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INFLUENCE OF THE SELECTION OF THE APPROXIMATING FUNCTION OF THERMOMETRIC CHARACTERISTICS ON THE MEASUREMENT RESULTS OF THERMAL RESISTANCE OF POWER MOSFETS

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Abstract

The paper describes the results of the investigations illustrating the influence of the method of determining the excess of the junction temperature and the selection of a function approximating the thermometric characteristic used in the procedure of measuring thermal resistance of a power MOS transistor on the measurement results. The investigations involved the measurements made using an indirect electrical method. Three methods of determining the excess of the junction temperature of the transistor are presented, using a linear function and nonlinear function approximating thermometric characteristics. The thermal resistance measurement results obtained using each of the considered methods were compared. The measurement error caused by the selection of the considered methods were also analyzed.

Keywords: thermal resistance, thermal parameters of semiconductor devices, thermometric characteristics, power MOS transistors, measurements.

1. Introduction

The junction temperature is an important parameter of semiconductor devices. The operation of these devices at high temperatures causes degradation of their reliability and shortening of their lifetime [1-3]. For example, according to the results presented in the paper [4] for the power LEDs an increase in the junction temperature from 38°C to 58°C causes a decrease in the lifetime even 6 times.

An important and current issue in modern electronics are reliable measurements of the junction temperature of semiconductor devices during their operation [5], as well as measurements of the values of their thermal parameters [6]. Thermal parameters are used both to design cooling systems and to determine the value of the junction temperature of semiconductor devices when they operate under specific cooling conditions, with a known course of the power dissipated in these devices and the ambient temperature.

The basic parameter of semiconductor devices that allows determining their junction temperature T_j at the steady state is thermal resistance R_{th} [7, 8]. In practice, values of the thermal resistance between the junction and the case R_{thj-c} and the thermal resistance between the junction and the ambient R_{thj-a} are important [9, 10]. In the datasheet of semiconductor devices, when the devices in cases are not adapted to the operation with an external heat-sink, only the R_{thj-a} value is provided. In turn, in the case of the devices intended for the operation with an external heat-sink, both the R_{thj-c} value (for the set case temperature) and the R_{thj-a} value (for the set method of mounting the device) are given. The R_{thj-a} value given in the datasheets most often applies to a device without an external cooling system. The R_{thj-a} value is also determined in the case of the devices cooperating with the selected cooling system, *e.g.* passive heat-sink~~s~~ [11].

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The junction-ambient thermal resistance is defined using the formula [6]

$$R_{thj-a} = \frac{\Delta T_j}{p_H} = \frac{T_j - T_a}{p_H}, \tag{1}$$

where T_a denotes the ambient temperature, at which the measurement is carried out and p_H is the power dissipated in the device.

Thermal resistance of semiconductor devices can be determined by measurements, and various measurement methods are used [6]. The indirect electrical method is most often used. It involves using the selected electrical parameter of the device, the so-called thermally sensitive parameter, to measure the junction temperature [12]. In the case of MOS (*Metal-Oxide-Semiconductor*) transistors, thermally sensitive parameters include, among others [12]: gate-source voltage V_{GS} of the transistor operating in the saturation range, voltage on a forward biased anti-parallel diode V_F or on-resistance R_{DSon} of the transistor.

In order to determine temperature T_j and thermal resistance using the considered method, it is necessary to perform several steps. The first is to measure the dependence of the selected thermally sensitive parameter on temperature, *i.e.* thermometric characteristics. Typically, these characteristics are non-linear [13], and the degree of their non-linearity depends on the choice of the thermally sensitive parameter [13].

In the paper [14] the influence of the forward current of the p-n junction on the nonlinearity of its thermometric characteristics was analyzed. The cited paper indicates phenomena that limit the range of values of this current both from below and above. A wide range of linearity of this characteristic was achieved for forward currents ranging from single to several dozen milliamps. Usually, the measurement conditions of thermometric characteristics are selected in such a way that they are as close to linear as possible and a linear approximating function is used [13, 14]. As shown in the paper [15], the inaccuracy of determining the slope of the thermometric characteristic may significantly affect the measurement error of junction temperature T_j and thermal resistance R_{th} of the IGBT (*Insulated Gate Bipolar Transistor*).

Currently, there is no analysis in the literature concerning the impact of the accuracy of determining thermometric characteristics on the results of the measurements of thermal resistance of power MOS transistors. Typically, non-linearity of the thermometric characteristics is omitted.

The aim of the paper is to analyze properties of thermometric characteristics of a power MOS transistor and an influence of the selection of a function approximating them on the values of the thermal resistance obtained using an indirect electrical method. The investigations used two thermometric characteristics. The first of them represents the dependence of the gate-source voltage on temperature $V_{GS}(T)$ at a constant value of the drain-source voltage ensuring the operation of the transistor in the saturation range. The other characteristic is the dependence of the anti-parallel diode forward voltage on temperature $V_F(T)$. Both the characteristics were determined for the fixed value of drain current I_D. An analysis of the accuracy of the approximation of the considered functions using polynomials of different degrees was carried out and the optimal degree of such a polynomial was indicated. The values of the R_{th} measurement error were determined and discussed for the tested functions approximating the thermometric characteristics.

