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MODELLING OF OVERHEATING IN SOLAR PHOTOVOLTAIC CELL PLATES WITH LOCAL ELECTRIC HEAT SOURCES

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A model and a calculation scheme that allow describing and investigating temperature and voltage drop distributions in solar photovoltaic cell plates in the presence of an overvoltage displacing the p-n junction of photovoltaic cell in the reverse direction are developed. It is found that for a solar photocell the temperature distribution stabilizes within several seconds after the overvoltage onset. In this case, the maximum temperature and size of the region of local heating (called a "hot spot") are set. An increase in the overvoltage value leads to an increase in the maximum temperature and the "hot spot" size. For solar cells with lower electrical resistances, local heating takes place at lower overvoltages and temperatures and "hot spot" sizes of are smaller.

Keywords: solar photovoltaic cell plate, overvoltage, electrical characteristics, modelling.

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1. Introduction

As you know, the occurrence of electrical overvoltage at reverse biased p-n junctions of solar photovoltaic cells leads to the flow of large currents through these elements, their local heating (the appearance of "hot spots") and subsequent degradation and failure [1-4]. Recently, it has been established that it is possible to implement protection against the aforementioned reverse electrical overvoltage and thermal breakdown of small area photocells (up to 4 cm^2) with built-in layers of posistor polymer nanocomposites with carbon fillers [5, 6]. Nevertheless, it should be noted that modern solar photovoltaic cells are elements of the distributed film type (thickness 0.1-0.2 mm, dimensions up to 15×15 cm^2). In a detailed study of electrothermal processes, in particular thermal breakdown, it is necessary to take into account the processes of heat propagation in the longitudinal direction in such structures, which ultimately leads to difficult problems in the mathematical and experimental sense [7-9]. The study of the temperature distribution in photovoltaic cells with large areas during local (point) heating is relevant for moving in the indicated direction.

The theoretical temperature and voltage drop distributions in the plate of an individual reverse biased solar cell are determined in the paper. The model based on the heat conduction equation with a local heat source of electrical origin is used.

2. Thermal processes in the plate and their mathematical description

The structure of a solar photovoltaic cell plate made of monocrystalline silicon is shown in Fig. 1.

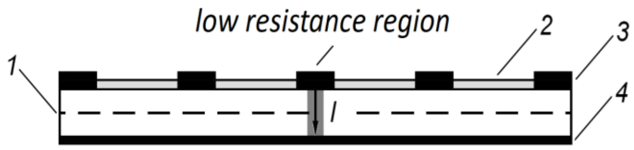

Fig. 1. Photovoltaic cell structure:
1 – p-n junction of the photovoltaic cell; 2 and 3 – antireflective coating and metal mesh (electrode); 4 – electrode layer.

In the presence of a region of the reverse biased p-n junction of a photovoltaic cell with a reduced electrical resistance, a significant electric current *I* flows through this region (Fig.1).

It leads to local heating of this region, as well as to the appearance of heat transfer Q to adjacent regions of the photocell plate (the formation of a “hot spot”) at reverse electric voltages U_0 exceeding the breakdown voltage U_b. Such local heating leads to accelerated degradation, thermal breakdown of solar cells, and other undesirable consequences [1, 2, 10].

The description of heat transfer in the situation considered here is possible using the heat conduction equation with a constant linear heat source.

The following approximations are adopted in the modelling.

1. The solar photovoltaic cell has the shape of a thin disk of radius L and thickness d, which allows using a polar coordinate system.

2. Thermal energy dissipation into the environment is described by the Newton–Richman equation [11].

3. Using the representations [12, 13], the dependence of the electrical differential conductivity $g_{p\text{-}n}(T)$ of reverse biased p-n junction of the photovoltaic cell plate can be approximated by the equation

$$g_{p-n}(T) = g_{p-n}(T_0)\exp\left[\frac{\Delta E_g}{n\,k\,T}\left(\frac{1}{T_0}-\frac{1}{T}\right)\right] \tag{1}$$

where ΔE_g is the band gap of the semiconductor material of the photovoltaic cell (silicon); k is the Boltzmann constant; n is the correction factor for determining the activation energy of the considered temperature dependence that is determined empirically [13, 14]; T is a solar photovoltaic cell plate temperature; T_0 is an environment temperature.

