lateral flows to neighboring module dies, are characterized by a thermal impedance matrix $Z_{\mathrm{Txy}}(j\omega)$:

$$\mathbf{T}_x(j\omega) = \mathbf{Z}_{\mathbf{T}xy}(j\omega)\cdot\mathbf{P}_y(j\omega), \quad (1)$$

where $\mathbf{T}_x = \begin{pmatrix} T_1 \\ \dots \\ T_m \end{pmatrix}$, $\mathbf{P}_y = \begin{pmatrix} P_1 \\ \dots \\ P_n \end{pmatrix}$, $\mathbf{Z}_{\mathbf{T}xy} = \begin{pmatrix} Z_{T11} & \dots & Z_{T1n} \\ \dots & \dots & \dots \\ Z_{Tm1} & \dots & Z_{Tmn} \end{pmatrix}$.

The one-dimensional arrays $T_{\mathrm{x}}(j\omega)$ and $P_{\mathrm{y}}(j\omega)$ are the frequency-dependent characteristics of the temperature at point X and the power dissipation at point Y, and $Z_{\mathrm{Txy}}(j\omega)$ defines the thermal coupling between points X and Y. To determine the thermal coupling between each pair of elements, which are part of the system, the authors of [9] proposed to use the PRBS method (Pseudorandom Binary Sequence – pseudo-random binary sequence). PRBS is a special signal that has an almost constant spectrum over a wide frequency range. Using PRBS as the input power $P_{\mathrm{y}}(t)$ and measuring the temperature response $T_{\mathrm{x}}(t)$, the elements of the thermal impedance matrix can be determined:

$$Z_{Txy}(\omega) = \frac{\boldsymbol{F}(T_x(t))}{\boldsymbol{F}(P_y(t))} = \frac{T_x(\omega)}{P_y(\omega)},$$

where $T_{\mathrm{x}}(t)$ и $P_{\mathrm{y}}(t)$ − time representations of the temperature at point X and the power dissipated at point Y, and F denotes the discrete Fourier transform.

Another approach was used in [10], where the authors used the modulation method of the effect of thermal power on the measurement object to measure the matrix elements. To do this, a sequence of heating current pulses with a fixed amplitude and repetition period, but with a duration varying according to a harmonic law, was passed through the transistors of the module [11]. This caused a periodic change in the die's temperature with the same modulation frequency as that of the heating power, but with a phase shift. By measuring the amplitude of the variable temperature component and the phase shift, it is possible to determine the elements of the thermal impedance matrix.

3. POWER MODULE THERMAL MODEL

The object of thermal modeling is the power module SK85MH10T, the design of which is shown in Fig. 1*a*. The module consists of four high-power MOSFETs mounted on a DBC board with dimensions $b \times c \times h_p$. Transistors are formed in silicon dies of square section $a \times a \times h_c$. The DBC board is mounted on a heatsink that keeps the bottom surface temperature constant.

The temperature field in the structure of the power module is found from the solution of the non-stationary heat conduction equation:

$$c_i(T_i)\,\rho_i(T_i)\frac{\partial T_i}{\partial t} = \nabla_{x,y,z}\left(\lambda_i(T_i)\,\nabla_{x,y,z}T_i\right), (\mathrm{i}=1,\ldots,5) \quad (2)$$

where $\lambda_i(T_i)$, $c_i(T_i)$, $\rho_i(T_i)$ are the coefficients of thermal conductivity, specific heat capacity, and density of the layers of the structure.

The initial and boundary conditions:

$T_i(x, y, z, 0) = T_0$,

where T_0 – ambient temperature. On the upper surface of the transistor dies, the density of the thermal power dissipated by the transistor die is set:

$$q_i(t) = -\lambda_i(T_i)\frac{\partial T_i}{\partial z}\bigg|_{z=h_p+h_c}, (i=1,\ldots,4). \quad (3)$$

On the lower boundary of the model structure, which is in the zone of contact with the base of the module, the heat flow spreading condition is set:

$$-\lambda_5(T_5)\frac{\partial T_5}{\partial z}\bigg|_{z=0} = \alpha_{sp}(T_5(x,y,0,t)-T_0),$$

where $\alpha_{sp} = 1/(b \times c \times R_{sp})$ – the effective heat transfer coefficient of the DBC board with the base of the power module and the heatsink, and RSP is the thermal spreading resistance [12]. On all other free surfaces Σ of the structure of the power module, there is no heat exchange with the external environment:

$$\frac{\partial T_i}{\partial n}\bigg|_{\Sigma} = 0.$$

The heat conductivity equation (2) was solved by the finite element method using the COMSOL Multiphysics software environment. The dimensions of the transistor die were $a \times a \times h_c = 6 \times 6 \times 0.5$ mm^3, and DBC-board $b \times c \times h_p = 40 \times 28 \times 1.0$mm^3.

