MEASUREMENTS OF THERMAL RESISTANCE OF SOLAR CELLS

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ABSTRACT

In the paper the problem of measurement of thermal resistance of solar cells is considered. The electric dc method of measurement of thermal resistance of semiconductor devices with the p-n junction is presented and the infrared and contact methods are described. Measurements of the dependence of thermal resistance of 3 types of solar cells on the current are made and the analysis of uncertainty of the measurement of the considered parameter is performed. It results from the carried out investigations that the use of the electric method is justified with big values of the current of the solar cell, assuring a significant rise of its internal temperature.

INTRODUCTION

A solar cell is an active device of the photovoltaic systems used for power plants to gain electrical energy, thanks to photovoltaic phenomena occurring in it. This device contains the p-n junction, whose properties strongly depend on its internal temperature T_j, and this temperature increases both in consequence of heating of solar cells due to solar radiation and as a result of self-heating. The value of an increase in the internal temperature of the semiconductor device depends on the system removing the heat generated in it and thermal properties of materials used to its construction [4, 5, 6]. If the value of an increase in the internal temperature of the solar cell is too high, then its watt-hour efficiency noticeably decreases [7, 8]. On the other hand, the correct delimitation of this temperature makes it possible to construct the optimal cooling system.

At the steady state the ability of the semiconductor device to remove the emitted in it heat is macroscopically characterized by thermal resistance R_{th}. The thermal resistance is defined as the quotient of an excess of the internal temperature over the ambient temperature T_a at the steady state and thermal power P dissipated in this device. This power is the cause of this increase, according to the formula [2, 4, 5]

$$R_{th} = \frac{T_j - T_a}{P} \quad (1)$$

To be in agreement with the above-definition, in order to limit thermal resistance, it is indispensable to measure the device internal temperature, the ambient temperature and the power dissipated in this device. As far as the measurement of the dissipated power and the ambient temperature is concerned, it is not complicated. Then, the internal temperature of the device can be measured only with the use of indirect methods. There are many methods of measuring R_{th} and the internal temperature of semiconductor devices with the p-n junction richly described in literature [1, 2, 3, 4, 5, 9, 10]. In the review papers [2, 3] 3 groups of methods of measurements of the internal temperature of semiconductor devices are shown. The first of them, called infrared methods, use the dependence of energy of the emitted infrared radiation on temperature. The second group includes contact-methods and uses thermoresistors or thermocouples mounted to the investigated surface. The third group of methods - electric methods, use the dependence of the chosen electric parameter of the device on temperature. In the group of electric methods one can distinguish impulse-methods – which realize switching power supply of the investigated device [5, 10] and dc methods based on measurement of the selected points on the dc characteristics of the investigated device and suitable analytical dependences [1, 4]. One of the dc methods of measurement of thermal resistance of semiconductor devices with the p-n junction was proposed in the paper [1].

The aim of the paper is to examine usefulness of the method described in the paper [1] to limit the R_{th} value of solar cells of different types and of different constructions.

In the first section the used non-electrical measuring methods are characterized. In the second section the considered electrical measuring-method is synthetically presented. The third section contains the results of measurement obtained by means of the considered electric method and, for comparison, by means of infrared and contact methods. In the fourth section the analysis of uncertainty of the measurement is performed.

1. SELECTED NON-ELECTRICAL METHODS OF MEASURING THERMAL RESISTANCE

As it was mentioned in the previous section, to universal methods of measurement of thermal resistance of electronic components belong, among others, the infrared and contact methods. The contact-method consists in measuring temperature of the surface of the investigated device eg. with the use of the thermocouple K. The basis of its operation is the Seebeck′s phenomena [3] describing dependences of the voltage on the point of the junction between two metals on temperature.

During the measurements the thermocouple must be fixed (eg. glued) to the measured surface. In turn, the infrared method uses measurement of the infrared radiation emitted by the surface of the investigated device to estimate temperature of this surface on the basis of the Stephan-Boltzmann law [3]. After limiting the temperature of the investigated device and measuring the ambient temperature and the power dissipated in this device, the value of thermal resistance is calculated from the equation (1).

2. DC METHOD FOR MEASURING THERMAL RESISTANCE

The considered method belongs to the group of dc indirect electric methods and is in detail described in the paper [1]. The description of the idea of this method is contained below. This method uses dependences of the voltage on the forward biased p-n junction on temperature. It demands measuring the non-isothermal current-voltage characteristics of the p-n junction operating in the forward mode. This characteristic is described by the following formula

$$u = f\left(i, T_j, \underline{par}\right) = N \cdot h \cdot T_j \cdot ln\left(\frac{i}{Is}\right) RS \cdot i \tag{2}$$

where i and u denote the current and the voltage of the tested device, h is the quotient of the Boltzmann constant and the electron charge, IS, N, RS are parameters of the p-n junction model.