The density of electrical power, which is spent on heating an annular element of the plate with an area $\Delta S = 2\pi\, r\Delta r$, is determined by the equation

$$dp(T,r) = U^2 dG_{p-n}(T,r) = U^2 g_{p-n}(T) f(r,\sigma) dS = p(T,r)\cdot dS \tag{2}$$

where U is the reverse electrical voltage applied to the p-n junction of the solar photovoltaic cell.

The redistribution of the voltage of the overvoltage source U_0 between its internal resistance R_s and the direct resistance of the solar photovoltaic cell p-n junction $R_{p\text{-}n}(T)=1/G_{p\text{-}n}(T)$ should be taken into account when determining the amplitude of the overvoltage U

$$U(T) = U_0\cdot\frac{R_{p-n}(T)}{R_{p-n}(T)+R_s} \tag{3}$$

where

$$R_{p-n}(T) = R_{p-n}(T_0)\exp\left[-\frac{\Delta E_g}{n\,k\,T}\left(\frac{1}{T_0}-\frac{1}{T}\right)\right],$$

the values $R_{p\text{-}n}(T_0)$ and n are determined experimentally.

4. The heat source belongs to the type of internal, continuously operating, and having axial symmetry with a normal-circular intensity distribution [15]. The dependence of its intensity on the coordinate (radius) is described by the expression

$$f(r,\sigma)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{r^2}{2\sigma^2}\right). \tag{4}$$

The value of the parameter σ is determined from the condition that the width of the heat source corresponds to the value of the radius $r = r_s$ at the level of 0.5 of the maximum value of the function $f(0,\sigma)$, i.e. by solving the equation $f(r_s,\sigma) / f(0,\sigma) = 0.5$. This approach makes it possible to provide such a property of the considered heat source of electrical origin as its released power independence of its radius changes.

Using the experimentally found dependences of the integral conductivity of the plate of the reverse-biased p-n junction of the solar cell $G_{p\text{-}n}(T)$, the equation for determining the temperature-dependent factor $g_{p\text{-}n}(T)$ can be obtained by integrating (2)

$$g_{p-n}(T)=\frac{G_{p-n}(T)}{\sigma\sqrt{2\pi}\left[1-\exp\left(-\frac{L^2}{2\sigma^2}\right)\right]}. \tag{5}$$

Equation (5) takes into account that the area $S = \pi L^2$ for the disc sample of the photovoltaic cell plate considered here.

The kinetics of the formation of a region of local Joule heating in a solar photovoltaic cell plate can be described by the heat conduction equation averaged over the film thickness [16].

The following equation for a part of a plate of annular shape with a thickness d and radii $[r, r+\Delta r]$ (with an area of $2\pi r\, d$) for the temperature distribution $u(r, t)$ in a polar coordinate system, taking into account axial symmetry, can be written in accordance with [17, 18] in the form

$$\frac{\partial u(r,t)}{\partial t}=\frac{k}{\rho\cdot c}\left[\frac{\partial^2 u(r,t)}{\partial r^2}+\frac{1}{r}\frac{\partial u(r,t)}{\partial r}\right]+\frac{p[u(r,t),r_s]}{\rho\cdot c\cdot d}-\frac{2h_z[u(r,t)-T_0]}{\rho\cdot c\cdot d} \tag{6}$$

where r is a radial coordinate in the plane of the plate; ρ, c and k are density, specific heat capacity and thermal conductivity of the solar cell plate; h_z is the coefficient of heat transfer per unit surface of the base of the plate with the environment.

The left term of equation (6) corresponds to the heat accumulation processes spent on heating the plate. The right-hand terms correspond to the processes of heat propagation in the longitudinal direction, heat generation by an internal source and heat dissipation through the surfaces of the bases in the transverse direction, respectively.

The problem under consideration has axial symmetry and the boundary condition for it can be written using the Newton-Richman law for the end surface of the plate, which has a circular shape in accordance with the adopted approximations

$$\frac{\partial u(r_0,t)}{\partial r}=h_r[u(r_0,t)-T_0] \tag{7}$$

where h_r is the coefficient of heat exchange per unit of the end surface of the plate with the environment.