The main physical properties of the materials of the structure of the studied power module are presented in **Table 1**. The temperature dependences of the thermophysical characteristics of silicon used in solving the thermal problem were taken from the COMSOL library of materials. Initial temperature $T_0 = 300$ K.

As in [10], the module heating by pulse-width modulated current pulses using only two transistors (1 and 2) was modeled. As a result of current pulses flowing through the transistor, the average heating power over the repetition period changed according to the harmonic law:

$$P(t) = P_{av} + P_1 \sin(2\pi\nu t),$$

where P_{av} – average heating power, $P_1 = aP_{av}$ – amplitude of the variable component of the heating power, ν – modulation frequency, a – modulation factor. The amplitude of the variable component of the heating power dissipated in the transistor 1, $P_1 = 1.12$ W, in transistor 2 – $P_1 = 1.04$ W, with modulation factor $a = 0.5$. With ν = 55 Hz the dependences of power density (3) on time will be determined by the expression:

$$q_1(t) = 62222[1+0.5\sin(2\pi 55t)],$$
$$q_2(t) = 57778[1+0.5sin(2\pi 55t)].$$

The effective heat transfer coefficient was a model parameter. Its value was calculated according to the method presented in [12] and

Table 1

Physical parameters of structural elements of the power module

Structure element	Material	ϱ, kg/m³	λ, W/(m·K)	c_p, J/(kg·K)
Die	Si	2330	λ(*T*)	$c_p(T)$
DBC board	Cu Al_2O_3	8700 3900	400 27	385 776

refined by the iterative method according to the experimental data on the heating temperature of the module structure element. In the presented calculation variant, this temperature was the junction temperature of the 1st transistor.

4. MODELING RESULTS AND THEIR ANALYSIS

The results of calculating the temperature field created by the heated dies of the module during the flow of current pulses through transistors No. 1 and No. 2 are shown in **Fig. 2**. On the right is a color temperature scale that allows you to evaluate the temperature at various points in the module.

Since the power modules mainly operate in a pulsed mode, when some of the transistors are open and the rest are closed, the temperature dynamics of all transistors, including transistors in the closed state, is of interest. The results of calculating the change in the overheating temperature of transistors under pulsed action are shown in **Fig. 3**.

The simulation results were compared with the experimental studies results [10]. The purpose of the research was to measure the elements of the thermal impedance matrix of the SK85MH10T power module, which consists of four powerful MOSFETs mounted on a copper-ceramic board. To solve this problem, a modulation method for measuring thermal resistance was used, using the heating

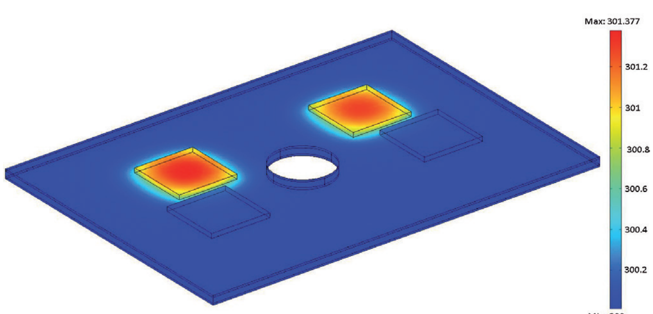

Fig. 2. *The results of the power module's temperature field calculation: 1…4 – MOSFET dies, 5 – DBC board.*

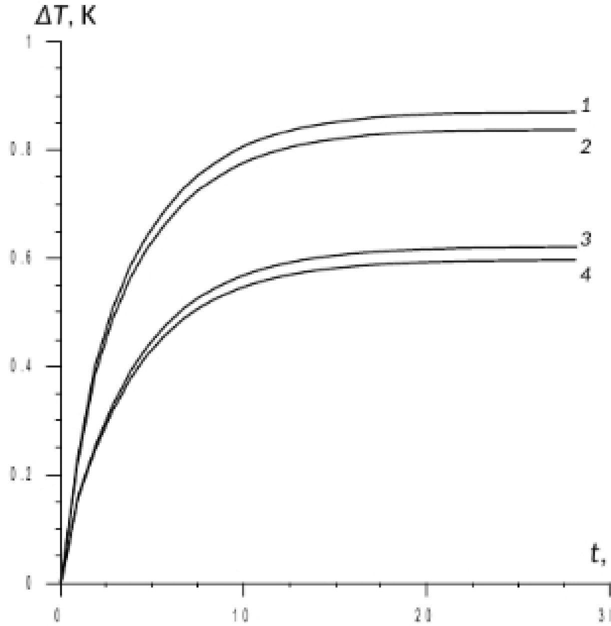

Fig. 3. *Changes in the overheating temperature of transistors under pulsed thermal exposure (curve number corresponds to the transistor chip number).*

of each transistor with a power modulated according to a harmonic law and measuring the variable temperature component of all other transistors of the power module. The ratio of the transition temperature amplitudes T_{j1} and power dissipation P_1 determines the modulus of the thermal impedance $Z_T(\nu)$ at the modulation frequency ν, and the ratio of the imaginary Im T_{j1} and the real Re T_{j1} Fourier transform of the transition temperature determines the phase tangent $\varphi(\nu)$ of the thermal impedance. This made it possible to determine both diagonal and off-diagonal elements of the thermal impedance matrix.