Section 2 describes the method used to measure R_{th}. Section 3 presents the measured thermometric characteristics of the tested transistors and the results of the approximation of these characteristics. Section 4 presents the results of the measurements of thermal resistance of the tested devices obtained using the considered approximation functions in a wide power range. The measurement error of R_{th} is also estimated.

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2. Measurement method

The measurement system used in the investigations is shown in Fig. 1. The thermally sensitive parameter in this system is gate-source voltage V_{GS} at the fixed value of drain current I_D for the transistor operating in the saturation range. The measurement of the value of the thermally sensitive parameter is carried out using a measurement module and proprietary software described in the paper [16]. The tested transistor is marked with the symbol M_1 in the diagram. An ammeter and a voltmeter are used to measure drain current I_D and drain-source voltage V_{DS} of the tested transistor. Based on the measured values of these quantities, power p_H dissipated in the transistor is determined. The remaining components are used to polarize the transistor in the desired way during the measurement procedure described below. Transistor M_2 is used to switch the value of the drain current. If switch S_1 is in position 1, transistor M_2 is switched-off and the tested transistor M_1 is heated. If switch S_1 is in position 2, transistor M_2 is switched-on and the drain current of transistor M_1 is equal to I_M.

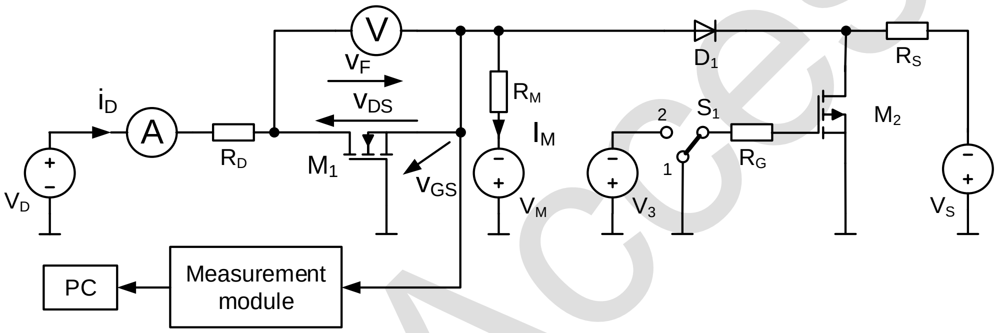

Fig. 1. Diagram of the measurement system.

Measuring thermal resistance or the junction temperature of a power MOS transistor requires several steps. In the first step, the thermometric characteristic $V_{GS}(T_j)$ is measured. For this purpose, the tested transistor is placed in a thermostatic chamber and then the V_{GS} voltage value is measured at various temperature values T_k inside this chamber. The correct measurement requires that during the measurement the junction temperature of the tested element T_j is equal to temperature T_k.

In this measurement step, S_1 switch is in position 2 and the tested transistor operates in the saturation range. Measurement current I_M flows through the transistor, the value of which is selected in such a way that its flow does not cause a significant increase in the junction temperature of the transistor (self-heating).

Based on the measured thermometric characteristics $V_{GS}(T_j)$, by changing variables, an auxiliary relationship $T_j(V_{GS})$ is determined, which is used in the last stage of the measurements to determine temperature T_j and thermal resistance R_{th}. The use of $T_j(V_{GS})$ dependence to determine the discussed parameters requires the approximation of the measurement data using a selected function. The selected approximating functions and the method of determining values of their coefficients are described later in this paper.

The remaining part of the measurement procedure is carried out outside the thermostatic chamber at the set temperature value T_a. Step 2 involves heating the tested transistor with power p_H until a steady state is obtained. In step 3, the transistor cools down.

During step 2, switch S_1 is in position 1. Transistor M_1 is polarized using voltage sources V_D, V_S and V_M in such a way that the power dissipated in it causes the transistor to heat up and its junction temperature to increase until it reaches a thermally steady state. While heating, in the transistor power $p_H = i_D \cdot V_{DS}$ is dissipated.

The transition to step 3 occurs at time t_0, when the position of switch S_1 changes from 1 to 2. After changing the switch position, the tested transistor is polarized using voltage sources V_D and V_M. Current $i_D = I_M$ flows through the transistor of the value equal to the current of this transistor, at which the thermometric characteristic was measured.

At the moment t_0, the registration of the so-called cooling curve $V_{GS}(t)$ begins. This curve presents time changes in the gate-source voltage. The measurement ends when the junction temperature T_j of the transistor equals the ambient temperature T_a.

