

Investigations of thermal parameters of GaAs and SiC MESFETs

Abstract. The paper deals with a problem of measuring of the thermal parameters – the thermal resistance and the transient thermal impedance of MESFETs made of both the gallium arsenide (GaAs-MESFET) and silicon carbide (SiC-MESFETs). The measuring set proposed by the authors, is presented. SiC and GaAs MESFETs operating at different cooling conditions are investigated. The strong influence of the ambient temperature and the device dissipated power on the device thermal parameters are observed. The new analytical dependence of the MESFET thermal resistance on the ambient temperature and the dissipated power is proposed. (**Badanie parametrów termicznych tranzystorów GaAs i SiC MESFET**).

Streszczenie. Praca dotyczy problematyki pomiaru i modelowania parametrów termicznych – rezystancji termicznej oraz przejściowej impedancji termicznej tranzystorów MESFET wykonanych z arsenku galu (GaAs-MESFET) oraz węgla krzemu (SiC-MESFET). Omówiono metodę pomiaru parametrów termicznych tranzystorów MESFET z wykorzystaniem zaproponowanego przez autorów systemu pomiarowego. Przedstawiono wpływ temperatury otoczenia oraz mocy ciepłej wydzielanej w tranzystorach na wartości ich parametrów termicznych.

Keywords: MESFETs, modeling, thermal variable measurement, temperature measurement.

Słowa kluczowe: tranzystory MESFET, modelowanie, pomiar parametrów termicznych, pomiar temperatury.

Introduction

Power MESFETs (Metal-Semiconductor Field Effect Transistors) have found applications in high frequency radiocommunication circuits e.g. power amplifiers, mixers and oscillators.

This is observed, that increase of the device inner (junction) temperature, resulting from the selfheating, influences on the static and dynamic characteristics of the power MESFETs. So, values of the thermal parameters: the thermal resistance and the transient thermal impedance of the considered devices have to be known.

The inner-to-ambient transient thermal impedance $Z_{thj-a}(t)$ of a semiconductor device is the basic thermal parameter describing the device thermal properties, defined as a thermal response of the device, excited by the Heaviside step function of the heat power and is defined by [1]:

$$(1) \quad Z_{thj-a}(t) = \frac{T_j(t) - T_a}{p_{th}(t)}$$

where $T_j(t)$ is the inner temperature of the device, T_a is the ambient temperature and $p_{th}(t) = P_o \cdot I(t)$ represents the device dissipated heat power.

The popular and frequently used model of the inner-to-ambient (surrounding) transient thermal impedance is of the form [1, 6, 7]:

$$(2) \quad Z_{thj-a}(t) = R_{thj-a} \cdot \left[1 - \sum_i a_i \cdot \exp\left(-\frac{t}{\tau_i}\right) \right]$$

where $R_{thj-a} \equiv Z_{thj-a}(t)|_{t \rightarrow \infty}$ is the thermal resistance between the inner and the ambient, the sum of a_i is equal to 1 and τ_i is the i -th thermal time constant.

Usually, in a manufacturers datasheets of MESFETs the value of the thermal resistance between the inner and the case of the MESFET is given only. This information is not sufficient to evaluate actual thermal properties and the inner temperature of the device.

Many techniques have been reported for measuring the thermal parameters of MESFETs. For example: liquid crystal thermography method (LCTM) [2], infrared microscopy method (IMM) [3], d.c. electrical method (DCEM) [4] and the pulsed electrical method (PEM) [5]. Three first cited methods allowing to determine the inner-to-ambient thermal resistance have some drawbacks, e. g. the

LCTM requires special materials – liquid crystals, the IMM uses costly and troublesome calibration equipment (infrared microscope), the DCEM is dedicated to MESFETs with a narrow-gate stripe only [4]. The PEM is designed for measuring of the inner-to-ambient transient thermal impedance, but requires a fast pulse generator and a transient capturing oscilloscope [5].