The values of parameters IS and RS depend on temperature according to the following equations [6]

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

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

where U_{go} = 1.206 V for silicon, I_0 is a parameter independent of temperature; T_0 – the reference temperature, RS_0 – series resistance in the temperature T_0; α_{RS} – the temperature coefficient of series resistance.

Analyzing equations (2) and (3) one can distinguish two groups of parameters describing the characteristics of the p-n junction. The first group contains parameters describing points on the isothermal current-voltage characteristic obtained in the reference temperature T_0 equal to 300 K. To this group belong: IS, N_0, RS_0. One can estimate by means of SPICE MODEL EDITOR, by introducing into this program the model of the diode, several points from the investigated characteristic.

In order to obtain the isothermal characteristic, the investigations should be carried out such manner that the internal temperature of the investigated solar cell is the same as the ambient temperature or insignificantly different from it. This is possible while performing measurements within the range of very low electric power dissipated in the solar cell. Simultaneously, one ought to assure with such big values of the current that on the shape of the characteristic the influence of the generation-combinatorial component of the current is not visible.

To the second group belong parameters I_0 and α_{RS}. These parameters were estimated by introducing the constant $N = N_0 \cdot T_j / T_0$, which was taken into account while estimating values of the coordinates on the forward characteristics, at several temperatures different from the temperature T_0.

In the next step, the coordinates of two points $P2(V_H, I_H)$ and $P3(V_{H1}, I_{H1})$, lying on the current-voltage characteristics of the not lit up solar cell that is forward biased are measured in the area of high currents. On the basis of the measured values of parameters IS_0, N_0, RS_0 and the coordinates of the points P2 and P3, the value of thermal resistance of the investigated solar cell was calculated from the formula

$$R_{th} = \frac{(V_H - V_L) \cdot F^{-1} + T_0 - T_a}{V_H \cdot I_H} \tag{5}$$

where V_H means the value of the forward voltage of the junction at the current I_H, obtained while omitting self-heating phenomena, F is the coefficient of temperature changes of the forward voltage. The voltage V_L and the coefficient F are calculated using the following equations

$$V_L = N_0 \cdot h \cdot T_0 \cdot ln\left(\frac{I_H}{IS_0}\right) + RS_0 \cdot I_H \tag{6}$$

$$F = \left.\frac{\partial u}{dT_j}\right|_{T_j = T_0} = \frac{V_L - U_{go} - I_H \cdot RS_0 \cdot (1 - \alpha_{RS} \cdot T_0)}{T_0} - 1.5 \cdot h \cdot N_0 \tag{7}$$

The value of the parameter α_{RS} is calculated using the dependence

$$\alpha_{RS} = \frac{1}{T_0} \cdot \left[1 - \frac{1}{RS_0} \cdot \frac{(V_L - X) \cdot (V_{H1} - V_{L1}) \cdot V_H \cdot I_H - (V_{L1} - X) \cdot (V_H - V_L) \cdot V_{H1} \cdot I_{H1}}{(V_L - V_H) \cdot V_{H1} \cdot I_{H1}^2 - (V_{L1} - V_{H1}) \cdot V_H \cdot I_H^2}\right] \tag{8}$$

where x is given by

$$X = U_{go} + 1.5 \cdot N_0 \cdot h \cdot T_0 \tag{9}$$

3. RESULTS OF MEASUREMENTS

By means of the measuring-method described in the second section, the measurements of thermal resistance of 3 arbitrarily selected silicon solar cells were performed. The first of them, called below the solar cell A, is made of the monocrystalline silicon and has the dimensions 15.5×15.5 cm. The second solar cell, called below the solar cell B, is made of the poly-crystalline silicon and has the area equal to 231 cm^2. The third solar cell, called the solar cell C, is made of the monocrystalline silicon embedded on the printed circuit board on the dimensions 3.5×7.5 cm and protected with the layer of glaze. For comparison, thermal resistance of the considered solar cells were measured also by means of the contact and infrared methods.