Based on the definition given by (1) and the measured cooling curve $V_{GS}(t)$, thermal resistance can be determined in three manners, which differ in the adopted approximation model of $T_j(V_{GS})$ dependence and the method of calculating the excess ΔT_j of the transistor junction temperature T_j over the ambient temperature T_a. These manners are marked with the letters L_1, L_2 and N and are defined as follows:

– Manner L_1 – linear approximation of $T_j(V_{GS})$ dependence, T_a measured with a thermometer

$$\Delta T_j = a_1 \cdot V_{GS1} + a_0 - T_a. \tag{2}$$

– Manner L_2 – linear approximation of $T_j(V_{GS})$ dependence

$$\Delta T_j = a_1 \cdot (V_{GS1} - V_{GS2}). \tag{3}$$

– Manner N – approximation of $T_j(V_{GS})$ dependence with a quadratic function

$$\Delta T_j = b_2 \cdot (V_{GS1}^2 - V_{GS2}^2) + b_1 \cdot (V_{GS1} - V_{GS2}). \tag{4}$$

In (2) - (4) - V_{GS1} is the value of the gate-source voltage of the tested transistor at the moment t_0 (just after switching the measuring system), and V_{GS2} is the value of the gate-source voltage of the tested transistor at the ambient temperature T_a.

The coefficients a_0, a_1 appearing in (2) - (3) correspond to the coefficients of a linear function approximating (1st degree polynomial) the dependence of temperature T_j on the gate-source voltage V_{GS} given by (5), while the coefficients b_0, b_1, b_2 – the coefficients of a quadratic function (polynomial of 2nd degree) are described by the (6)

$$T_j = a_0 + a_1 \cdot V_{GS}, \tag{5}$$

$$T_j = b_0 + b_1 \cdot V_{GS} + b_2 \cdot V_{GS}^2. \tag{6}$$

To determine the value of the junction temperature and its excess over the ambient temperature, it is necessary to select the type of the function approximating $T_j(V_{GS})$ dependence and to determine the values of the parameters of this function. The least squares method (polynomial least squares regression) was used in the papers [17, 18]. In this method, the measure of the fit of the approximating function to the measurement data is the coefficient of determination R^2 and the standard error SE. The values of the considered parameters were determined from the formulas [17, 18]

$$R^2 = \frac{\sum_{i=1}^{n}(T_{ji} - T_j)^2}{\sum_{i=1}^{n}(T_{ji} - T_j)^2}, \tag{7}$$

$$SE = \sqrt{\frac{\sum_{i=1}^{n}(T_{ji} - T_{ji})^2}{n-k-1}}. \tag{8}$$

where T_{ji} is the junction temperature value predicted by the regression model at V_{GSi}, T_j is the mean value of the junction temperature calculated using all the measurement points, T_{ji} is the measured value of the junction temperature at a given value of V_{GSi}, *n* is the number of measurement points, k is the degree of the modeling polynomial. The formula (8) takes into account an increase in the SE value associated with a small sample size, *i.e.* a small number of measurement points.

As mentioned earlier, the nonlinearity of $T_j(V_{GS})$ dependence is typically ignored in the literature and a linear function is used to model this dependence. Taking into account the non-linearity of the dependence under consideration requires the use of another function, *e.g.* a polynomial model. The optimal degree of the polynomial can be determined by the null hypothesis testing method based on the probability value p determined from the distribution F with a specific number of degrees of freedom and their values for variable F. The values of p and F were determined from the following formulas [17, 18]:

$$p = FDIST(F, df_{Reg}, df_{Res}), \tag{9}$$

$$F = \frac{MS_{Reg}}{MS_{Res}} = \frac{SS_{Reg}}{df_{Reg}} \Big/ \frac{SS_{Res}}{df_{Res}}, \tag{10}$$

$$SS_{Reg} = \sum_{i=1}^{n} (T_{ji} - T_j)^2 \ , \tag{11}$$

$$SS_{Res} = \sum_{i=1}^{n} (T_{ji} - T_{ji})^2 \ , \tag{12}$$

where FDIST means the F-distribution of variable F, $df_{Reg} = k$ is the degree of freedom of the residuals, $df_{Res} = n - k - 1$ is the degree of freedom of the regression, MS_{Reg} and MS_{Res} are the mean of squares of the regression and the mean of squares of the residuals, SS_{Reg} and SS_{Res} are the sum of squares of the regression and the sum of squares of the residuals.

The optimal degree of the polynomial is selected by comparing the value of parameter p determined for a polynomial of the degree n+1 with the value of this parameter determined for a polynomial of the degree n at the assumed value of the significance level α. The significance level α is defined as $\alpha = 1 - c$, where c is the selected confidence level.

The highest degree of the polynomial satisfying the inequality is optimal. This means that with the adopted significance level α, the use of a polynomial of the degree n+1 does not have a statistically significant impact on the obtained results compared with a polynomial of the degree n.

3. Results of the measurements of thermometric characteristics

Power MOSFETs (*Metal-Oxide-Semiconductor Field Effect Transistors*) by On Semiconductor, type FDB52N20, in a D^2PAK (*Double Decawatt Package*) surface-mount package were selected for testing. These transistors are characterized by the following parameter values [19]: V_{DSmax} = 200 V, i_{Dmax} = 52 A, $R_{DS(on)max}$ = 49 mΩ. Thermal resistance value of the junction-case $R_{thj-c} \leq 0.35$ K/W. The manufacturer also provides in the datasheet the maximum value of the junction-ambient thermal resistance R_{thj-a} for two variants of transistor cooling. In the case of mounting the transistor on a standard soldering pad, the maximum value of R_{thj-a} = 62.5 K/W, and in the case of mounting on a soldering pad increased by a metallization area with the total area of 6.45 cm^2 (1 in^2) it should not exceed R_{thj-a} = 40 K/W.