In the paper, the computer-aided measuring set of the thermal parameters of the MESFETs proposed by the authors is presented. Known pulse electrical method described in [7] is implemented in the measuring set. A usefulness of the measuring set was tested for many types of semiconductor devices, e. g. p-n and Schottky diodes, BJTs, Darlington transistors, IGBTs, JFETs and MOSFETs [7]. In the paper, a usefulness of the considered measuring set is illustrated by means of measurements of the thermal parameters of the gallium arsenide power MESFET – NE650103M manufactured by California Eastern Labs [9] and the silicon carbide power MESFET – CRF24010F manufactured by Cree, Inc. [10]. The results of measurements of the inner-to-ambient thermal impedance and the inner-to-ambient thermal resistance of the MESFETs operating without any heat-sink, and situated on a small heat-sink at a different values of the ambient temperature and the device dissipated heat power, are presented and discussed. Moreover, an analytical dependence of the MESFET inner-to-ambient thermal resistance on the ambient temperature and the dissipated heat power is proposed.

Measuring method

The presented method is similar to the method of measurement of the thermal parameters of JFETs, reported in [6]. The considered method uses the gate-to-source voltage u_{GS} of a forward biased Schottky junction of the transistor as a thermally-sensitive parameter.

In the method three steps can be distinguished. In the first step the calibration of the characteristic $u_{GS}(T_a)$ of the Schottky gate-to-source (G-S) junction for the small value of the measurement current I_M is carried out. In this measurement the inner temperature is equal (approximately) to the ambient one (the selfheating phenomenon does not appear). Additionally, from the appropriate formula, the parameter $k = du_{GS} / dT_a$ is calculated.

In the second step, the measurement of the inner-to-ambient transient thermal impedance based on the warming curve of the device is carried out [7]. In this step, the device

is excited by the power of the form of the square wave train with the filling factor equal to 0.999, whereas the MESFET is in the saturation region and the junction G-S is reversed biased. In the steady state, during the break of heating, the thermally-sensitive junction G-S is changed from the reverse to the forward range, at the fixed current value equal to I_M . Next, the voltage u_{GS} is measured. The time t_0 between the break of heating and the voltage u_{GS} measuring should be sufficiently long, in order to achieve the electrical steady state in the transistor. In the method the time t_0 is equal to 1 ms, whereas frequency of the voltage u_{GS} measurement is equal to 1 Hz. The second step ends, while the transistor is in the thermally steady state.

In the third step, measurement of the inner-to-ambient transient thermal impedance based on the cooling curve of the device is carried out [7]. In this step, during the break of heating, until $T_j \approx T_a$, the automatic repeated measurements of the junction voltage u_{GS} are carried out. Frequencies of the measurements of the voltage u_{GS} assigned to each time sections are presented in Table 1.

Table 1. Frequencies of measuring of the voltage u_{GS} (third step)

Time section	Frequency
0 ÷ 16 ms	12500 Hz
16 ms ÷ 220 ms	1000 Hz
220 ms ÷ 2.2 s	100 Hz
2.2 s ÷ 22 s	10 Hz
22 s ÷ 300 s	1 Hz
300 s ÷ ∞	0,1 Hz

The block diagram of the measuring set is shown in Figure 1a. It consists of two basic elements. The first element is the transistor bias circuit, containing: the investigated device at the ambient temperature, voltage and current sources which sets the operating point of the transistor, switches S_1, S_2 designed for heating cutoff and for changing of the polarization of the G-S junction between forward and reverse range. The another element is the IBM PC microcomputer, which contains 12-bit analog-to-digital converter and control circuit for the switches S_1 and S_2 .

The voltage on the junction G-S of the MESFET (D. U. T.) is measured by the analog-to-digital converter and written to the RAM. The measuring amplifier (M. A.) allows to use a full voltage range of the converter (-5 V to +5 V) and minimizes the discretisation error. The network representation of the transistor bias circuit is shown in Figure 1b.