In the contact method the thermocouple of the class I (the thermocouple made of NiCr-Ni, with the range of measured temperatures from –40 to +375°C and tolerance ±1,5(°C)) is fastened permanently. For the solar cells A and B, it is attached directly to the structure of the solar cell, and for the solar cell C directly to its points of junction being found on the other side of the printed circuit board. The values of temperature were read by means of the multimeter APPA 207.

To realize the infrared method, the thermo-hunter Optex PT-3S, situated over the active area of the investigated solar cell, is used.

According to the description of the dc electric method, parameters describing the dc characteristic of the p-n junction contained in the investigated solar cells are measured. Obtained values of parameters IS, N and RS of these solar cells are contained in Table 1.

Table 1. Values of parameters of the model of the solar cell a) monocrystalline, b) poly-crystalline, c) monocrystalline embedded on the PCB

Parameter	**N**	**IS [nA]**	**RS [mΩ]**
solar cell **A**	1.479	284.1	6.76
solar cell **B**	1.679	843.25	13.77
solar cell **C**	1.254	0.814	40.7

For the purpose of verifying the correctness of the calculated values of parameters of the model of the solar cells the measured dark characteristics of the considered solar cells (points and dashed lines) and the corresponding to them isothermal characteristics calculated from the equation (2) (solid lines) are taken down. These characteristics were shown in Fig. 1.

As one can notice, in all the examined cases, the dark characteristics of the investigated solar cells are shifted left by relation with the calculated isothermal characteristics. This shows that the temperature coefficient of changes of the forward voltage is negative in whole the considered range of the forward current.

In Fig. 1 the dependences of the measured thermal resistance on the forward current I_H, performed by means of 3 considered methods, are shown. For the electric method, the current I_H corresponds to the coordinate of the point P2, and the coordinate of the point P3 $I_{H1} \approx I_H/2$. The analysis of the obtained characteristics makes it possible to notice that for each investigated solar cell the decreasing dependence $R_{th}(I_H)$ is obtained.

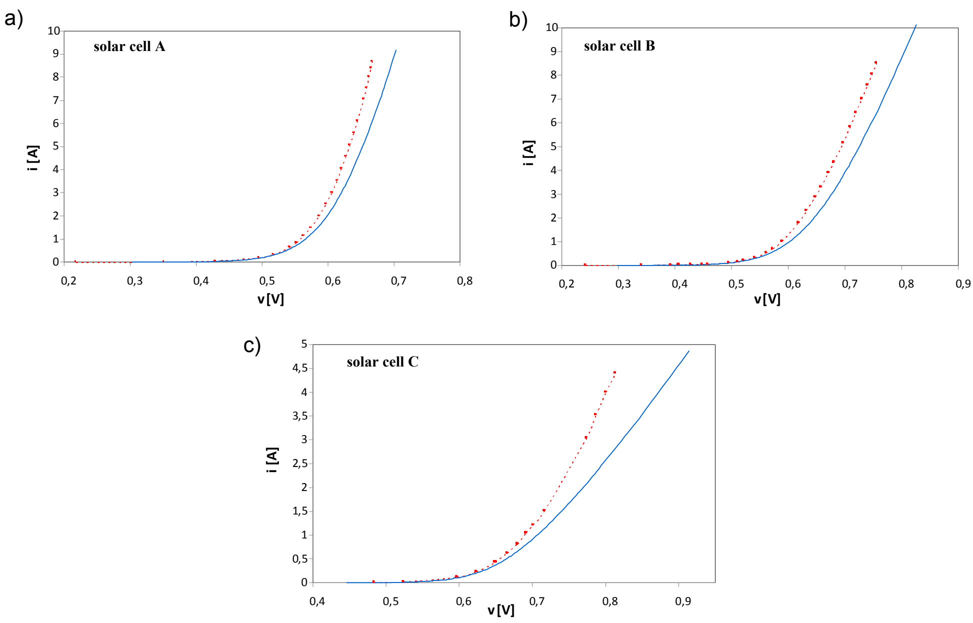

Fig. 1. The measured (points and dashed lines) and calculated (solid lines) dark characteristics of the examined solar cells

The values of R_{th} obtained by means of the considered measuring-methods differ from one another considerably. The biggest values were obtained by means of the dc electrical method and the smallest – by means of the contact method. In the case of the infrared and contact methods the characteristics are shifted down, which results mostly from the fact that the temperature of the solar cell is measured in the points distant from the interior of the semiconductor structure. As it was noticed in Introduction, the internal temperature of the device can be measured only with indirect methods. Hence, also the values R_{th} obtained by means of the dc electric method, for the same values of the current are considerably higher even 6-times, from the value of R_{th} obtained with the remaining methods. It is especially visible for the solar cell C, for which R_{th} accepts the values from 5 to 26 K/W. For the remaining solar cells, R_{th} is equal from 2 to 5 K/W for the solar cell A to and from 2 to 4 K/W for solar cell B.

