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THE ANALYSIS OF ACCURACY OF SELECTED METHODS OF MEASURING THE THERMAL RESISTANCE OF IGBTs

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Abstract

In the paper selected methods of measuring the thermal resistance of an IGBT (Insulated Gate Bipolar Transistor) are presented and the accuracy of these methods is analysed. The analysis of the measurement error is performed and operating conditions of the considered device, at which each measurement method assures the least measuring error, are pointed out. Theoretical considerations are illustrated with some results of measurements and calculations.

Keywords: IGBT, thermal resistance, measurements, transistor, semiconductor devices.

1. Introduction

IGBTs (Insulated Gate Bipolar Transistors) are commonly used in power electronic circuits as electronic switches [1–4]. The range of safe operation area of this type transistor is limited, among other things, by self-heating phenomena, which cause an excess of the internal temperature of this device resulting from electrical power dissipation [5–7]. The value of this excess depends on the thermal resistance, characterising cooling conditions of this device [8, 9]. Producers usually provide information only about the value of thermal resistance of a device at ideal cooling of its case. In real operating conditions of semiconductor devices, some additional elements in the heat flow path are used, *e.g.* isolation pads, Peltier's modules, heat-sinks, *etc*. [10–13]. Moreover, in the real conditions the value of thermal resistance strongly depends on the cooling system construction and measurement of this parameter value is required [13, 14].

In literature one can find descriptions of different measurement methods of this parameter [15–21]. These methods are based on the well-known dependence of electrical parameters of the device on temperature (electrical methods) or on detection of infrared radiation emitted by the examined device (optical methods). The electrical methods can be divided into two groups: impulse methods and dc methods. Yet, there is no information about accuracy of the measurement results obtained with these methods. The papers [17, 22, 23] analyse the error of the thermal resistance measurement carried out using dc methods performed for semiconductor devices with a p-n junction.

In the paper, which is an extended version of the paper [24], selected electrical and optical methods of measuring the thermal resistance of an IGBT are described and the error of measurements performed using these methods is analysed. On the basis of the obtained results of the analysis, an influence of selected factors on the measurement accuracy of thermal resistance is discussed.

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2. Methods of thermal resistance measurements

The thermal resistance R_{th} of a semiconductor device is defined with the following equation [15, 16]:

$$R_{th} = \frac{T_j - T_a}{P}, \tag{1}$$

where T_j denotes the internal temperature of this device, T_a – the ambient temperature, and P – the power dissipated in this device.

Practically, all methods of thermal resistance measurements are based on the (1). The value of the power P at a steady state is obtained on the basis of measuring terminal voltages and currents of the examined device, while the temperature T_a is measured with a thermometer. For an IGBT measuring the power P and the temperature T_a is easy. The problem arises with measuring the device internal temperature. Depending on the way of measuring the temperature T_j, one can distinguish optical and electric methods of measuring R_{th} [15].

In optical methods the value of temperature T_j is measured indirectly on the basis of measuring infrared radiation emitted by the examined device with a thermo-hunter. In optical methods two basic problems appear:

a) the examined solid-state structure is located in a case and measurements of the internal temperature of the device demand destruction of the case, which results in a change of efficiency of the cooling system;
b) emissivity of the examined device surface is not exactly known.

The first of the mentioned problems causes that typically, instead of the device internal temperature, the temperature of its case is measured, which results in underestimating the measured value of thermal resistance. The other problem also causes underestimating of the R_{th} value. Depending on the applied material, the value of emissivity of the semiconductor device case can change even by about 50% [25]. To avoid this, one can cover the examined device surface with a layer of black mat paint, but it causes a change of cooling conditions of the examined device and a drop in the value of thermal resistance [26].