This paper describes the results of thermal resistance tests of selected transistors soldered to the test boards shown in Fig. 2.

The test boards differ in the solutions used to cool the tested transistors. M1 and M2 transistors are soldered on B1 board and only the standard solder pads for D^2PAK cases are used. In turn, M3 and M4 transistors were soldered on B2 board, and in order to improve cooling, metallization fields, the so-called thermal pads, are used. The metallization fields in the upper and lower layers of B2 board are connected by 49 thermal vias of the diameter 0.6

mm located under the transistors, within the outline of their soldering fields. Additionally, a surface-mount heat-sink is used, soldered on the transistor side [20]. The tests were carried out under natural convection conditions. During the tests, the boards were arranged horizontally with the transistors facing upwards. The test boards are described in detail in the paper [21].

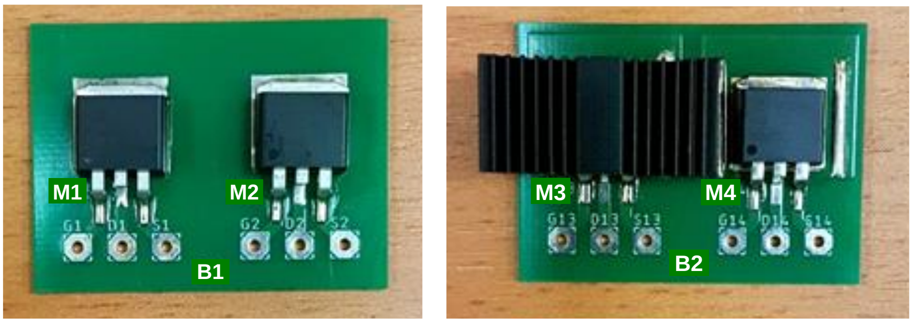

Fig. 2. View of the test boards B1 and B2 with the tested transistors M1 – M4.

Figures 3 and 4 show the dependences of the junction temperature of the tested transistors on V_{GS} voltage, obtained by changing the variables of thermometric characteristics $V_{GS}(T_j)$ of the tested transistors. The dependences presented in the figures were obtained at measurement current $I_D = I_M = 2$ mA and drain-source voltage $V_{DS} = 10$ V. In the figures, the points denote the measurement results, and the lines – the functions approximating the measured dependences. Fig. 3 presents the results of the use of the linear function approximation of the measured characteristics, and Fig. 4 - the quadratic function approximation. The results corresponding to transistor M1, M2, M3 and M4 are highlighted in blue, red, gray and yellow, respectively.

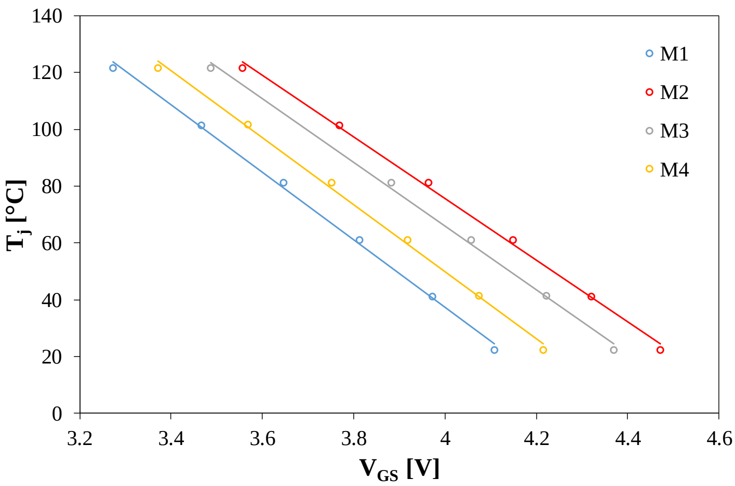

Fig. 3. Dependences $T_j = f(V_{GS})$ of the tested transistors when approximated by a linear function.

As can be seen in Fig. 3 and 4, the fit of the approximating function to the measurement results differs depending on whether it is a linear function or a quadratic function. The maximum deviation of the temperature values obtained using the linear function from the measured values is 2.3 °C, while when using the quadratic function it is only 0.4 °C. The use of the quadratic approximating function therefore provides a much better fit to the measurement data. The visible differences between the considered characteristics measured for the tested transistors prove that for each of them different values of the threshold voltage are observed. Such differences are the biggest between transistors M1 and M2. In this case this difference is

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up to 0.4 V. According to the datasheet [19] this voltage should have the values between 3 and 5 V.

Apart from using the voltage between the gate and the source of the transistor, voltage V_F across a forward-biased anti-parallel diode can be used as a thermally sensitive parameter. Fig. 5 shows the measured (points) and approximated (lines) $T_j(V_F)$ dependences for the tested transistors. Fig. 5a presents the approximation with a linear function, and Fig. 5b - with a quadratic function.

