Modulation method for measuring thermal resistance of solar batteries and its practical implementation

V I Smirnov¹,², V A Sergeev¹,² and A A Gavrikov¹

¹Ulyanovsk Branch of Kotelnikov Institute of Radio-Engineering and Electronics of Russian Academy of Sciences, 48, Goncharov Street, Ulyanovsk, 432071, Russia
²Ulyanovsk State Technical University, 32, Severnyi Venets Street, Ulyanovsk, 432027, Russia

E-mail: a.gavrikoff@gmail.com

Abstract. This paper describes a modulation method of measuring the thermal impedance of power solar batteries. The analysis of the dependence of thermal impedance on modulation frequency allows determining thermal impedance components corresponding to the structural elements of a battery. The apparatus used for the experiments, its principles, functional diagram and experiment conditions are described. It is experimentally shown that the magnitude of the variable component of junction temperature is mostly independent of the value of the heating power. This is explained by current crowding, that is a non-uniform distribution of the current through the junction and formation of local heating areas of the semiconductor. The formation of local heating areas is confirmed by the experimentally detected thermal resistance component, which takes place due to the temperature difference between local heating areas and the other part of a semiconductor of a solar battery. Another confirmation of the local heating areas is a sharp thermal resistance decrease with an increase of the heating current. The experiments confirm the possibility of the apparatus, which uses the modulation method, to measure the thermal resistance of power (up to 500W) solar batteries.

1. Introduction

The most of light energy absorbed by solar batteries is converted to heat and causes significant heating of the batteries and, as a result, causes negative changes in their thermoelectric properties, namely the efficiency of converting light energy to electrical energy. This makes it urgent to study the processes of heat removal from the active area of a battery (p-n-junction) to a battery case and further to surroundings. The heat sink quality characterizes the thermal resistance “junction-to-case”, which is determined by the ratio of the temperature increment of the p-n-junction to the power dissipated in the device. The lower thermal resistance between the p-n-junction and the substrate is, the lower their temperature is and the higher output power of the solar cell becomes. Despite the importance of measuring the thermal resistance of solar cells, there are no standards for measuring this parameter, and the number of publications on this topic is very small [1–3].

The important work on the topic [1] suggests considering solar cells as a set of diodes connected in series and in parallel. This makes it possible to use thermal transient testing using well-known JEDEC standards. In this case, the device under test (DUT) is heated by passing forward current pulses through the p-n junction. The p-n-junction temperature is determined indirectly and based on a forward voltage drop on the junction at low measuring current, which is a temperature-sensitive parameter (TSP); the
forward voltage drop is linearly related to the junction temperature. Measurement of thermoelectric parameters in power solar cells has a lot of peculiarities that complicates experimental research.

Firstly, the measurement of thermal resistance must be carried out with the battery completely shielded from the light; otherwise electric current may be generated in the battery and lead to errors in the measurement. In this case, the magnitude of the heating current must be large enough to ensure the heating of the battery by at least 20 °C [1]. Otherwise, the measurement accuracy will not be high enough.

Secondly, after each pulse, the junction temperature changes should be measured with a certain delay relative to the end of the pulse. During this time, transient electrical processes caused by switching from high-current to the temperature-sensitive parameter (TSP) measuring mode must be completed. The duration of these transient processes depends on the solar battery p-n-junction capacity, which is determined by the area of the battery. The area of the battery can vary within wide limits. Therefore, the delay time for almost every DUT should be different.

Thirdly, all standard methods require the temperature of a DUT to remain constant during the measurement. Usually liquid-cooled copper “cold plates” are used. However, the dimensions of the “cold plates” are smaller than most power solar batteries. Therefore, their use for fixing the temperature of the body is impossible in many cases. The modulation method using varying harmonically heating power [4] allows reducing the influence of the delay time and temperature trend of the DUT’s case.

2. Modulation method of measuring thermal impedance

The principle of the modulation method is as follows [4]. A pulse sequence of heating current, with the pulse length varying harmonically, is passed through the device under test, repetition period \( t_p \) is constant and pulse length \( \tau_p \) varies harmonically:

\[
\tau_p = \tau_{p\text{ avg}} \left( 1 + a \cdot \sin 2\pi vt \right),
\]

where \( \tau_{p\text{ avg}} \) is the average pulse length; \( a \) is the modulation factor of the heating power and \( v \) is the modulation frequency, \( t \) – time.