In turn, in electrical methods the device internal temperature is measured indirectly on the basis of the measured value of a selected electric parameter of known and univocal dependence on temperature [13−15, 17]. That is why pulse and dc methods of thermal resistance measurements are used. In the first case, switching the power supply of the tested device between the heating power and the measuring power is used [13−15, 17−20]. In turn, in dc methods suitably converted analytical dependences describing the dc characteristics of the tested device are used [27−29]. In these methods the coordinates of several points lying on the dc characteristics of the tested device are measured. In the case of IGBTs, the role of thermally sensitive parameters is played either by the voltage between the gate and the emitter u_{GE} at a fixed value of the collector current i_C for the transistor operating in the active mode [27, 28], or the voltage u_{EC} on the forward biased anti-parallel diode at a fixed value of the collector current [24].

The dc methods are especially convenient to use [17, 29], and − contrary to the classical impulse methods [14, 16, 18] − they do not demand switching the power supplies of the investigated device. The accuracy of the thermal resistance measurements with electrical methods depends mostly on choosing an appropriate thermally sensitive parameter.

The method of measuring thermal resistance of an IGBT, described in [27], belongs to the group of electrical dc methods. In this method the voltage between the gate and the emitter of the investigated transistor at a selected value of the collector current i_C is used as the thermally sensitive parameter.

The method is based on two foundations:

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a) dependence of the thermal resistance on the operating point of the investigated transistor is weak enough to be neglected,
b) dependence of the voltage u_{GE} on the voltage u_{CE} at a selected value of the collector current is linear, and its slope results only from self-heating phenomena.

In Fig. 1 the diagrams of measurement sets for measuring the thermal resistance of an IGBT with the pulse method (Fig. 1a) and with the dc method (Fig. 1b) are shown.

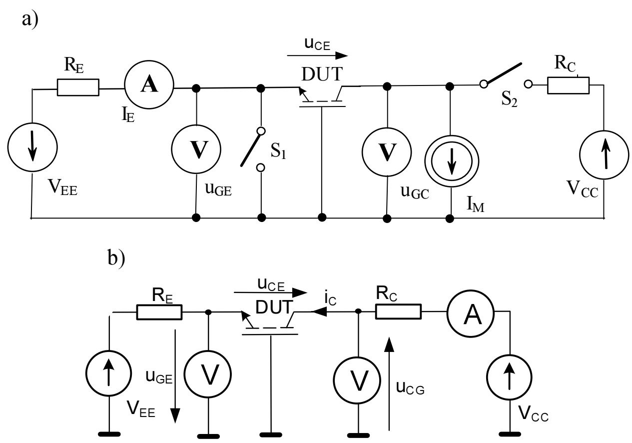

Fig. 1. The sets for measuring the thermal resistance of an IGBT with: a) the pulse method; b) the dc method.

Implementation of the pulse method is carried out in three steps:

a) measuring the thermometric characteristics $u_{EC}(T_a)$ at the collector current equal to the measuring current I_M – then the switch S_1 is closed, and the switch S_2 is open;
b) stimulation of the tested device by a train of rectangular power pulses of the duty factor close to 1; during the heating pulse the switch S_1 is open and the switch S_2 is closed, whereas during the interval between pulses the thermally-sensitive voltage u_{EC} is measured at the switch S_1 closed and the switch S_2 open;
c) calculation of the R_{th} value after obtaining a thermally steady state in the tested transistor.

In turn, performing the dc method requires the following steps:

a) measuring the thermometric characteristics $u_{GE}(T)$ at selected values of the voltage u_{CE} and the current i_C;
b) calculation of the slope α_U of the measured thermometric characteristics;
c) measuring the value of the gate-emitter voltage u_{GE} in two operating points: A(u_{GE1}, u_{CE1}, i_C) and B(u_{GE2}, u_{CE2}, i_C), of the examined transistor;
d) calculation of the value of thermal resistance R_{th} of the examined transistor using the following formula:

$$R_{th} = \frac{u_{GE1} - u_{GE2}}{\alpha_U \cdot i_C \cdot \left(u_{CE1} - u_{CE2}\right)}. \tag{2}$$

Points A and B should be chosen in such a way that the voltage between the gate and the collector is negative.