If the measurement object has a complex structure and the heat flow propagates through the elements of this structure from the die to the case and further through the radiator to the environment, then the total thermal resistance includes several components, for example, "transition-case", "case-radiator", "radiator-environment". They can be determined by measuring and analyzing the dependence of the real part Re $Z_T(\nu)$ or the phase $\varphi(\nu)$ of the thermal impedance on the modulation frequency

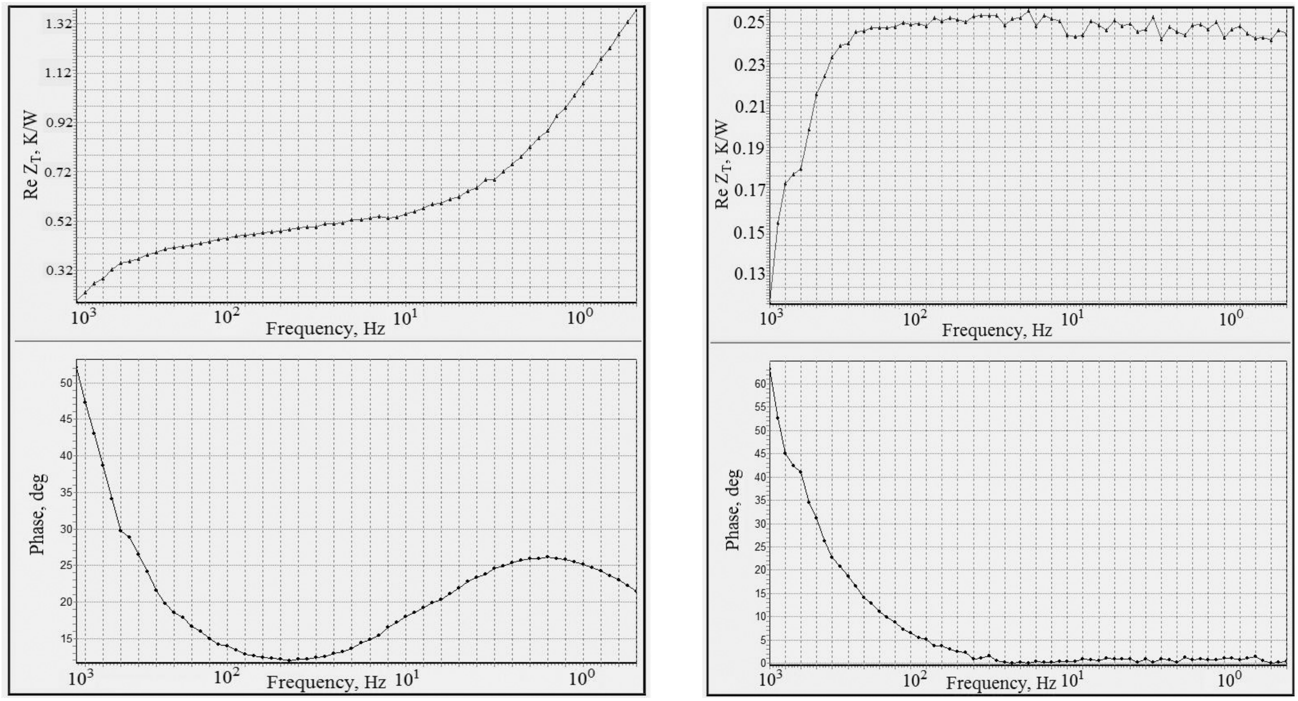

Fig. 4. *Dependence Re $Z_T(v)$ (top) and $\varphi(v)$ (bottom): a) for Z_{22}; b) for Z_{13}* [10].

of the heating power ν. **Fig. 4***a* shows the results of measuring such dependences for one of the diagonal terms of the thermal impedance matrix Z_{22}, when the heating current pulses were passed through transistor 2, and the junction temperature T_{j1} was also measured for it. Fig. 4*b* shows a similar dependence for the Z_{13} matrix element, when the thermal power was dissipated in transistor 1, and the temperature response was measured for transistor 3. It can be seen that the character of the Re $Z_T(\nu)$ dependence for Z_{13} differs from that for Z_{22}: there is no increase in thermal impedance with a decrease in the modulation frequency to several hertz. In addition, unlike Z_{22}, there is no minimum in the frequency dependence of the phase $\varphi(\nu)$ of the thermal impedance, and the value of the phase itself in a wide frequency range is only a few angular degrees.