The average value of the heating power for a pulse period, \( \overline{P}(t) \), as the pulses length (3), also varies harmonically:

\[
\overline{P}(t) = P_{\text{avg}} (1 + a \cdot \sin 2\pi vt) = P_{\text{avg}} + P_1 \cdot \sin 2\pi vt,
\]

where \( P_{\text{avg}} = I_{\text{heat}} \cdot U_{\text{heat}} \frac{\tau_{p\text{ avg}}}{t_p} \) is the average value of heating power; \( U_{\text{heat}} \) voltage on the DUT in time of heating pulse; \( P_1 = a \cdot P_{\text{avg}} \) is the amplitude of the changing component of the heating power.

The modulation of heating power causes corresponding changes of the p-n junction temperature \( T_j \) that are phase-shifted with respect to power

\[
T_j(t) = T_{j0} + T_{j1} \cdot \sin(2\pi vt - \phi),
\]

where \( T_{j0} \) is the constant component of the junction temperature; \( T_{j1} \) is the amplitude of the variable component of the junction temperature at the modulation frequency; \( \phi \) is the phase shift between the variable components of the junction temperature and the heating power.

The junction temperature with respect to the battery’s case or environment is determined (as in the JESD51-1 standard) based on a TSP. Under the TSP forward voltage \( U_{\text{TSP}} \) on the battery is taken, with low measuring current \( I_{\text{meas}} \) passing through the battery. The p-n-junction temperature can be determined if the voltage temperature coefficient (VTC) determined with the standard method [5], and the measured \( U_{\text{TSP}} \) value are known.
The $T_j(t)$ spectrum is calculated by Fourier transform and then digitally filtered. After that, the combined dependency $T(t)$ is restored. The thermal impedance magnitude, $Z_T(\nu)$, on the modulation frequency, $\nu$, is determined by the ratio of the magnitudes of the variable components of the junction temperature, $T_1$, and power, $P_1$. Thermal impedance phase is determined by the ratio of the real $\text{Re} T_{j1}$ and imaginary $\text{Im} T_{j1}$ Fourier transforms:

$$Z_T = \frac{T_{j1}}{P_1}, \quad \varphi = \arctg \frac{\text{Im} T_{j1}}{\text{Re} T_{j1}}.$$

Usually the thermal impedance of the device under test (DUT) includes a few components, corresponding to the construction elements (die, substrate, case, heat sink). Thermal resistance components are measured based on the frequency dependencies of magnitude, $Z_T(\nu)$; phase, $\varphi(\nu)$, and the real part of thermal impedance, $\text{Re} Z_T(\nu)$. They have peculiarities such as flat graph sections or inflexion points corresponding to various thermal resistance components. In order to identify such peculiarities, the derivatives of these values are determined by modulation frequency. According to Smirnov et al. [6], the analysis of the $\text{Re} Z_T(\nu)$ frequency dependency gives more accurate results.

3. Apparatus for thermal impedance measurement

The apparatus uses the principals of the modulation method and includes the thermal resistance meter, personal computer and post-processing software. It is functional diagram shown in figure 1. The meter works under control of ATmega128 microcontroller (MCU), which generates heating current pulses, measures the voltage on device under test (DUT) during the passage of pulses and in pauses between them, receives data about measurement parameters from a computer and transmits measurement results to a computer, controls the occurrence of abnormal situations and transmits error codes to the computer. The measuring current source $I_{\text{meas}}$ of the heating current was implemented according to the well-known scheme based on operational amplifiers with field-effect transistors in the feedback circuit. The pulse-width modulation of the heating current $I_{\text{heat}}$ is implemented by electronic switch. The magnitude of the pulses is set using a digital potentiometer controlled by a microcontroller.

![Figure 1. Functional diagram of hardware-software complex](image)

Voltage drop on the device under test (TSP) measured between heating pulses may vary widely depending on the device under test. For this reason, the differential amplifier subtracts constant voltage $U_0$ from $U_{\text{TSP}}$. A front-end 16-bit AD converter with a sequential output converts measurable voltage into a digital code, which arrives at the MCU. The AD converter interacts with the MCU by means of the high-speed serial interface SPI. The measurement results are registered in the memory of the MCU.
As the measurements are finished, the result data are transmitted to the computer for postprocessing. The MCU interacts with the computer through the USB-interface.

In case of emergency situations, for example, overvoltage on the DUT, the controller connects the shunt to the object using a relay. The shunt is also connected when the power is turned on and off, because at this moment power current pulses can pass from the power supply through the object, which can lead to negative consequences.

The software includes a MCU program and personal computer program LED Meter that provides mode setting, results processing and monitoring of measurements. MCU program provides the following functions.

1) Setting of the pulse width modulation sequence of heating current with a specified amplitude, cycle time, and frequency of modulation.

2) Forward voltage drop measuring on the device under test during heating pulse pass. This allows estimation of the value of heating power.