The initial condition is

$$u(r,0)=T_0\,. \tag{8}$$

3. Temperature distribution in the plate

3.1. Time dependency

The mathematical problem (4)-(8) was solved with a numerical method using the built-in library program *pdesolve* of the Mathcad package [19].

The temperature distribution profiles along the *r* coordinate are shown in Fig. 2. The following values of specific heat $c = 0.7$ W·s/(g·K) and specific thermal conductivity $k = 0.84$-1.50 W/(cm·K), density $\rho = 2.328$ g/cm^3 [20], the thickness $d = 0.01$ cm and the linear size (radius) $r_0 = 10$ cm of the solar photovoltaic plate, ambient temperature $T_0 = 300$ K, the radius of the heat source $r_s = 0.01$ cm are were in the simulation.

As can be seen, at first the maximum temperature of the heat source (point $r = 0$) and the width of the local heating region increase with time. The size of the local heating region can be quantitatively determined by the value of the longitudinal coordinate (the radius) r_{60}, which corresponds to the permissible temperature (equal to 333 K) for the normal operation of silicon solar photovoltaic cells [21].

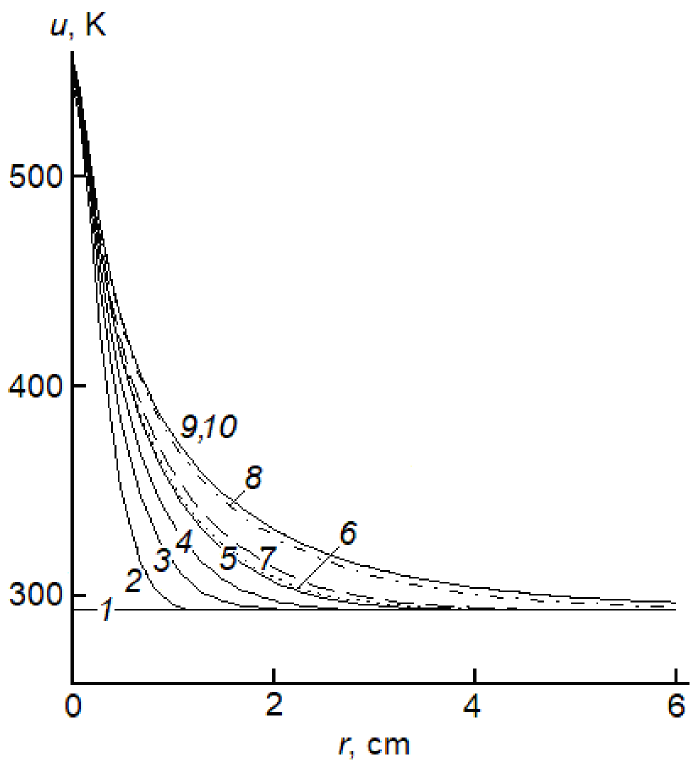

Fig. 2. Temperature distribution along the *r* coordinate in the solar photovoltaic cell plate after the application of electric overvoltage (U_0 = 11 V) at times *t*, s: *1* – 0; *2* – 0.2; *3* – 0.5; *4* – 1; *5* – 2; *6* – 2.25; *7* – 3; *8* – 10; *9* – 50; *10* – 100.

The temperature distribution is practically stabilized over a time interval of order 10 s, and after that the maximum temperature (at $r = 0$) and the size of the local heating region is established (Fig. 3).

At real overvoltages of 11-13 V, the amplitude value of the temperature is quite high (~ 700 K), and thus, the occurrence of thermal breakdown of the reverse-connected p-n junction of the solar photovoltaic cell is real [1, 10, 22].

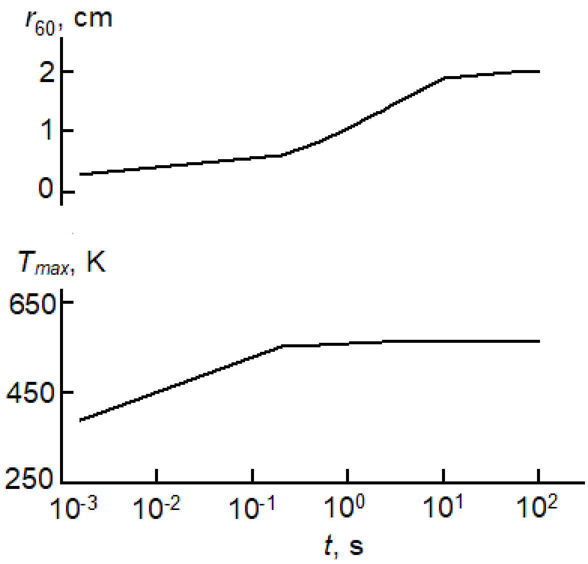

Fig. 3. Dependences of the radius of the region of local heating of the plate r_{60} and the maximum temperature $T_{max} = u(0, t)$ of the solar photovoltaic cell on the action time of a constant overvoltage t.