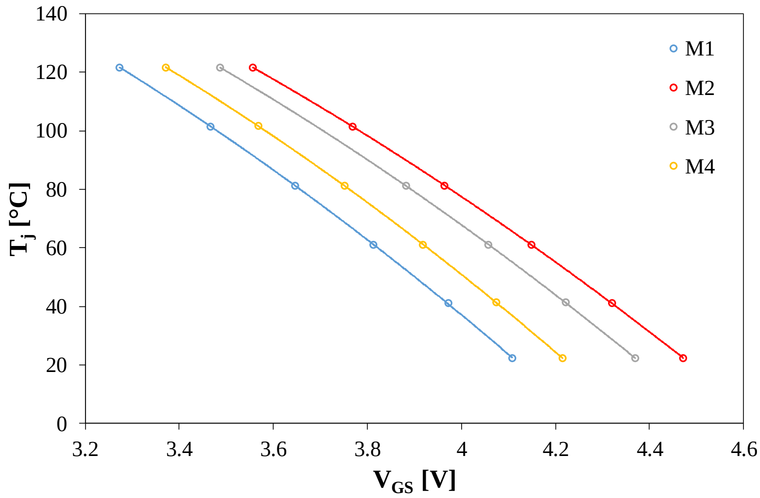

Fig. 4. Dependences T_j =f(V_{GS}) of the tested transistors when approximated by a quadratic function.

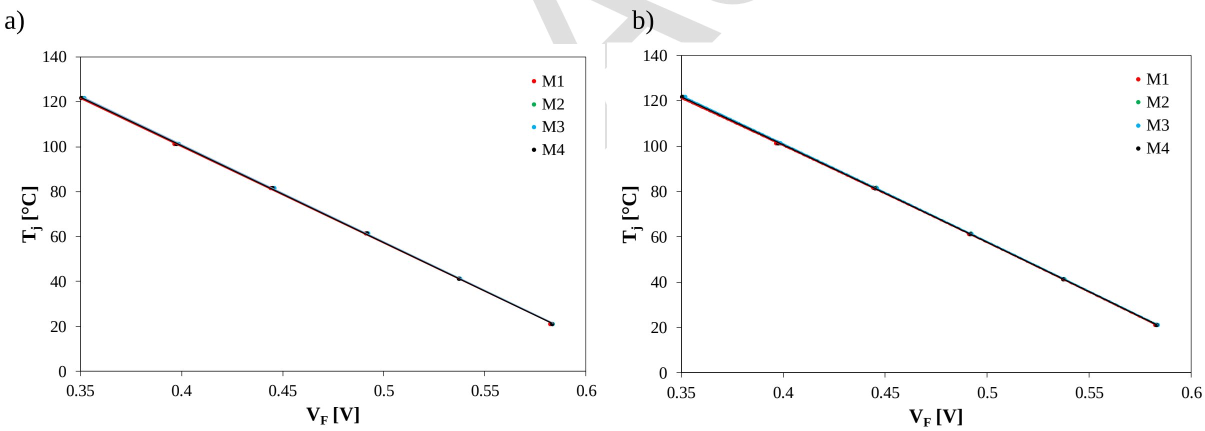

Fig. 5. Dependences T_j =f(V_F) of the tested transistors approximated by a linear function a) and a quadratic function b).

As can be seen in Fig. 5, $T_j(V_F)$ the characteristics measured for 4 different transistors practically do not show any visible differences between them. There are no visible differences in the curves of the functions approximating the measured characteristics, either. This proves high repeatability of these characteristics, in contrast to $T_j(V_{GS})$ dependences presented in Fig. 3 and 4, where the differences between the V_{GS} voltage values at the fixed temperature T_j exceed even 0.3 V. However, the sensitivity of V_{GS} voltage to changes in T_j reaches approximately 8 mV/°C and is much higher than the sensitivity of V_F voltage to temperature changes, reaching only 2.3 mV/°C.

When selecting an approximating function and using a polynomial for this purpose, the problem of selecting its optimal degree is important. This selection is made based on the calculation of the values of p and R^2 parameters. The results of the calculations of the optimal degree of the approximating polynomial for $T_j(V_{GS})$ dependence of the tested transistors are shown in Table 1, and for $T_j(V_F)$ dependence - in Table 2. The values of R^2 and p parameters were calculated from (7) and (9) – (12). The validity of using the polynomials of the degree 1 to 4 in the approximation was considered. The significance level value $\alpha = 0.01$, corresponding to the confidence level c = 0.99, was adopted in the analysis.

As can be seen from the data shown in Table 1, in the case of all four transistors, the values of p parameter for the polynomials of the order 3 and 4 are higher than the assumed significance level α. Therefore, the use of a polynomial of the degree higher than 2 does not result in a statistically significant improvement in the accuracy of fitting the model to the measurement data. Therefore, the optimal degree of the polynomial approximating $T_j(V_{GS})$ dependence for all the tested transistors is the second degree. In turn, Table 2 shows that for all the tested transistors it is optimal to use the first-degree polynomial to approximate $T_j(V_F)$ dependence.