In both electrical methods the value of the temperature excess $T_j - T_a$ is equal to the quotient of the change of the value of thermally sensitive parameter Δu and the slope α_U of thermometric characteristic $u(T)$. In the commonly used electrical pulse methods, switching the supplying system of the examined device between the heating and measuring modes is indispensable [14–16, 18]. A disadvantage of the pulse methods is underestimation of the value of internal temperature resulting from the time interval between the end of heating pulse and the moment of measurement of the thermally sensitive parameter, and a necessity to measure the thermometric characteristics in a wide range of temperature changes [16].

3. Analysis of the error of the measurement methods

In order to estimate usefulness of the proposed measuring method in practice, the causes of errors of the measurement of thermal resistance of an IGBT by means of this method are analysed. In compliance with the classical theory of the measurement error two components of this error can be distinguished. The first one results from inaccuracies of instruments used to measure the values of quantities occurring in the (1). In turn, the other component of the error results from non-performances of the foundations of the measuring method.

The measuring error of thermal resistance for all considered measuring methods can be estimated using the method of the complete differential in relation to the (1). As a result, the following formula describing the relative error of the R_{th} measurement is received:

$$\delta_{Rth} = \frac{\Delta T_j}{T_j - T_a} + \frac{\Delta T_a}{T_j - T_a} + \frac{\Delta P}{P}, \tag{3}$$

where ΔT_j, ΔT_a, ΔP denote the absolute errors of measurement of temperatures T_j, T_a and power P, respectively.

From the form of dependence (3), it is visible that at a fixed accuracy of measurement of the mentioned quantities, the measuring error of R_{th} is a decreasing function of both the power and the difference of temperatures $T_j - T_a$. Typically, the value of power dissipated in a semiconductor device is measured indirectly by measurement of terminal voltages and currents of the device. Thus, the relative error of the measurement of the power $\Delta P/P$ with typical laboratory multi-meters – with correctly selected measurement ranges - does not exceed 0.1 %. In turn, the absolute error of the ambient temperature ΔT_a measured with a thermometer typically does not exceed 0.5 K.

The error of the measurement of the internal temperature ΔT_j depends on the applied measuring method. In the case of the indirect electrical method, this error is given by the formula:

$$\Delta T_j = \Delta u / \alpha_U + u \cdot \Delta \alpha_U / \alpha_U^2, \tag{4}$$

where Δu denotes the absolute error of delimitation of the value of thermally sensitive parameter, while $\Delta \alpha_U$ – the error of estimating the slope of thermometric characteristic. For typical laboratory multi-meters $\Delta u \leq 1$ mV, whereas for a correctly selected value of the measuring current, assuring linearity of the thermometric characteristic $u(T)$ over a wide range of temperatures, the error $\Delta \alpha_U \leq 20$ μV/K.

The error ΔT_{jt} of the measurement of the value T_j , connected with the existing time interval t_1 between the switch-off of the pulse of the heating power and the moment of measuring the voltage u, depends on cooling conditions of the examined device, characterised by its thermal resistance R_{th}, the shortest thermal time constant τ_{th1} and the weight coefficient a_1 [31, 32]. This error can be estimated using the following formula:

$$\Delta T_{jt} = R_{th} \cdot P \cdot a_1 \cdot t_1 / \tau_{th1}. \tag{5}$$

In turn, in the optical method, the measuring error of the temperature T_j – obtained by a thermo-hunter or an infrared camera – provided by the producer is typically $\Delta T_j = 2$ K. The resolution of such instruments is near 0.1 K. Additionally, the error connected with inaccurate estimation of emissivity ε of the examined surface is:

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$$\Delta T_{j\varepsilon} = \Delta\varepsilon/\varepsilon \cdot \left(T_j - T_a\right), \tag{6}$$

whereas the relative error of delimitation of emissivity $\Delta\varepsilon/\varepsilon$ typically does not exceed 5%. The error ΔT_{jc} results from the fact that in the optical methods the case temperature is measured, instead of the internal temperature, which can be described with the dependence:

$$\Delta T_{jc} = R_{thj-c} \cdot P, \tag{7}$$

where R_{thj-c} is the value of thermal resistance between the junction and the case, given by the producer.

