Simulation of thermoelectric processes in the semiconductor structure of a solar cell

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Abstract. The paper describes a solar cell thermoelectric model with taking into account the nonlinear temperature dependence of the thermal power density. The temperature distribution in the structure and dependence of the p–n junction overheating on the heating current are reviewed. The results obtained by the modeling and the results obtained with the original apparatus for measuring the thermal resistance of solar cell are compared.

1. Introduction
The efficiency of Si-based solar modules is usually about 12 – 28% [1]. This means that more than 70% of the light energy absorbed by the module is converted to heat. With a temperature increase of 1 °C, the nominal power of solar modules is reduced by approximately 0.4%, so the resulting power reduction of the modules can reach 15 – 25% [2]. At temperatures above 100 – 125 °C, they can temporarily lose the capacity to work, and higher temperatures can irreversibly damage them. Additionally, the increased temperature accelerates solar module degradation. Thus, requirements on the quality of a solar module heat sink are very strict.

Heat removal from a semiconductor to surroundings can be implemented in three ways: convection, thermal radiation, and conduction. The efficiency of heat dissipation due to convection depends on external conditions, primarily on the ambient temperature and the airflow velocity where the module is placed [3]. The power of thermal radiation is determined by the temperature of the radiating object, i.e. semiconductor plates of the module. The efficiency of heat dissipation by conduction is determined by the design of the module and its manufacturing technology, primarily by the substrate thermal conductivity and by the quality of the thermal contact between the substrate and semiconductor.

The quality of the thermal contact between the semiconductor and the substrate depends on thermal resistance, $R_T$, “junction-to-case”, defined as follows:

$$R_T = \frac{T_j - T_c}{P} = \frac{\Delta T_{av}}{P},$$

where $T_j$ is the p-n junction temperature in a steady state test condition; $T_c$ is the reference temperature of the case or surroundings; $P$ is dissipated power; $\Delta T_{av}$ is the average overheating temperature.
Lower thermal resistance, $R_T$, between the p-n-junction and the module case (substrate) corresponds to the lower temperature of the semiconductor dies and higher output power of the solar module. Despite the importance of measuring the thermal resistance of solar modules, there are no standards for measuring the thermal resistance of solar modules and the number of publications on the topic is very low [1, 3–6].

2. Thermoelectric model

Work [1] suggests that solar cells be considered as a set of diodes connected in series and in parallel, so for temperature distribution in the semiconductor structure, the thermoelectric model was developed for solar element working in diode mode. The model has a rectangular shape and double-layer structure with layer area, $S_i$, and thickness, $H_i$, (Figure 1).

It is usually assumed [7] that since the thickness and depth of the active region of the structure are small in comparison with the thickness of the die, all heat sources can be considered located on the upper surface of the die. In this case, the homogeneous heat equation is solved with the surface density of thermal power.

The temperature distribution in the structure is found by solving the heat equation

$$c_i\rho_i\frac{\partial T_i(x, y, z, t)}{\partial t} = \nabla_x (\lambda_i \nabla_{x, y, z} T_i), \quad (i = 1, 2) \tag{2}$$

where $T_i = (T_{si} - T_0)$; $T_{si}$, $T_0$ are the temperatures of the structure layers and environment; $\lambda_i(T_i)$ $c_i(T_i)$ $\rho_i(T_i)$ is the thermal conductivity, density, specific heat capacity of the structure layers.

The initial and boundary conditions will be as follows:

$T_i(x, y, z, 0) = 0. \tag{3}$

**Figure 1.** The model of the solar element structure:
1 is heat sink, $S_1 \times H_1$; 2 is semiconductor structure, $S_2 \times H_2$.

At the top surface, $H = H_1 + H_2$, of the semiconductor structure, the heat flux density is set
on the other surfaces, $\Sigma$, of the solar element structure, the condition of natural convection with a heat transfer coefficient, $h$, is set

$$- T_{\Sigma, z}(x, y, H, t) = J(x, y, H, t) U,$$  \hspace{1cm} (4)

where current density, $J$, is determined from the non-linear equation of thermoelectric positive feedback [8], taking into account the temperature dependence of the current density of the semiconductor structure active region:

$$J(T_z(x, y, H, t)) = J_0 \cdot \exp \left( \frac{-E_g - e(U - r S_{ar} J(T_z(x, y, H, t)))}{k_B T_z(x, y, H, t)} \right),$$  \hspace{1cm} (6)

where $U$ is the voltage on the solar cell, $J_0$ is the parameter slightly dependent on temperature, $E_g$ is the semiconductor band gap, $r$ is the structure resistance, $S_{ar}$ is the active area surface, $k_B$ is the Boltzmann constant, $e$ is the electron charge.