If the switches S_1 and S_2 are switched ON, the current I_M flows through the forward biased junction G-S. If S_1 and S_2 are switched OFF, the current $I_H + I_M$ flows through the transistor (the device is heated) and for typical working conditions, the junction G-S is reverse biased.

As the switches S_1 and S_2 the power MOS transistors IRF540 and IRF9540 are used, respectively. The diodes $D_1 - D_4$ are to eliminate undesirable influence of the heating current I_H on the measuring current I_M , while the heating is switched off.

In the presented measuring set the inner-to-ambient transient thermal impedance $Z_{thj-a}(t)$ is calculated from the dependence:

$$(3) \quad Z_{thj-a}(t) = \frac{-(u_{GS}(t_{off}) - u_{GS}(t))}{k \cdot P_H}$$

where $u_{GS}(t_{off})$ is the gate-source junction voltage at the moment the thermal power is turned off, $u_{GS}(t)$ is the gate-source junction voltage changing itself with the time, while the parameter k is calculated from the formula du_{GS}/dT_a with the use of the device measured thermometric characteristic.

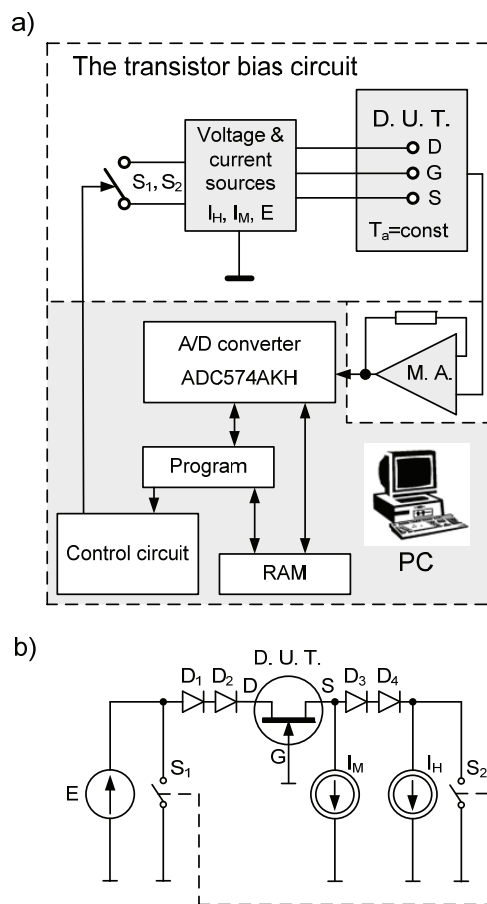


Fig.1. Block diagram of the measuring set (a) and the transistor bias circuit (b)

Results of measurements

By means of the presented measuring set the measurements of the inner-to-ambient transient thermal impedance Z_{thj-a} and the inner-to-ambient thermal resistance R_{thj-a} of the GaAs power MESFET NE650103M and the SiC power MESFET CRF24010 operating with no heat-sink, as well as situated on the small heat-sink of the area equal to 24 cm^2 , at different values of the ambient temperature and the device dissipated heat power, were carried out. The catalog admissible parameter values of the NE650103M MESFET are [9]: $U_{DSmax} = 15 \text{ V}$, $U_{GSmax} = -7 \text{ V}$, $I_{DSSmax} = 5 \text{ A}$, $P_{TOT} = 33 \text{ W}$, $f_{max} = 2,7 \text{ GHz}$, $T_{jmax} = 175 \text{ }^\circ\text{C}$, whereas the catalog admissible values of the CRF24010 MESFET are [10]: $U_{DSmax} = 120 \text{ V}$, $U_{GSmax} = -20 \text{ V}$, $I_{DSSmax} = 1.8 \text{ A}$, $P_{TOT} = 10 \text{ W}$, $f_{max} = 2,7 \text{ GHz}$, $T_{jmax} = 255^\circ\text{C}$.

The characteristics $i_G(u_{GS})$ of the forward biased gate-source junction of the considered transistors corresponding to four ambient temperature values, are presented in Figure 2a and 2b, respectively.