In the optical methods the relative error of the thermal resistance measurements can be defined with the following formula:

$$\delta_{Rth} = \frac{\Delta T_{j\varepsilon} + \Delta T_{jc} + \Delta T_j}{T_j - T_a} + \frac{\Delta T_a}{T_j - T_a} + \frac{\Delta P}{P}. \tag{8}$$

In the dc measurement method, described in [27], the first component of the measurement error resulting from inaccuracy of the instruments can be obtained applying the complete differential method [30] to the (2). As a result, the following expression defining the relative error of the measurement of thermal resistance is obtained:

$$\delta_{Rth} = \pm\left\{\left|\frac{2\cdot\Delta u_{GE}}{u_{GE1} - u_{GE2}}\right| + \left|\frac{2\cdot\Delta u_{CE}}{u_{CE1} - u_{CE2}}\right| + \left|\frac{\Delta i_C}{i_C}\right| + \left|\frac{\Delta\alpha_U}{\alpha_U}\right|\right\}, \tag{9}$$

where Δu_{GE}, Δu_{CE} and Δi_C denote the absolute errors of the measurements of the gate-emitter voltage, the collector-emitter voltage, and the collector current, respectively.

It results from the analysis of the (9) that for the purpose of minimisation of the measurement error, it is necessary to perform the measurement of thermal resistance at a big difference of collector-emitter voltages and a high value of the collector current, which simultaneously will guarantee a big difference of the internal transistor temperature in chosen measuring points and a big difference of the gate-emitter voltage $u_{GE1} - u_{GE2}$.

In the considered method an important role plays linearity of the characteristic $u_{GE}(u_{CG})$ at a selected value of the collector current. In order to determine the range of linearity of the characteristics $u_{GE}(u_{CG})$, some additional measurements are performed. The results of these measurements are shown in [27]. Analysing the obtained characteristics, it is possible to say that the considered dependence is linear over a wide range of changes of the u_{CG} voltage for the current $i_C \leq 50$ mA only. For higher values of the collector current, the considered characteristics has a form of a broken line, whereas the change of slope of the characteristics $u_{GE}(u_{CG})$ appears at $u_{CG} \approx 8$ V. It can be also clearly noticed that this range is reduced together with an increase in the value of the collector current.

If we substitute in the (2) the coordinates of points lying outside linearity of the characteristics $u_{GE}(u_{CG})$, we will obtain over-estimated values of the thermal resistance. In this range of the transistor operation the measuring error can exceed even 50% [27].

In the light of the presented results of measurements, it is necessary to state that the presented method guarantees a small value of the measurement error only for not high values of the voltage u_{CG}, for which the dependence $u_{GE}(u_{CG})$ is linear.

4. Results

In order to estimate the measurement error of thermal resistance of an IGBT calculated with the electrical and optical methods, some calculations using the (1–9) are performed for an

IRG4PC40UD transistor produced by International Rectifier operating at different cooling conditions. In these calculations the value of thermal resistance of the examined device is indispensable. In Fig. 2 dependences of the thermal resistance on the power for the transistor placed on a heat-sink (Fig. 2a) and without any heat-sink (Fig. 2b) measured with the pulse electrical method and the optical method are presented.

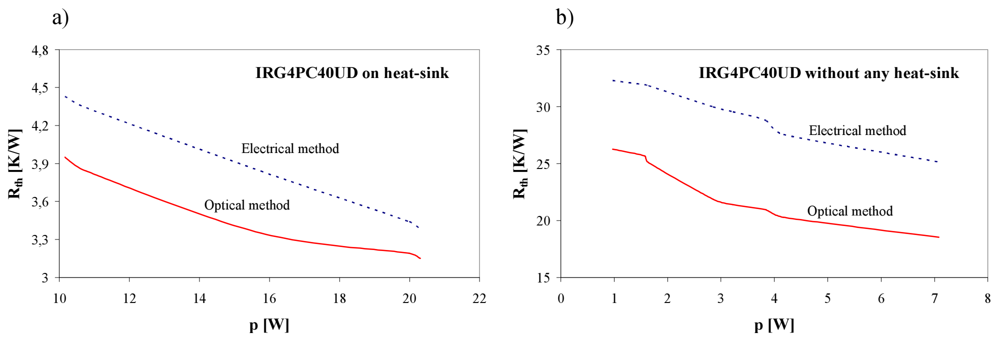

Fig. 2. The measured dependences of the thermal resistance on the power for the IRG4PC40UD transistor placed on a heat-sink (a) and operating without any heat-sink (b).

