A New Method of Measurement of the Thermal Resistance of the Silicon P-N Diodes

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Abstract – This paper deals with the problem of measuring the thermal resistance of silicon p-n diodes. The values of this parameter given in the catalogues rarely correspond to the real conditions of device cooling, e.g. the diode operating on the heat-sink. Therefore, the value of the thermal resistance has to be obtained from measurements. In the paper a new comfortable method of the measurement of the thermal resistance of silicon p-n diodes, based on measurements of their d.c. current-voltage characteristic and the estimation of the model parameter values with the use of PARTS-software, is presented. The results of measurements obtained by the new method are compared to the standard pulse method.

I. Introduction

The thermal resistance (R_{th}) is a very important parameter of any semiconductor device, allowing to calculate the device junction temperature for a given value of the dissipated power. The values of R_{th} given in the catalogue data concern either the ideal conditions of the heat removal from the device or the conditions of the device cooling are not defined. On the other hand, as it results from literature [1, 2 ,3] and the authors' experience [4], the device thermal resistance value can change even in the wide range depending on both: the device operating point coordinates (e.g. the current or power value) and the used method of measurement of the considered device.

Generally, to measure the device thermal resistance the optical, chemical and electrical methods can be used. It is important to notice, that only electrical methods are nondestructive ones. In these methods the dependence of a selected electrical parameter (most often the voltage on the forward biased diode) on temperature (called a thermosensitive parameter) is used. Such a dependence is called the device thermosensitive characteristic (DTC). The thermal resistance is obtained from

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

where P – the power dissipated into the investigated device, T_a – the ambient temperature, T_j – the junction (inner) temperature calculated on the basis of DTC.

The existing electrical methods of measurement of the thermal resistance of silicon p-n diodes have some disadvantages. For example, these methods demand two ambient temperatures [5], the special measuring set using the pulse method [1] or they can be realized only at the breakdown range [5].

In this paper a new measuring method of the thermal resistance of silicon p-n diodes, based on the measurements of one nonisothermal d.c. characteristic and the use of PARTS-tool for the estimation of the diode parameter values is presented. The main advantage of the method is its easy realization with the use of simple measuring instruments, available in each laboratory. The method has been verified for two diodes of the allowable current equal to about 1A – the Zener diode BZX85C24 and the rectifier one 1N4005.

II. Description of the method

In the proposed method, to obtain the diode thermal resistance R_{th}, the voltage-current characteristic of the investigated device is taken into account [6]

$$u = f\left(i, T_j, \underline{par}\right) = N \cdot h \cdot T_j \cdot \ln\left[\frac{i \cdot \left(i + \sqrt{i^2 + 4 \cdot IKF^2}\right)}{2 \cdot IKF \cdot IS}\right] + RS \cdot i \tag{2}$$

where i, u denote the current and voltage on the diode, h is the quotient of the Bolzmann constant and the electron charge, whereas $\underline{par}$ = [IS, N, RS, IKF] is the vector of the model parameters.

The values of the saturation current (IS) and the diode series resistance (RS) depend on temperature. The following temperature dependence of these parameters has been taken into account [6]

$$IS = I_0 \cdot \left(\frac{T_j}{T_0}\right)^{1.5} \cdot \exp\left(-\frac{U_{go}}{h \cdot T_j}\right) \tag{3}$$

$$RS = RS_0 \cdot \left(1 + TWR \cdot \left(T_j - T_0\right)\right) \tag{4}$$

where U_{go} = 1.206 V for silicon, I_0 is the parameter independent of temperature, T_0 denotes the reference temperature, RS_0 denotes the value of the diode series resistance in the temperature T_0, whereas TWR is the temperature coefficient of this resistance.

In the further part of this chapter the estimation of the diode parameter values by means of PARTS-software is described and the algorithm of the new method is presented.

A. PARTS estimation

In the equations describing the diode (Eqs 2 – 4), two groups of parameters can be distinquished. The first of them (parameters: IS_0, N_0, RS_0, IKF_0) describes the isothermal voltage – current characteristics of the diode at the fixed room temperature T_0 equal to 300 K. The values of these parameters can be determined by means of PARTS (SPICE MODEL EDITOR). To this end the coordinates of some measured points lying on the considered characteristic obtained at 300 K have to be introduced to PARTS as its input data. As results from the authors' experience (also in the case of other devices investigated with PARTS [7, 8]), the number of test points as well as their distribution affects the final result of estimation. To obtain all parameter values, at least four test points should be taken into account, but the best solution can be expected when a dozen or so points distributed uniformly on the characteristic are taken into account.

As the isothermal characteristic of the diodes are necessary the electrical power at the test points should be negligible so that the diode junction temperature and the ambient one could be of the nearly the same values. On the other hand, the diode current has to be of a sufficiently high value so that the generation-recombination current component (not included in Eq. (2)) could be neglected.