To find voltage, $U$, it is necessary to solve the equation with known current, $I$, flowing through the structure and temperature distribution at the active die area

$$\iint_{S_{ar}} J(T_z(x, y, H, t)) \, dx \, dy = I.$$  \hspace{1cm} (7)

The model (2) – (7) was solved using the finite elements method with a specially developed software working together with COMSOL Multiphysics. For the numerical study of the model, a silicon solar cell with an aluminium heat sink was considered, its geometric dimensions were $S_1 = S_2 = 52 \times 52 \, mm^2$, $H_1 = 5 \, mm$, $H_2 = 0.2 \, mm$. The thermophysical characteristics of the structure layers were taken from the COMSOL program database. The natural convection heat transfer coefficient was $h = (4 – 10) \, W/m^2K$. Heating current, $I$, was ranged from 0.25 to 2.0 A. The initial structure temperature is $T_0 = 300K$. The calculated and experimental results were compared. Experimentally, the overheating temperature of the p–n junction was determined using the modulation method of measuring thermal resistance [9].

In contrast to the standard methods, the modulation method uses harmonically varied heating power. Technically, the most convenient way of heating power modulation is the way when the pulses sequence of heating current goes through the device under test (DUT) with pulses length, $\tau$, varying harmonically [9]:

$$\tau = \tau_{p, \text{avg}}(1 + a \cdot sin(2 \pi f t)), \hspace{1cm} (8)$$

where $\tau_{p, \text{avg}}$ is the average pulse length; $a$ is the modulation factor of the heating power; $f$ is the modulation frequency. Pulse period and peak value, $T_p$, of heating current on the DUT are constants.

The voltage at the top of heating pulses, $U_{heat}$, can be taken as a constant considering variations in the voltage on the LED caused by the temperature cycling of the die active area are notably lower than the voltage caused by heating current. Then the average value of heating power for a pulse period, $\bar{P}(t)$, also varies harmonically:

$$\bar{P}(t) = \frac{1}{T_p} \int_{0}^{T_p} P(t) \, dt = \frac{\tau}{T_p} = \bar{P}(1 + a \cdot sin(2 \pi f t)) = \bar{P} + P_f \cdot sin(2 \pi f t),$$  \hspace{1cm} (9)
where $\bar{P} = IU \frac{T_{p \text{avg}}}{T_p}$ is the average value of heating power; $P_1 = \bar{P} \cdot a$ is the magnitude of the changing component of heating power.

Modulation of heating power causes corresponding changes of the device under test (DUT) p-n junction temperature that is phase-shifted with respect to power. The phase offset depends on the modulation frequency and thermal time constants of the device under test. The junction temperature with respect to the case or environment is determined based on a temperature sensitive parameter (TSP). Under the TSP, forward voltage, $U_{TSP}$, on the DUT is taken, with low measuring current, $I_{\text{meas}}$, passing through the DUT. The p-n junction temperature can be determined if the voltage temperature coefficient, which is determined with the standard method [1], and the measured $U_{TSP}$ value are known. When amplitude values of heating power, $P_1$, and transition temperature, $T_1$, oscillations are known, it is possible to determine the modulus and phase of the thermal impedance of the DUT.

The TSP is measured between heating pulses with a small time delay with respect to pulse edges. The time delay is necessary for finishing transitional electrical processes caused by switching LED from the heating mode to the measurement mode. Voltage, $U_{TSP}(t)$, on the p-n junction between the heating current pulses will repeat the p-n junction temperature (negative).

Thermal impedance module, $[Z_T(\omega)]$, will be determined by the ratio of first temperature harmonics, $T_1(\omega)$, to heating power, $P_1(\omega)$, at the modulation frequency.

$$|Z_T(\omega)| = \frac{T_1(\omega)}{P_1(\omega)}.$$  \hspace{1cm} (10)

First harmonic, $T_1(\omega)$, is determined by the discrete Fourier transform:

$$A_1(\omega) = \frac{2}{N} \sum_{i=1}^{N} T(t_i) \cdot \cos\left(\frac{2\pi i}{N}\right), \quad B_1(\omega) = \frac{2}{N} \sum_{i=1}^{N} T(t_i) \cdot \sin\left(\frac{2\pi i}{N}\right),$$

$$T_1(\omega) = \sqrt{A_1^2(\omega) + B_1^2(\omega)},$$  \hspace{1cm} (11)

where $A_1(\omega)$ and $B_1(\omega)$ are the real and imaginary Fourier transforms at modulation circular frequency, $\omega$; $T(t_i)$ is the temperature value at the point of time, $t_i$; $N$ is the number of signal values measured over a period.

The thermal impedance phase angle is determined by the ratio of real and imaginary Fourier transforms, $A_1(\omega)$ and $B_1(\omega)$, at the modulation frequency, from which

$$\varphi = \arctg \frac{B_1(\omega)}{A_1(\omega)}.$$  \hspace{1cm} (12)

Using the developed model, the calculated values of the p-n-junction overheat temperature depending on current, $I$, flowing through the solar element were obtained. The results are represented in Figure 2. There is a weak nonlinearity in the region of high currents, which is caused by the influence of a positive thermal feedback. Figure 3 shows graphs of the temperatures of the solar element p-n junction measured with various magnitudes of the heating currents. As a result of the comparison, it was found that the difference between the calculated and experimental values of the maximum p-n junction overheat is from 10 to 15%.