As seen from Figure 2, for the both investigated transistors the values of the voltage u_{GS} at the fixed gate current e.g. $I_M = 1 \text{ mA}$ decrease with increase of the ambient temperature. Values of the voltages $U_{GS1} - U_{GS4}$ versus the ambient temperature, determined from Figure 2a and 2b, are presented in the devices thermometric characteristics shown in Figure 3a and 3b, respectively.

The dependences of the inner temperature, which are approximately equal to the ambient one, versus the junction voltage u_{GS} are linear. Values of the temperature parameters k , calculated from Figure 3, are equal to $-1.69 \text{ mV}/^\circ\text{C}$ and $-1.25 \text{ mV}/^\circ\text{C}$ for GaAs MESFET and SiC MESFET, respectively.

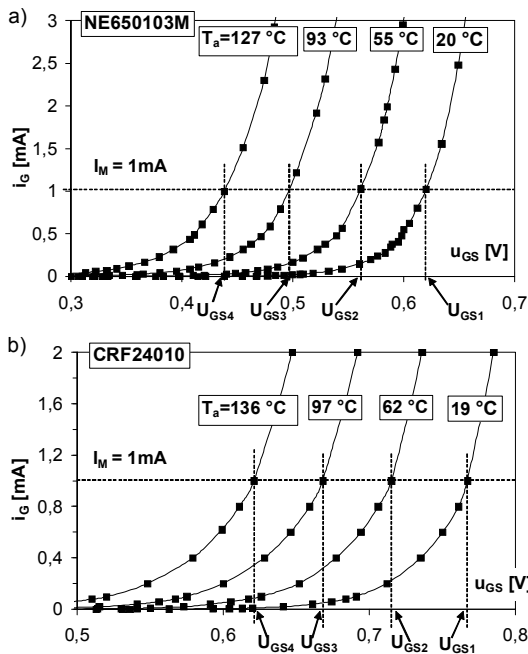


Fig.2. The forward biased gate-source junction characteristics of the transistor NE650103M (a) and CRF24010 (b)

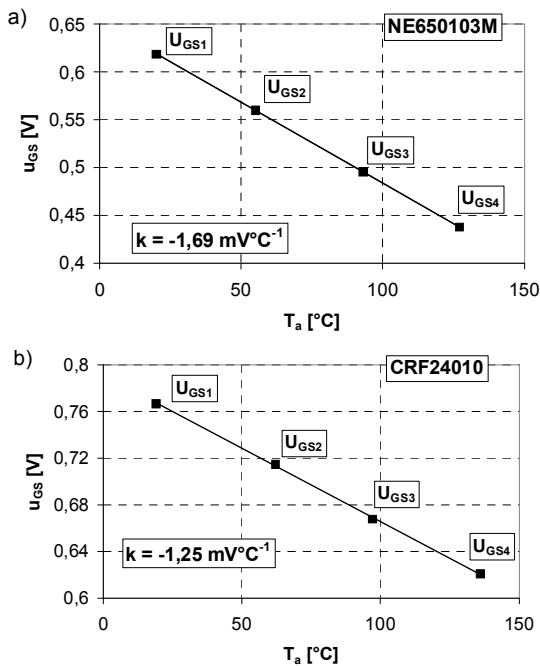


Fig.3. The thermometric characteristics of the gate-source junction of the transistor NE650103M (a) and CRF24010 (b)

The results of measurements of the inner-to-ambient transient thermal impedance at different values of the dissipated heat power in the room temperature for both transistors are presented in Figure 4.

As seen in Figure 4a and 4b, the thermal steady state in the devices operating without and with the heat-sink is reached after about 600 s and 2000s, respectively. Very important information from Figure 4 is the inner-to-ambient thermal resistance dependence on the dissipated heat power. Values of the thermal resistance R_{thj-a} (transistors with no heat-sink) are higher (about 25%) for the SiC MEFET, because this transistor has smaller case area than the GaAs MEFET.