Table 1. Calculation results of the optimal degree of the polynomial approximating the dependence $T_j = f(V_{GS})$ of the tested transistors.

Transistor	M1		M2		M3		M4	
Poly. degree	R^2	p	R^2	p	R^2	p	R^2	p
1	0.9978251	-	0.9978301	-	0.9974163	-	0.997446	-
2	0.9999539	0.001318	0.9999942	0.000059	0.9999866	0.002595	0.9999842	0.000208
3	0.9999544	0.892341	0.9999943	0.85022	0.9999866	0.746147	0.9999879	0.512428
4	0.9999687	0.62208	0.9999986	0.33352	-	-	0.9999888	0.823604
Optimal degree	2		2		2		2	

Table 2. Calculation results of the optimal degree of the polynomial approximating the dependence $T_j = f(V_F)$ of the tested transistors.

Transistor	M1		M2		M3		M4	
Poly. degree	R2	p	R2	p	R2	p	R2	p
1	0.999843	-	0.999888	-	0.999941	-	0.999926	-
2	0.999941	0.112978	0.999952	0.138851	0.999975	0.132319	0.999974	0.103405
3	0.999987	0.118533	0.999961	0.560907	0.999984	0.399311	0.999984	0.358027
4	0.99999	0.661403	0.999988	0.38335	0.999998	0.219324	0.999999	0.186779
Optimal degree	1		1		1		1	

Using the least squares method, the values of the polynomial coefficients approximating the measured characteristics $T_j(V_{GS})$ and $T_j(V_F)$ were determined. The values of these coefficients for the first- and second-degree polynomials are given in Table 3 for $T_j(V_{GS})$ dependence and in Table 4 - for $T_j(V_F)$ dependence. For each case, the values of the R^2 fit coefficient and the standard error SE of the fit of the approximating function to the measurement results were also calculated.

As can be seen from Table 3, in the case of using the non-linear approximation (with the second-degree polynomial) of $T_j(V_{GS})$ dependence, the values of the coefficient of determination R^2 are much higher, and the values of the standard error SE - much lower, compared with the values of these parameters obtained using the linear approximation (with the polynomial of the first degree). In the case of the tested transistors, the SE values obtained using the linear approximation are several to a dozen or so times higher than the values of this parameter obtained using the nonlinear approximation. The use of the non-linear approximation allows obtaining a low value of the approximation error of thermometric characteristics

$T_j(V_{GS})$, which translates into the measurement error T_j negligible from the point of view of many practical applications.

Table 3. Values of the coefficients of the approximating polynomials, the fit coefficient R^2 and the standard error SE for selected functions approximating $T_j(V_{GS})$ dependence.

transistor	Polyn. degree	a_0 [ºC]	a_1 [ºC/V]	b_0 [ºC]	b_1 [ºC/V]	b_2 [ºC/V^2]	R^2	SE [ºC]
M1	1	512.77	-188.85				0.997825	1.94
	2			206.59	48.01	-22.6	0.999954	0.33
M2	1	509.45	-108.46				0.997830	1.94
	2			205.41	43.92	-18.97	0.999994	0.12
M3	1	513.76	-111.97				0.997416	2.25
	2			195.21	51.75	-20.9	0.999987	0.2
M4	1	521.25	-117.84				0.997446	2.11
	2			175.73	8.36	-24.15	0.999984	0.19

In turn, Table 4 shows that the use of the non-linear approximation of $T_j(V_F)$ characteristic does not result in a noticeable improvement in the accuracy of this approximation. The values of R^2 parameter for both the approximating functions are practically indistinguishable. Therefore, the use of the linear approximation of the thermometric characteristics is fully justified.

Table 4. Values of the coefficients of the approximating polynomials, the fit coefficient R^2 and the standard error SE for selected functions approximating $T_j(V_F)$ dependence

transistor	Polyn. degree	a_0 [ºC]	a_1 [ºC/V]	b_0 [ºC]	b_1 [ºC/V]	b_2 [ºC/V^2]	R^2	SE [ºC]
M1	1	271.93	-429.73				0.999843	0.53
	2			258.75	-371.44	-62.56	0.999941	0.37
M2	1	273.49	-432.05				0.999888	0.44
	2			262.69	-384.43	-50.98	0.999952	0.34
M3	1	274.20	-433.14				0.999941	0.32
	2			266.20	-397.90	-37.67	0.999975	0.24
M4	1	273.03	-431.40				0.999926	0.36
	2			263.79	-390.58	-43.72	0.999974	0.25

Analyzing the SE values obtained from the calculations, it should be noted that when using the linear approximation of $T_j(V_{GS})$ dependence, already at the junction temperatures of the tested transistors of around 50 °C, the value of this error in relation to the excess in the junction temperature is approximately 4% and it decreases to the value of approximately 1.3 % at T_j = 150 °C. In turn, the use of a quadratic function causes the value of the standard error normalized with respect to the temperature increase to decrease to below 0.6% at temperature T_j = 50 °C and below 0.2% at temperature T_j = 150 °C, respectively. For $T_j(V_F)$ characteristic, the quotient of the SE value by the temperature increase does not exceed 0.4%.