By means of PARTS, using the test current values up to 100 mA, the following values of parameters have been obtained: for BZX85C24: IS_0 = 7.16 fA, N_0 = 1.0478, RS_0 = 0.335 Ω, IKF_0 = 1 kA and for 1N4005: IS_0 = 4.63 nA, N_0 = 1.7756, RS_0 = 0.15 Ω, IKF_0 = 1 kA. Because the value of IKF is much higher (two orders of magnitude), than the considered range of currents, this parameter practically does not affect our characteristic. In our further considerations IKF = ∞ is assummed.

In turn, the parameters of the other group: I_0, TWR (N is considered as the temperature independent parameter), indispensable to calculate the diode characteristic at the other temperature T_j ($T_j \neq T_0$) cannot be obtained directly from PARTS. However, after the application of any "trick" we can use PARTS with reference to the temperature of less or higher value than T_0. In this case we have to introduce the value of $N = N_0 \cdot T_j / T_0$ and the coordinate values of the measured points (similarly as it was at the room temperature) corresponding to the new temperature T_j. As a result the set of parameter values describing the diode characteristic at the various temperatures is obtained. This approach was repeated for eight temperature values, which finally results in the parameter values ilustrated in Fig.1. Note, that N and IKF parameters are not considered here. In Fig.1 the squares denote the estimated results (based on measurements), whereas the solid lines correspond to the results of the calculations according to Eqs (3, 4) along with the following values of parameters: for BZX85C24: I_0 = 153 kA, TWR = $1.7 \cdot 10^{-3}$ K^{-1} and for 1N4005: I_0 = 1.18 kA, TWR = $1.5 \cdot 10^{-3}$ K^{-1}.

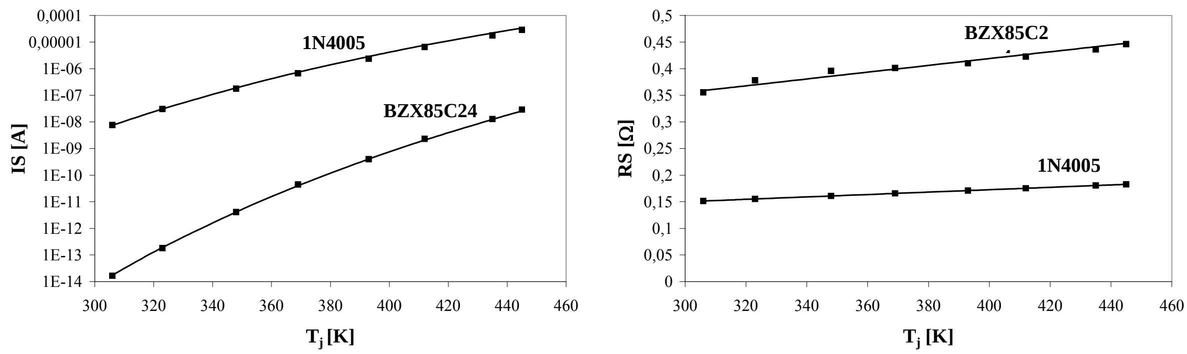

Fig.1. The dependence of the diode model parameter values on the junction temperature

As seen, the assumed temperature dependences fit well to the experimental results for both the considered diodes of much different values of parameters.

One should underline that this stage of investigations, in spite of its great time consumption, was indispensable to reveal that the Eqs. (3, 4) have been correctly chosen. In the presented method the knowledge of I_0 is unnecessary (only IS_0 is considered in the method), whereas the value of TWR is obtained directly from the diode nonisothermal characteristics, which corresponds to the non-ideal cooling conditions.

B. The main algorithm

To realize the proposed method we have to:

- Measure the forward d.c. current-voltage characteristic of the investigated diode (see Fig.2a, b) operating in the simple measuring set (see Fig.2c) at one fixed ambient temperature T_a in the range of small values of dissipated power (the part of the isothermal characteristic from points A to B is considered) and at one point $P_2(U_H, I_H)$ in the high-current level (nonisothermal characteristic), for which the thermal resistance value should be obtained. Additionally, to get the TWR value, the current and voltage coordinates of the nonisothermal point $P_3(U_{H1}, I_{H1})$, situated below the point P_2, have to be measured.

a) b) c)

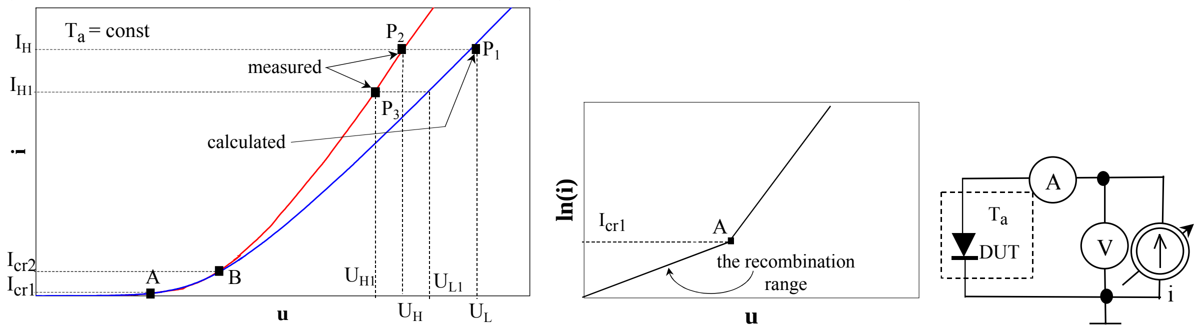

Fig.2. The illustration of the method (a, b) and the measuring set (c)