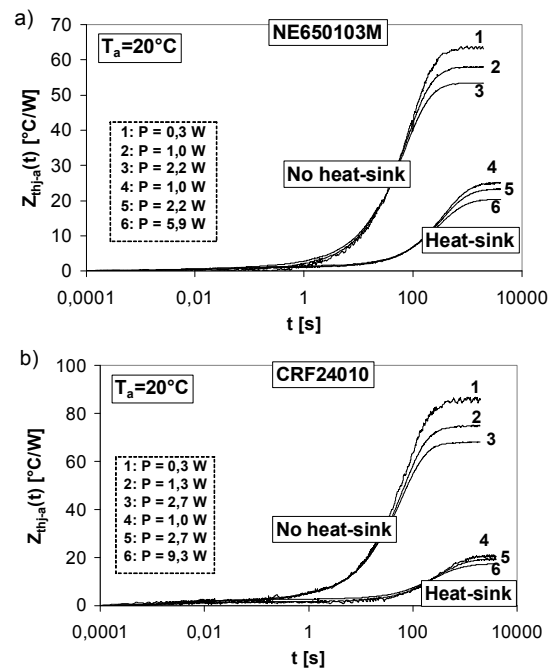


Fig.4. The transient thermal impedance $Z_{thj-a}(t)$ of the transistor NE650103M (a) and CRF24010 (b)

From the results of the measurements of the inner-to-ambient transient thermal impedance measured in the wide ambient temperatures range, the values of the parameters a_i and τ_i existing in the model of the $Z_{thj-a}(t)$ (see Equation 2) have been estimated using the computer program reported in [8]. For example, the values of the coefficients a_i and τ_i for NE650103M MEFET estimated from Figure 4a corresponding to the curve no. 1 (no heat-sink, $T_a=20$ °C, $P_H=0.3$ W) are: $a_1=0.512$, $\tau_1=131.1$ s, $a_2=0.452$, $\tau_2=54.6$ s, $a_3=0.025$, $\tau_3=5.9$ s, $a_4=0.011$, $\tau_4=0.42$ s, whereas for the CRF24010 MEFET values of the coefficients corresponding to the curve no. 1 from Figure 4b are: $a_1=0.764$, $\tau_1=471.3$ s, $a_2=0.198$, $\tau_2=167.7$ s, $a_3=0.032$, $\tau_3=0.056$ s, $a_4=0.006$, $\tau_4=4 \cdot 10^{-5}$ s. As seen, a sum of the coefficients a_i for each curve is equal to 1. Depending on the estimated values of the parameters describing the inner-to-ambient transient thermal impedance, the thermal model in the form of RC network (e.g. Foster chain) can be created and used for modelling of thermal properties of the considered semiconductor device [1, 8].

The measured values (points) of the inner-to-ambient thermal resistance versus dissipated heat power for the considered transistors operating with no heat-sink and situated on the heat-sink are shown in Figure 5.

As seen, the values of the inner-to-ambient thermal resistance decreases with increase both, the dissipated power and the ambient temperature. The value of R_{thj-a} for GaAs-MEFET changes about 8 % for the transistor operating with no heat-sink, and about 6 % for the transistor on the heat-sink at the fixed ambient temperature $T_a=90$ °C, whereas for SiC-MEFET this parameter changes about 15 % and 10 %, respectively. So, if the ambient temperature increases then the device cooling conditions are better and better.

Using the measuring results from Figure 5, the description of the thermal resistance inner-to-ambient as a function of both the dissipated power p and the ambient temperature T_a are proposed of the empirical formula:

$$(4) \quad R_{thj-a}(p, T_a) = R_{thj-a(1W)} \cdot [1 - \alpha \cdot (T_a - T_0)] + -\beta \cdot [1 - \gamma \cdot (T_a - T_0)] \cdot \log(p + P_0)$$

where: $R_{thj-a(1W)}$ – the value of the parameter R_{thj-a} at the dissipated heat power equal to 1 W, α – the temperature coefficient for the parameter $R_{thj-a(1W)}$, T_0 – the nominal temperature, β , γ , P_0 – the model parameters.