4. Results of the measurements of thermal resistance

Figure 6 shows the measured dependences of the thermal resistance junction-ambient R_{th} of transistor M1 on B1 board, and Fig. 6 - of transistor M3 on B2 board on the junction temperature of these transistors. The calculations were performed using three manners described in

Section 2. The results corresponding to the approximation of $T_j(V_{GS})$ dependence with a quadratic function (N manner) are marked in blue, while the results obtained using the linear approximation, respectively - L_2 manner and L_1 manner, are marked in green and orange.

As can be seen in Fig. 6, the nature of the dependence of thermal resistance on the junction temperature varies depending on the type of the function used to approximate thermometric characteristics of the transistor. When using L_2 manner, an increasing function $R_{th}(T_j)$ was obtained, and in the case of L_1 and N manners - a decreasing one. Compared with N manner, the use of L_2 manner results in the underestimation of the R_{th} value in the range of low temperature T_j values and the overestimation of the value of this parameter in the range of high temperature T_j values. In turn, the use of L_1 manner causes the overestimation of the R_{th} value in the entire analyzed temperature range, *i.e.* the discrepancies between the obtained R_{th} measurement results reach up to 20%.

Based on the nature of changes in $R_{th}(T_j)$ dependence, conclusions can be drawn about the physical mechanism determining the efficiency of the heat flow between the junction of the device and the surroundings. In the case of the decreasing $R_{th}(T_j)$ dependence, a decrease in the R_{th} value with the increasing temperature is related to an increase in the effectiveness of convection from the surface of the device and its cooling system as the temperature increases [22]. In turn, the increasing nature of $R_{th}(T_j)$ dependence may indicate the decisive role of conductivity in the heat flow from the junction of the device to the surroundings, resulting from the decreasing dependence of thermal conductivity of the materials on temperature [22].

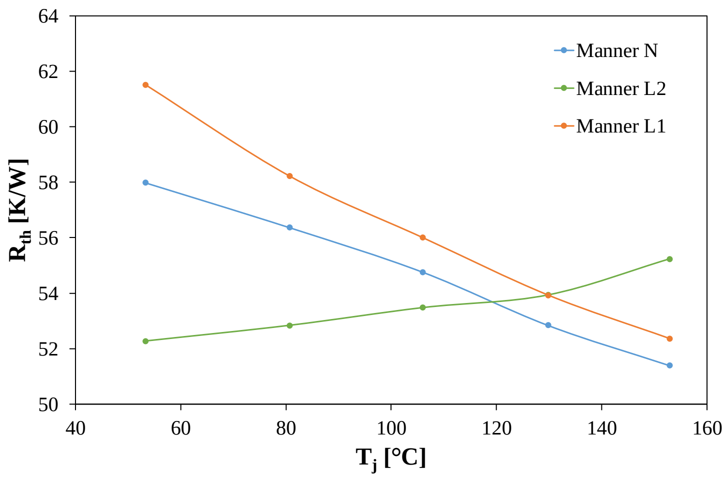

Fig. 6. Dependence of the thermal resistance of transistor M1 on its junction temperature.

The courses of the curves presented in Fig. 6 show that the use of an inappropriate manner of determining the excess junction temperature may lead to incorrect interpretation of the phenomena occurring in the tested cooling system and incorrect conclusions regarding the assessment of whether the cooling system used is optimal.

As can be seen in Fig. 7, in the case of M3 transistor mounted on B2 board, the type of the approximation function used does not affect the nature of $R_{th}(T_j)$ dependence. In each case it is a monotonically decreasing function. The difference between the R_{th} values measured using a linear function and a quadratic function approximating $T_j(V_{GS})$ dependence decreases as the power dissipated in the transistor increases. As in the case of M1 transistor, the R_{th} values obtained using L_2 manner are underestimated and the results obtained using L_1 manner are overestimated compared with the values of this parameter obtained using N manner. The discrepancies between the obtained R_{th} values exceed even 20%.

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Based on the results presented in Figures 6 and 7, the relative error δ_{Rth} of the R_{th} values of transistors M1 and M3 obtained using L_1 and L_2 manners was calculated. The R_{th} values obtained using N manner were used in the calculations as the reference values. The obtained calculation results are shown in Fig. 8.

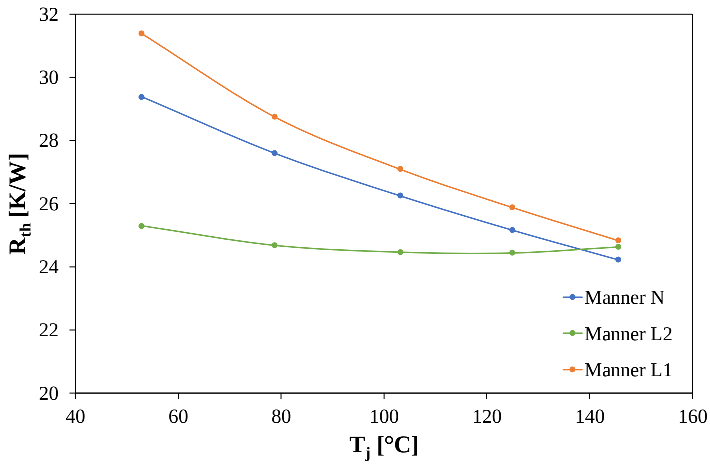

Fig. 7. Dependence of the thermal resistance of M3 transistor on its junction temperature.