- Remember the coordinates of at least four points on the isothermal part of the characteristic and the values of U_H, I_H, U_{H1}, I_{H1}.
- Estimate the parameter values: IS_0, N_0, RS_0, IKF_0 for the reference temperature T_0 = 300K, by means of PARTS. At least, the coordinate values of the four points laying on the d.c. characteristic between points A and B are needed to this end. The values: I_{cr1} and I_{cr2} denote the upper limitations of the recombination current range and the isothermal characteristic range, respectively.
- Calculate the isothermal value of the U_L voltage corresponding to the current I_H, according to the equation

$$U_L = N_0 \cdot h \cdot T_0 \cdot \ln\left(\frac{I_H}{IS_0}\right) + RS_0 \cdot I_H \tag{5}$$

- Calculate the value of TWR from the following dependence

$$TWR = \frac{1}{T_0} \cdot \left[1 - \frac{1}{RS_0} \cdot \frac{(U_L - X)\cdot(U_{L1} - U_{H1})\cdot U_H \cdot I_H - (U_{L1} - X)\cdot(U_L - U_H)\cdot U_{H1} \cdot I_{H1}}{(U_L - U_H)\cdot U_{H1} \cdot I_{H1}^2 - (U_{L1} - U_{H1})\cdot U_H \cdot I_H^2}\right] \tag{6}$$

where

$$X = U_{go} + 1.5 \cdot N_0 \cdot h \cdot T_0 \tag{7}$$

whereas U_L and U_{L1} denote the isothermal diode voltages corresponding to the diode currents I_H and I_{H1}, respectively.

- Calculate the temperature coefficient F of the diode voltage from

$$F = \left.\frac{\partial u}{dT_j}\right|_{T_j = T_0} = \frac{U_L - U_{go} - I_H \cdot RS_0 \cdot (1 - TWR \cdot T_0)}{T_0} - 1.5 \cdot h \cdot N_0 \tag{8}$$

- Finally, calculate the thermal resistance from the dependence

$$R_{th} = \frac{(U_H - U_L)\cdot F^{-1} + T_0 - T_a}{U_H \cdot I_H} \tag{9}$$

III. Results

As an example of efficiency of the new method, the results of measurements of the thermal resistance of the medium power Zener diode BZX85C24 (Fig.3a) and a rectifier diode 1N4005 (Fig.3b) for some values of the heat current I_H (see points in Fig.3) are presented. Additionally, for comparison, the thermal resistance measurements of the investigated diodes were repeated (at the same I_H current values) by means of the pulse standard method [1] (see line in Fig.3). As it is seen, the differences between two methods are less than a few percentages.

One can revealed that the total systematic error δ_{Rth} of the method (obtained by the differentiation of Eq. (9)) decreases with respect to an increase of the current I_H. Assuming that the relative errors of both the used measuring instruments and estimation of parameters are equal to 0.1% and 1% respectively, we can reveal that the order of magnitude of δ_{Rth} can be 10% for the currents greater than 0.5 A.

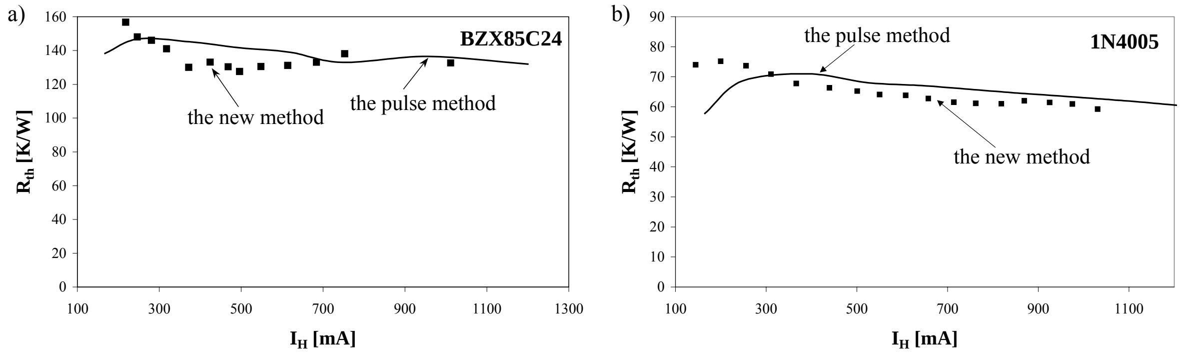

Fig.3. The measured dependence of the BZX85C24 (a) and 1N4005 (b) diodes thermal resistance on the current value

IV. Conclusions

The new method presented in the paper is very simple in realization, comfortable and as was revealed (see Fig.3) fully correct. To realize this method we need only one d.c. current-voltage characteristic of the diode and easily available, free of charge software PARTS (demo version). The error of the method is fully acceptable taking into account its simplicity.

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