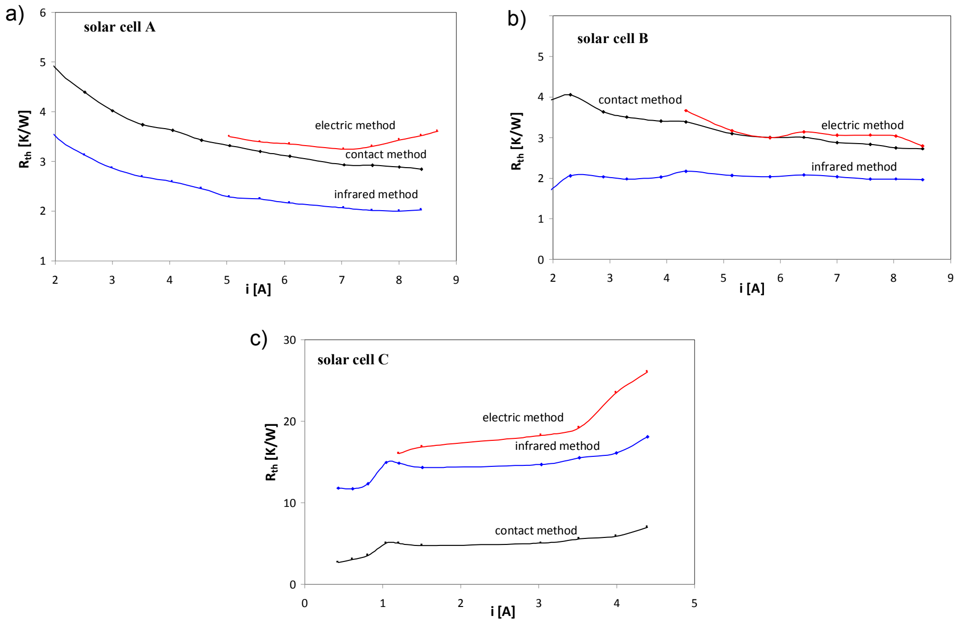

Fig. 2. Dependence $R_{th}(I_H)$ for: monocrystalline solar cell (a), polycrystalline solar cell (b) and monocrystalline solar cell mounted on a PCB (c)

4. ESTIMATION OF THE ACCURACY OF MEASUREMENTS

In order to estimate reliability of the obtained results of measurements, the dependences describing the measuring error for every considered method were formulated. Using the classical method of the complete differential with reference to equations (5) and (1), the following dependences describing the systematic error of the measurements performed by means of the considered methods were obtained. For the dc electric method this equation has the form

$$u_{Rth} = \left(\frac{\partial R_{th}}{\partial V_H}\right)\cdot u_{VH} + \left(\frac{\partial R_{th}}{\partial V_L}\right)\cdot u_{VL} + \left(\frac{\partial R_{th}}{\partial I_H}\right)\cdot u_{IH} + \left(\frac{\partial R_{th}}{\partial F}\right)\cdot u_F + \left(\frac{\partial R_{th}}{\partial T_0}\right)\cdot u_{To} + \left(\frac{\partial R_{th}}{\partial T_a}\right)\cdot u_{Ta} \quad (10)$$

whereas, for the contact and infrared methods it has the following form

$$u_{Rth} = \left(\frac{\partial R_{th}}{\partial T_j}\right)\cdot u_{Tj} + \left(\frac{\partial R_{th}}{\partial T_a}\right)\cdot u_{Ta} + \left(\frac{\partial R_{th}}{\partial I_H}\right)\cdot u_{IH} + \left(\frac{\partial R_{th}}{\partial V_H}\right)\cdot u_{VH} \quad (11)$$

In the equation (10) of uncertainty of delimitation of the voltage V_H, the current I_H, temperatures T_0 and T_a and beyond the accuracy of the applied instruments and of carried out properly they are $u_{VH} = 1$ mV, $u_{IH} = 1$ mA, $u_{T0} = 0.1$ K, $u_{Ta} = 0.1$ K.