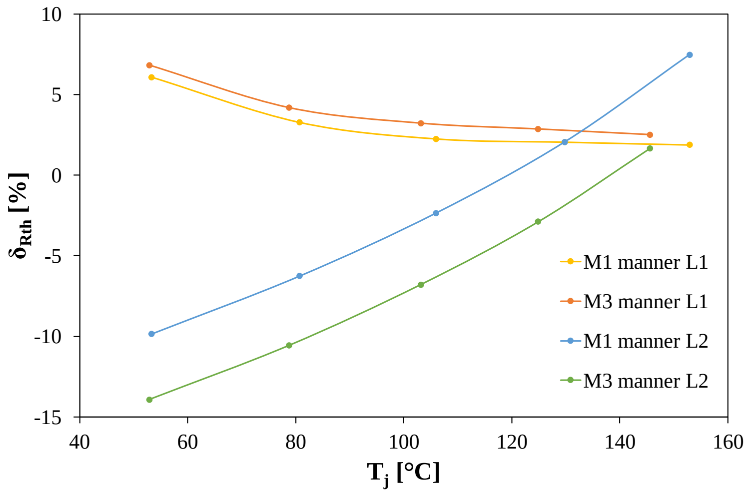

Fig. 8. Dependence of the relative error of the R_{th} value of transistors M1 and M3 on the junction temperature of the tested transistors obtained using manners L_1 and L_2.

As one can see, ignoring the nonlinearity of the thermometric characteristics of the transistors (L_1 and L_2 manners) may lead to significant errors in R_{th} measurements, especially in the low temperature range. The results obtained with L_2 manner are underestimated by up to 14% in the case of transistor M3 and by 10% in the case of transistor M1. The error modulus of the measurements of the R_{th} value obtained in this way reaches its minimum at the junction temperature of the tested transistors of approximately 120 °C. A smaller measurement error can be obtained using L_1 manner. In this case, the measurement error decreases as the junction temperature of the transistors increases throughout the considered temperature range. At the junction temperature of the tested transistors of 50 °C, the value of this error is approximately 7% and it decreases to approximately 2.5% at the temperature of 150 °C.

The underestimation of the R_{th} value obtained from the measurement may later lead to an underestimation of the junction temperature of the transistor during its operation. In extreme cases, this may mean that the transistor operates at the junction temperature exceeding the permissible value, which may lead to its damage. The difference in the measurement results obtained using manners L_1 and L_2 at temperature T_j = 50 °C exceeds even 20%.

The problem of the incorrect determination of the transistor junction temperature practically does not occur when the voltage on a forward-biased anti-parallel diode is used as a thermally sensitive parameter and the value of the measurement current is equal to a few miliampers. The tests performed by the authors confirmed that regardless of whether a linear or quadratic approximation of the thermometric characteristics was used, no noticeable changes in the R_{th} value were observed.

5. Conclusions

This paper describes the results of the investigations illustrating the influence of the method of calculating the excess of the junction temperature of the power MOS transistor and the selection of a function approximating its thermometric characteristics used in the thermal resistance measurement procedure on the measurement results. Thermal resistance was measured using an indirect electrical method. Three manners of determining the excess of the junction temperature of the transistor are presented, using a linear function and a non-linear function approximating the thermometric characteristics $T_j(V_{GS})$ and $T_j(V_F)$.

It was shown that the use of a linear function commonly used in the literature is justified when V_F voltage is used as a thermally sensitive parameter. In this case, virtually identical $T_j(V_F)$ characteristics were obtained for all the tested transistors. In turn, the use of V_{GS} voltage as a thermally sensitive parameter causes significant differences in the thermometric characteristics measured for individual transistors. Additionally, the use of a linear function to approximate $T_j(V_{GS})$ characteristic may lead to significant R_{th} measurement errors and even the incorrect interpretation of the physical phenomena occurring in the cooling system.

Depending on the adopted method of determining the excess of the junction temperature, the measured value of thermal resistance may be overestimated or underestimated. The differences in the thermal resistance values obtained from the measurements using L_1 and L_2 manners compared with the values obtained using the approximation of $T_j(V_{GS})$ dependence with a quadratic function (N manner) reach 15% at the junction temperature of the tested transistors of 50 °C. The difference in the results obtained using L_1 and L_2 manners at this temperature exceeds even 20%. The discrepancies may be even greater when the junction temperatures of the transistors are lower than 50 °C.

The research results presented in this paper may be useful for designers of measurement systems intended to monitor the junction temperature of power MOS transistors operating in modern electronic systems. They may also be useful for designers of power transistor cooling systems.

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