In the presence of several thermal resistance components, the dependence Re $Z_T(\nu)$ has features in the form of flat sections or inflection points. To reveal these features, the Re $Z_T(\nu)$ curve was differentiated with respect to the modulation frequency ν. The result of processing $Z_T(\nu)$, which includes the calculation of $(dReZ_T/d\nu)^{-1}$ as a function of ReZ_T, is shown in **Fig. 5**. The components of thermal resistance appear as maxima, the position of which relative to the abscissa axis determines their values. For transistor 2, these components are R_{T1} = 0.495K/W, R_{T2} = 0.532K/W and R_{T3} = 0.596K/W. The results of similar measurements for other transistors of the module differ from each other by no more than 3%.

The sequential heating of all transistors of the module at different frequencies of the heating power modulation and the measurement of the response to this effect made it possible to determine the diagonal and off-diagonal elements of the thermal impedance matrix Z_{Txy} [10]:

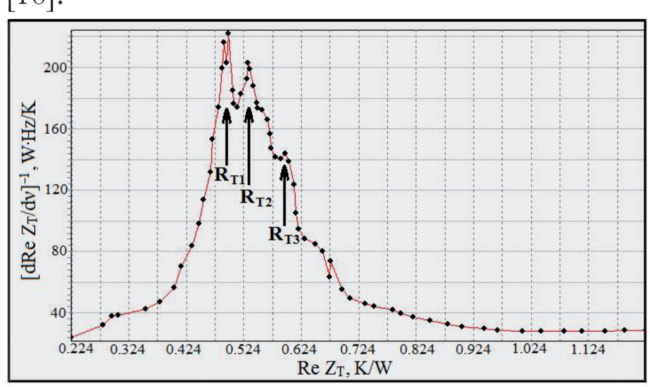

Fig. 5. *Thermal resistance components of power module transistor 2* [10]

$$\mathbf{Z}_{\mathrm{T}xy}=\begin{pmatrix}0.534+0.102j & 0.263 & 0.243 & 0.268\\ 0.267 & 0.532+0.104j & 0.273 & 0.263\\ 0.264 & 0.278 & 0.546+0.103j & 0.268\\ 0.273 & 0.261 & 0.264 & 0.536+0.100j\end{pmatrix}. \quad (4)$$

Diagonal members of the matrix are complex quantities, the real parts of which determine the components of the thermal resistance "transition – the base of the module" of all transistors of the module. For the off-diagonal terms of the matrix, which determine the thermal cross-links between transistors, the phase does not exceed 2°; therefore, the imaginary part of the off-diagonal terms is practically equal to zero.

Using the elements of the matrix Z_{Txy} (4), and knowing the power dissipated in certain transistors, it is possible to calculate the die temperature of any transistor of the power module using formula (1). To check this, the 1st and 2nd transistors were simultaneously heated with a power modulated according to a harmonic law, and the overheating temperatures ΔT of all transistors of the module were measured. The results are shown in the first row of Table 1. The second row of **Table 2** shows the results of calculating the overheating temperature based on the measured values of the elements of the thermal impedance matrix Z_{Txy} and the power dissipation in the 1st and 2nd transistors. The third line shows the simulation results using a numerical method for solving the heat equation. It can be seen that the values of the overheating temperature of all transistors of the power module, obtained by various methods, are in good agreement with each other, which confirms the correctness of the developed thermal model of the power module.

Table 2

The results of measurement and calculation of the module transistors overheating temperature

	ΔT_1, K	ΔT_2, K	ΔT_3, K	ΔT_4, K
Experiment	0.87	0.82	0.63	0.61
Calculation based on Z_{Txy}	0.87	0.84	0.62	0.60
Calculation based on model	0.88	0.86	0.59	0.58

5. CONCLUSION

To study thermoelectric processes in a power module consisting of four high-power MOSFETs, a thermal model based on the solution of the heat equation by the finite element method using the COMSOL Multiphysics software environment is proposed. Within the framework of the model, the calculation of the thermal field was made under the pulsed action of thermal power on a part of the module died. This made it possible to estimate the degree of thermal influence of the dies among themselves and to calculate the overheating temperatures of all the module dies.

To check the reliability of the obtained simulation results, they were compared with results obtained experimentally. As experimental results, the results of measuring the elements of the thermal impedance matrix obtained by the modulation method, as well as the results of direct measurements of the overheating temperature of the dies under the pulsed action of thermal power on individual dies of the module, were used. An analysis of the data obtained allows us to conclude that the calculated and experimental values of the die overheating temperature are in good agreement with each other, therefore, the developed model adequately describes the thermal processes in the considered power module.

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