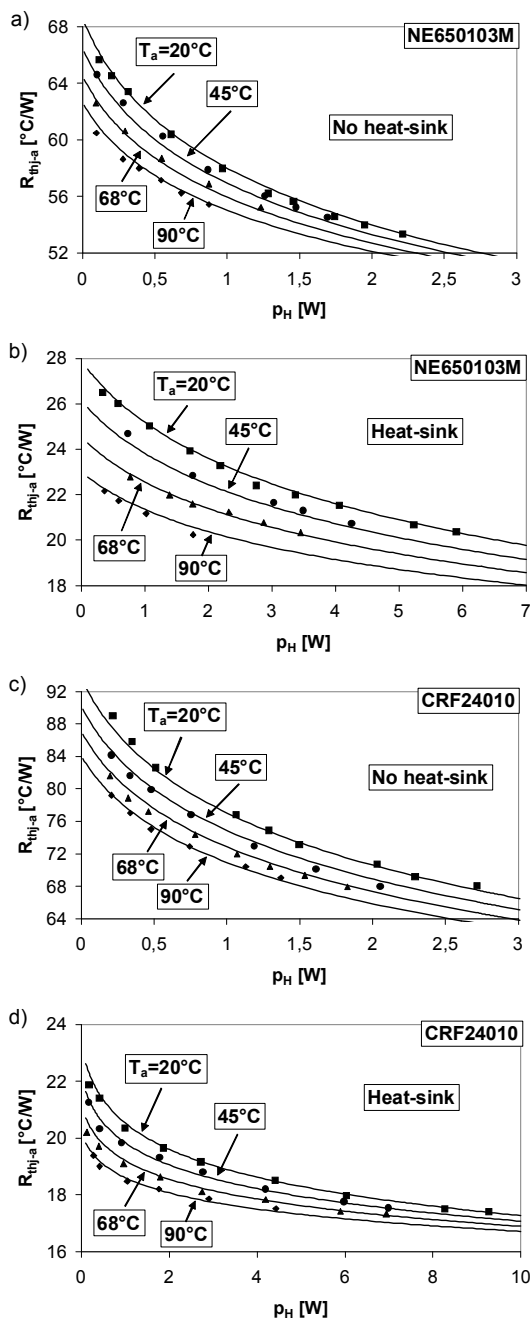


Fig.5. The dependence $R_{thj-a}(p)$ of the GaAs-MESFET (a, b) and SiC-MESFET (c, d) operating without heat-sink (a, c) and situated on the heat-sink (b, d)

Experimentally chosen values of the model parameters for the curves from Figure 5 are given in Table 2.

Table 2. The values of the $R_{thj-a}(p, ta)$ model parameters

MESFET type	NE650103M		CRF24010	
Heat-sink	No	Yes	No	Yes
$R_{thj-a(1W)}$ [K/W]	59.7	27.9	80	20.8
α [K ⁻¹]	$8.3 \cdot 10^{-4}$	$2.5 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$
β [K ⁻¹]	16	9	26	3,5
γ [K ⁻¹]	$4 \cdot 10^{-3}$	$5,5 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	$6 \cdot 10^{-3}$
P_0 [W]	0.28	1	0.3	0.2

The calculated values of R_{thj-a} versus dissipated power and the ambient temperature for the considered transistors are presented in Figure 5 (solid lines). As seen, the proposed model fits well to measurements for the both considered transistors.

Conclusion

In the paper, the measuring set of the thermal parameters of MESFETs is examined. The results of measurements of the thermal parameters of the GaAs and SiC MESFETs at the different values of the ambient temperature and the device dissipated heat power, are presented and discussed. The values of the thermal parameters depend strongly on both, the dissipated power and the ambient temperature. The new model of the inner-to-ambient thermal resistance as a function of both the dissipated power and the ambient temperature is proposed. The model fits well to the results of measurements for the GaAs and SiC MESFETs at the different cooling conditions.

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