3.2. Dependence on the resistance of the reverse biased p-n junction of the photovoltaic cell

The results of a numerical study of the effect of the value of the electrical resistance of the reverse biased p-n junction of the solar photovoltaic cell plate $R_{p\text{-}n}(T_0)$ on the temperature distribution along the coordinate r in its plate with prolonged application of electrical overvoltage are shown in Fig. 4.

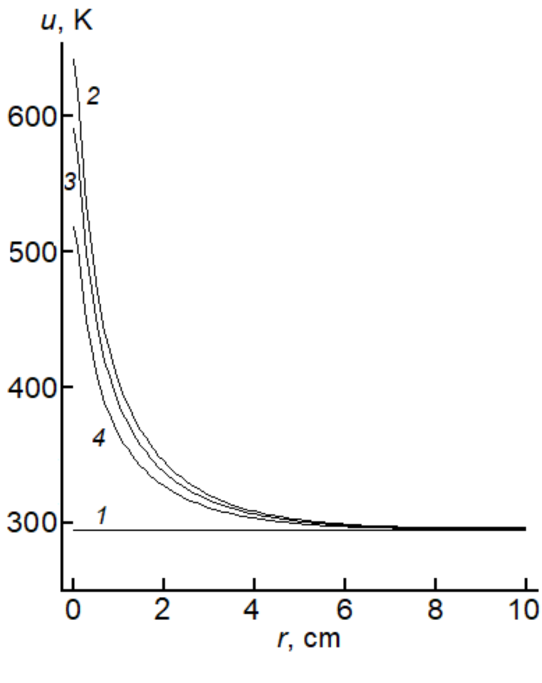

Fig. 4. Static temperature distributions along the coordinate r in the plates of solar photovoltaic cells when an electrical overvoltage (U_0 = 11 V) is applied to photovoltaic cells with integral reverse electrical resistances $R_{p\text{-}n}(T_0)$, Ohm: *1* – 2000; *2* – 1000; *3* – 100; *4* – 50.

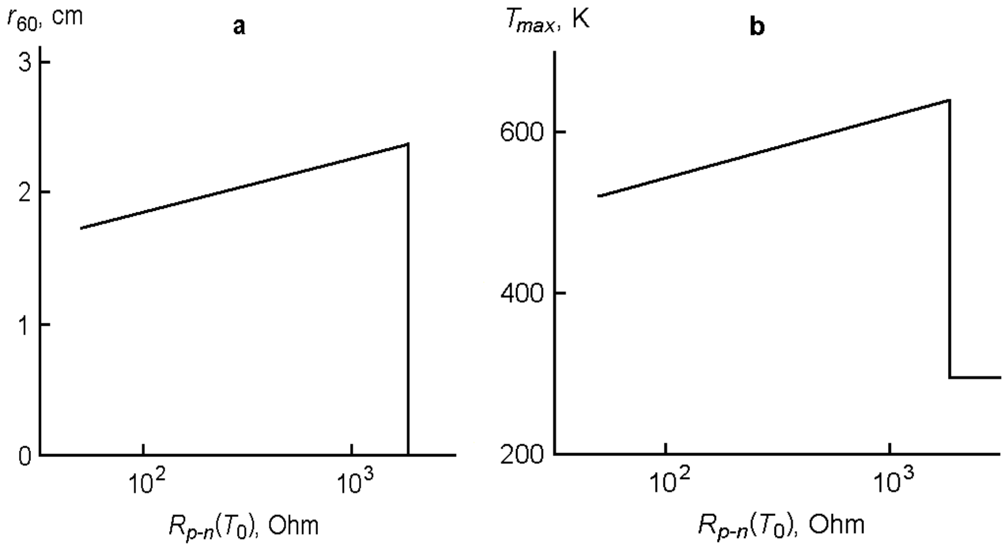

Fig. 5. Dependences of the radius of the local heating region r_{60} (a) and the maximum temperature $T_{max} = u(0, t)$ (b) of the solar photovoltaic cell plate on the value of the initial integral resistance of the photovoltaic cell.