In turn, uncertainties of the delimitation of the slope of the thermometric characteristics F and the voltage V_L are calculated with the method of the complete differential for equations (6) and (7), respectively. In the equation (11), uncertainty of the delimitation of temperatures T_j and T_a, the voltage V_H and the current I_H are equal to uncertainties of applied instruments and they are u_{Tj} = 3 K, u_{Ta} = 0.1 K, u_{IH} = 1 mA and u_{VH} = 1 mV.

Using dependences (10) and (11), uncertainties of the measurement of thermal resistance of the examined solar cells on the current I_H are estimated. In Fig. 3, the considered dependences normalized to the measured value of thermal resistance are presented. As one can notice, for every considered measuring method the decreasing dependence of the normalized uncertainty on the current I_H is obtained. For the solar cells A and B the least uncertainty of measurement is obtained with the use of the contact method. In turn, for the solar cell C – the most accurate measurement is obtained by means of the dc electric method and the infrared method.

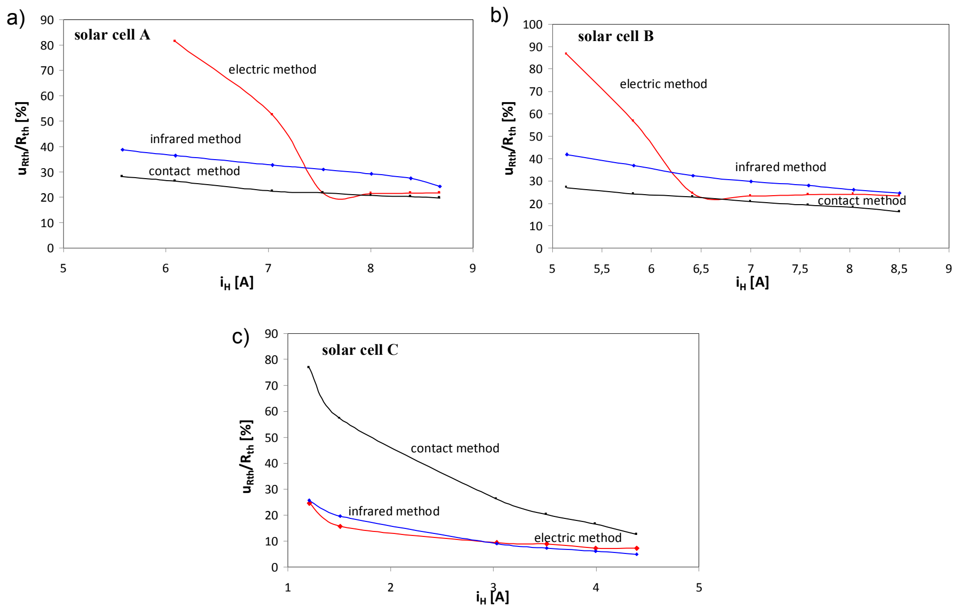

Fig. 3. Dependence of uncertainty obtained with three methods for three solar cells: monocrystalline (a), poly-crystalline (b) and the monocrystalline solar cell embedded on the PCB (c), on the forward current

Of course, the inaccuracy of the measurement is also due to factors, which were not taken into account in the analysis of uncertainty of the measurement. Such factors are: unequal spatial distribution of temperature on the surface of the measured device and the considerable distance of the temperature sensor from the source of the heat. The first factor concerns the infrared and contact methods for all the investigated solar cells, and the second - only the contact-method and the solar cell C. It is visible in the comparison of the results of the measurement obtained by means of the considered measuring methods that a significant meaning has location of the temperature sensor in the contact method opposite the printed circuit board in relation with the active area of the solar cell. This causes that the result of the measurement is understated by even about 50%.

CONCLUSIONS

In the paper the problem of measurement of thermal resistance of solar cells of different construction are analyzed. Particularly, usefulness of the dc electrical method of measurement of thermal resistance of the p-n junction to measure the value of this parameter for the solar cells is examined. For comparison, also the measurement of thermal resistance of the considered solar cells with the use of the infrared and contact methods are performed. From the carried out investigations it results that the values of thermal resistance obtained by means of every considered method are a decreasing function of the current of the solar cells.

The values of thermal resistance obtained by means of the electric method are the highest, which is justified, because the remaining measuring-methods are based on measuring the surface temperature of the solar cell or its surface, and the dc electric method uses the information about the value of the forward voltage of the p-n junction, dependent directly on temperature inside solar cells. The performed analysis of uncertainty of measurement shows that the use of every considered methods is justified with the big values of power dissipated in the solar cell, and that the values of relative uncertainty of e measurement in this range do not exceed several percent.

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