From the obtained results of measurements, it is visible that the dependence $R_{th}(p)$ is a decreasing function at both types of the considered cooling conditions of the examined transistor. It is also visible that the values of R_{th} obtained with the optical method are smaller than those obtained with the electrical method. The differences between the results of measurements obtained by means of both methods reach even 20%.

In Fig. 3 the measured dependences of the thermal resistance of the investigated transistor on the power dissipated in this transistor are presented. In this figure, the dashed lines denote the results of measurements obtained with the dc electrical method, whereas the solid lines mark the results obtained with the optical method.

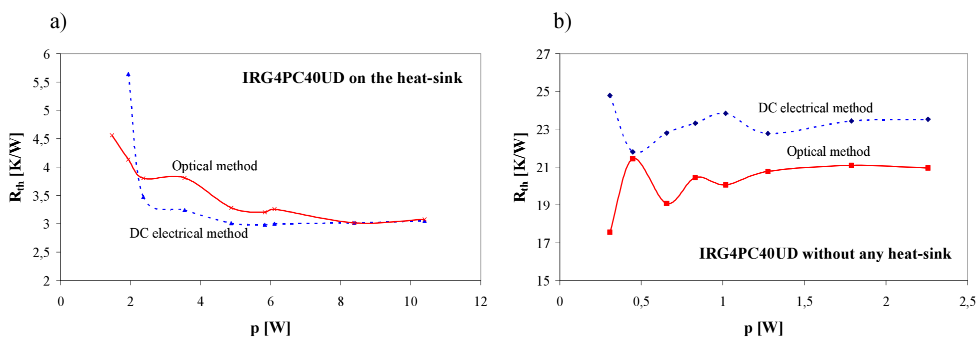

Fig. 3. The measured dependences of the thermal resistance of the investigated transistor on the dissipated power for the transistor a) placed on a heat-sink; b) operating without any heat-sink.

As it is visible, the values of thermal resistance of the investigated transistor operating without any heat-sink obtained with the dc electrical method are about 2 K/W higher than those obtained with the infrared method. This difference is well justified and satisfies expectations, because with the optical method (for capsulated devices), the value of thermal resistance between the transistor case and its surroundings is measured. On the other hand, with the dc electrical method – thermal resistance between the device interior and its surroundings is measured. The difference between them is equal to the thermal resistance R_{thj-c} between the interior and the case of the device. Additionally, the temperature of the device case measured with a thermo-hunter is lower than the real value, because the value of emissivity of the case surface is less than 1 and the temperature on the surface is averaged in the circle with about 2.5 mm diameter [33].

For the transistor placed on a heat-sink, a good agreement between the results of the measurements performed with the electrical and infrared methods is obtained. Of course, using a heat-sink results in obtaining several times smaller values of the thermal resistance than those obtained without any heat-sink.

The differences between the measured values of thermal resistance of the considered transistor presented in Figs. 2 and 3 can be a result of different location of the investigated device, its space orientation and the ambient temperature [13].

In Fig. 4 the calculated dependences of the relative error of the thermal resistance measurement on the power are shown. In the calculations, performed with the (3) and (8), the values of parameters existing in the (1–6) collected in Table 1 are used. For the transistor placed on a heat-sink R_{th} = 4 K/W, whereas for the transistor without a heat-sink R_{th} = 30 K/W.

Table 1. The values of parameters existing in the (1–6) for the IRG4PC40UD transistor.

parameter	ΔT_a [K]	ΔP/P [%]	T_a [K]	u [V]	α_U [mV/K]	Δu [mV]
value	0.5	0.1	300	0.45	–2.3	1
parameter	ΔT_{jP} [K]	τ_{th} [ms]	t_1 [ms]	Δε/ε [%]	R_{thj-c} [K/W]	$\Delta\alpha_U$ [μV/K]
value	2	1	0.1	5	0.77	20

As one can observe, the measuring error is a decreasing function of the power. The value of this error calculated for the electric method is considerably smaller than for the optical method. It is worth noticing that – together with improvement of cooling conditions of the examined transistor – the measurement error of thermal resistance increases.