As can be seen, local heating is not observed at large values of $R_{p\text{-}n}(T_0)$ (curve 1). Such heating occurs when the specified parameter decreases. The "hot spot" radius r_{60} and the maximum temperature T_{max} tend to decrease with decreasing $R_{p\text{-}n}(T_0)$ with all other things being equal (Fig. 5).

3.3. Dependence on the magnitude of the overvoltage

The influence of the electric overvoltage amplitude U on the radius r_{60} and maximum temperature T_{max} of the "hot spot" is shown in Fig. 6.

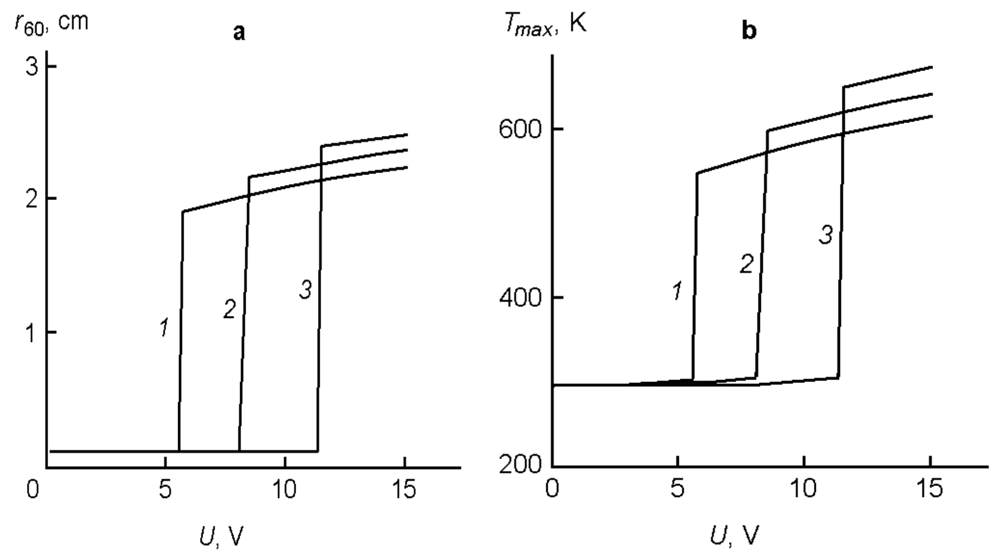

Fig. 6. Dependences of the radius of the local heating region r_{60} (a) and the maximum temperature $T_{max} = u(0,t)$ (b) of the solar photovoltaic cell plate on the value of applied overvoltage at the values of the integral resistance of solar photovoltaic cells $R_{p\text{-}n}(T_0)$, Ohm: *1* – 500; *2* – 1000; *3* – 2000.

These data correspond to the existing concepts of the local overheating appearance in solar photovoltaic cells. Overheating can be realized only at voltages that provide releasing power that exceeds the power dissipated. Fig. 6a shows that the “hot spot” expansion over the area takes place with an increase in the overvoltage U, and it is clear from Fig. 6b that this is accompanied by an increase in its maximum temperature T_{max}. The value of the reverse resistance of the p-n junction is also significant. With its increase, local thermal heating occurs at higher temperatures and covers a larger area.

4. Conclusions

The results of the theoretical analysis of the temperature distribution in a solar photovoltaic cell plate at local (point) heating of the electrical nature are presented.

It is shown that when a voltage is applied to the reverse biased p-n junction of a solar photocell, which leads to heat release at the point of its plate with a minimum resistance, the temperature and area of distribution of local heating in its vicinity increases with time. The temperature distribution is stabilized within a few tens of seconds, and after that the certain values of maximum temperature and size of the local heating region are set.

An increase in the overvoltage value leads to an increase in the maximum temperature and the size of the “hot spot”. For solar cells with lower electrical resistances, local heating takes place at lower overvoltages and temperatures, and the size of “hot spots” is smaller.

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