3) Measuring of $U_{TSP}$ at heating pulse intervals. This allows measurement of the variable component of the p-n junction temperature.

4) Transmission of measured data from the device to a personal computer for visualization and postprocessing.

Moreover, the MCU program monitors thermal impedance measuring and has an alarm-reporting function.

The LED Meter software provides the following functions:

1) Setting of the pulse width modulation sequence of heating current with a specified amplitude, cycle time, and frequency of modulation.

2) System mode setting.

3) Data transmission of measurement options to the meter (heating current value, heating pulse period, modulation frequency, and a number of other parameters).

4) Measurement results processing in accordance with the set modes.

5) Textual and graphical representation of the processing and measurement results.

6) Measurement results database management.

7) Determination of thermal impedance frequency and current dependences.

The figure 2 shows the results of 50W solar battery thermal resistance components [6]. The upper graph shows the real part $Re\ Z_T(\nu)$ of thermal impedance dependence on frequency, the lower graph shows the result of its processing. The dependence of $Re\ Z_T(\nu)$ was measured in the frequencies range from 0.0032 to 100 Hz. The measurements were made in the direction of the frequency decreasing with a uniform step in the logarithmic scale. The heating current pulses magnitude was 1000 mA.

To identify the features of $Re\ Z_T(\nu)$ dependence, was performed its differentiation with respect to ln$\nu$, calculation of $[dReZ_T/d(ln\nu)]^1$ function, which depends on the thermal resistance $R_T$. The result is shown at the lower graph in figure 2. The peaks positions relative to the $R_T$ axis determines the thermal resistance components. Three peaks are clearly observed for the solar battery DUT, corresponding to three components: $R_{T1} = 0.0115$ K/W, $R_{T2} = 0.055$ K/W and $R_{T3} = 0.121$ K/W. The $R_{T2}$ component corresponds to the "junction-to-case" thermal resistance of the solar battery at a modulation frequency of 0.5 Hz, component $R_{T3}$ - the "junction-to-frame" thermal resistance at a modulation frequency of 0.01 Hz.

The reason for the $R_{T1}$ component appearance is the inhomogeneity of current distribution through the p-n-junction and, therefore, non-uniform temperature distribution on the battery surface. The appearance of more heated local areas, surrounded by less heated areas leads to temperature differences at the boundary between them. This causes the $R_{T1}$ component to appear at a modulation frequency of 35 Hz.

The presence of this thermal resistance component confirms the assumption of the authors of [7] about the non-uniform current distribution over the battery structure and the occurrence of “current crowding”. 

...
4. Conclusion
The hardware-software complex based on the modulation method was developed to measure the thermal resistance of solar batteries. Pulse-width modulation of heating power allows decreasing the influence of the DUT temperature trend and, therefore, increasing the accuracy of the measurement. An important feature of the method is that it allows determining the components of thermal resistance corresponding to the design peculiarities of the DUT.

The complex provides thermal resistance measurement range from 0.001 to 10K/W, measurement error less than 5%, heating currents from 0.25 to 10 A, power modulation frequency from 0.001 to 1000Hz. The voltage on the DUT can be up to 48V, it is enough for measuring the thermal resistance of solar batteries with power up to 300W.

5. Acknowledgments
The work was carried out within the framework of the state task and was supported by the Russian Foundation for Basic Research and Government of Ulyanovsk region (Project no. 18-48-730018).

References
[1] Siegal B 2010 Proc. of the 26th Annual IEEE on Semiconductor Thermal Measurement and Management Symposium (Santa Clara, CA USA) (New Jersey: IEEE ) pp 132–5
[2] Dupré O, Vaillon R and Martin A 2017 Thermal Behavior of Photovoltaic Devices: Physics and Engineering (Switzerland: Springer) p 130
[3] Jang S H and Shin M W 2010 Electron. Device Lett. 31 743–5
[4] Smirnov V, Sergeev V, Gavrikov A and Shorin A 2018 Microelectron. Reliab. 80 205–12
[5] Methodology for the thermal measurement of component packages (single semiconductor device) 2005–2010 JEDEC standard JESD 51 1–14

[6] Smirnov V I, Sergeev V A and Gavrikov A A 2019 Specificity of measuring thermal resistance in solar cells IEEE J. of Photovoltaics 9(3) 775–9 DOI: 10.1109/JPHOTOV.2019.2897349

[7] Plesz B, Ress S, Szabó P, Hantos G and Dudola D 2014 20th Int. Workshop on Thermal investigations of IC’s and Systems (Greenwich, London) (New Jersey: IEEE ) pp 11–4