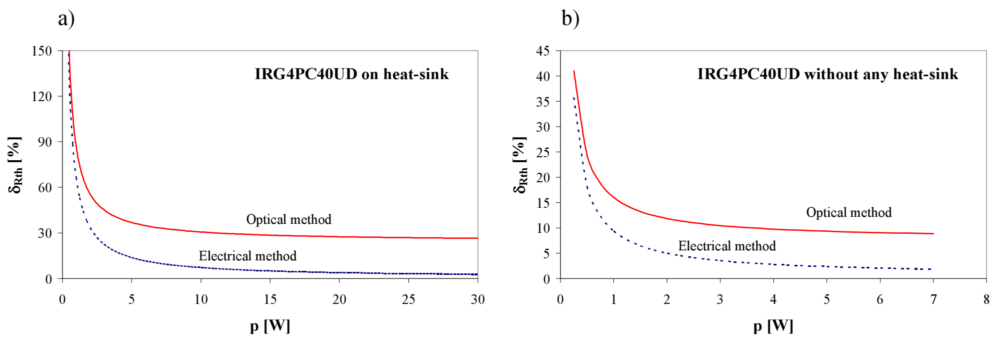

Fig. 4. The calculated dependences of the measurement error on the power for the IRG4PC40UD transistor placed on a heat-sink (a) and operating without any heat-sink (b).

Figure 5 shows the dependence of the error of the IGBT thermal resistance measurement performed with the dc method on the power. The calculations are made on the basis of the formula (9) for fixed values of the voltage u_{CE} equal to u_{CE1} = 2 V and u_{CE2} = 6 V, respectively. In the calculations it is assumed, on the basis of the thermometric characteristics presented in [27], that α_U = −8.84 mV/K, $\Delta\alpha_U$ = 0.2 mV/K. The values of other components of the errors are shown in Table 1.

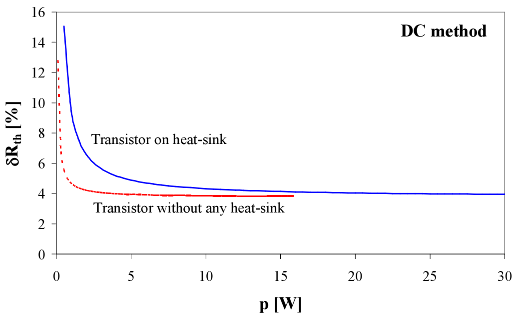

Fig. 5. The calculated dependences of the measurement error of the dc method on the power.

In this figure it is visible that the measurement error is a decreasing function of the power dissipated in the tested transistor. For the same value of power dissipated in the transistor, the smaller value of the measurement error is obtained for the transistor operating without any heat-sink. This is due to the fact that for the same value of power the greater increase in the device internal temperature of the transistor above the ambient temperature is achieved when the cooling conditions of the test device are worse.

5. Conclusions

In the paper accuracy of commonly used methods of measuring the thermal resistance of semiconductor devices is analysed. The components of the measurement error characteristics for the optical and electrical methods are identified. The investigations are performed for an IGBT operating at different cooling conditions. On the basis of the obtained results of investigations it is proved that the electrical methods are characterised by a smaller value of the measurement error than the optical ones. The value of this error is a decreasing function of the power dissipated in the examined device. The error of measurements performed with the electric method can be even 5 times smaller than that obtained with the optical method.

The measurement error of the dc method is also analysed. It is pointed out that there is a limitation in the scope of accuracy of this method to the extent, to which the characteristic of $U_{GC}(U_{GE})$ is linear. It is also shown that even for this method the measurement error is a decreasing function of the power, and for the same power the value of this error decreases with worsening of cooling conditions of the tested transistor.

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