The higher values of the solar element structure overheat are possibly caused by, as shown in [9], the fact that thermal resistance of such structures decreases nonlinearly from the magnitude of the heating current, whereas the calculated results of $R_T$ shown for this version of the model are mostly independent of the heating current values.
Figure 2. Dependence of the p-n junction overheat on the heating current value; dotted is without a positive thermal feedback; + is the experiment[9].

Figure 3. Graphs of the junction temperature at various magnitudes of the heating current pulses:

a) $I = 0.5 \text{ A}$; b) $I = 1.0 \text{ A}$.

Therefore, the next stage of the model refinement was the construction of the model scheme of a solar element closer to the real structure (Figure 4), taking into account current, $I$, delivered to the solar cell using an electrode.
Figure 4. Refined solar element model:
1 is the heat sink, 2 is the semiconductor structure; 3 is the current electrode.

A new version of the thermoelectric model included the joint solution of the equations of electrical conductivity and thermal conductivity with a bulk density of Joule heat sources:

\[-\nabla(\sigma_i(T_i) \nabla U(T_i)) = I_{w_i} \quad (i = 1, 2, 3),\]  

(13)

where \( \sigma_i(T_i) = \sigma(T_i)(I + \alpha_i(T_i - T_{0}))^{-1} \) is the effective conductivity coefficient of the \( i \)-th element of the structure, which is a model parameter; \( \alpha_i \) is the resistance thermal coefficient; \( I_{w_i} = I / w_i \) is the bulk density of current, \( I \); \( w_i \) is the volume of the \( i \)-layer;

\[-\nabla(\kappa_i(T_i) \nabla T_i) = I_{w_i} (T_i)U(T_i).\]  

(14)

The potential of the upper surface of the current-carrying metallization of the solar cell:

\[U(x, y, H + H_f) = U_{p-n} .\]  

(15)

The \( U_{p-n} \) value is determined by the current-voltage characteristic of the cell. The potential of the bottom surface is equal to zero. Other structure surfaces are electrically isolated.

The dependence of the maximum, \( \Delta T_m \), and average, \( \Delta T_{av} \), temperatures of the p-n junction overheating on heating current, \( I \), was investigated. The result is shown in Figure 5. The value of the effective conductivity coefficient of the semiconductor structure was chosen in accordance with the experimental data on the magnitude of the overheating of the active region of the cell obtained using an IR microscope.
As it seen from the represented results, for such kind of semiconductor structures, the values of maximal and average overheats do not significantly differ from each other. There is a weak nonlinearity at \( I > 0.8 \) A caused by positive thermal feedback influence.

![Figure 5](image1.png) **Figure 5.** P-n junction overheat temperature by heating current: solid is maximal; dashed is average; + is experimental.

![Figure 6](image2.png) **Figure 6.** Coefficient of heterogeneity of the temperature distribution in the active region of the semiconductor structure.

The value of temperature distribution inhomogeneity coefficient over the semiconductor structure active region defined as \( \delta = \frac{(\Delta T_m - \Delta T_{av})}{\Delta T_{av}} \) is less than 1% (Figure 6). Moreover, in the region of large currents, the temperature distribution equalizes along with the p-n junction region.

![Figure 7](image3.png) **Figure 7.** Dependence of thermal resistance by the heating current; a) dashed is calculation, solid is approximation, b) experimental [9].
Calculations of the thermal resistance on the heating current, $I$, dependence was taken. The results are presented in Figure 7a. It can be seen that the dependence is non-linear in nature: it decreases sharply in the region of small currents and tends to a constant value at high currents. Qualitatively, this pattern is confirmed by the results obtained in [5, 9] (Figure 7b).

3. Conclusions
The developed thermoelectric model of the solar cell semiconductor structure allowed obtaining temperature distribution in the structure and the value of the junction-to-case thermal resistance. The calculations show that for such kind of semiconductor structure the influence of the positive thermal feedback is rather weak, the values of the maximal and average overheat vary a little from each other. The heating current increase causes the decrease of the coefficient of heterogeneity of temperature distribution in the active region, i.e. temperature distribution becomes more homogeneous. The dependence of the thermal resistance of the junction on the heating current is nonlinear. The thermal resistance value decreases sharply in the range of small currents and tends to a constant at high currents. Qualitatively, this pattern is confirmed by the experimental results.

4. References
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Acknowledgments
The work was realized within the framework of the state task and was partially supported by the Russian Foundation for Basic Research, the project No. 18-48-730018.