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Control Device for Temperature Characteristics of a Solar Cell

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The device for measuring of the temperature coefficients of the photovoltaic characteristics of a solar cell is developed. This device provides a real-time monitoring and study of the energy and photovoltaic parameters of a solar cell and its temperature dependence.

Keywords: Temperature coefficient, Solar cell, Temperature conversion efficiency, Photoconverter.

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1. INTRODUCTION

Interest to solar elements (SE) which directly convert solar radiation into electrical energy is caused by intensive and ever-expanding search of the renewable energy sources, among which solar power engineering is the most fast developing. Such increased interest to the renewable energy sources is explained by the limited mineral reserves, worsening of the environmental situation, and ever-increasing level of the environmental pollution by combustion products, large risk and increased safety expenses connected with the use of atomic energy.

Search of ways of formation of qualitative and stable in characteristics SE represents a fundamental problem. Temperature is an important factor which influences the stability of the output characteristics of SE.

Increase in the temperature of SE during radiation of sunlight negatively influences its efficiency of photoconversion, whereby the output load power decreases [1]. Experimental investigations of the characteristics of monocrystalline solar panel KV 150/24(12) in winter conditions [2] have shown that solar modules consisting of SE generate the maximum output power at low temperatures, clear sky, and intensive solar radiation. However, as it is known, different types of SE differ in the dependences of the output photoelectrical characteristics on the temperature [3]. Therefore, it is reasonable to perform the study of the temperature dependence of the output photoelectrical characteristics of SE.

So, temperature coefficients of the output parameters of SE are important characteristics of both separate elements and solar modules which should be quickly and precisely controlled. Thus, the assigned problem to develop a device for the investigation of the temperature characteristics of SE is timely and topical.

Techniques and equipment for measuring the temperature dependence of the output characteristics of SE are given in many publications [4-6]. These methods use temperature dependences of the light current-voltage characteristic (CVC) of photoconverters (PC). But, as known, such measuring equipment is very expensive. We note that in this case the following correlation is used for the estimations of the output power:

$$P_M = I_{mp} \cdot V_{mp} = I_{SC} \cdot V_{OC} \cdot FF \, .$$

Analysis shows that among three multipliers, temperature coefficient of the filling factor (FF) is almost 20 times less than V_{OC} and 5 times less than I_{SC} [7]. Therefore, in order to obtain a relatively reliable dependence $P_M(T)$, it is enough to investigate the dependences $V_{OC}(T)$ and $I_{SC}(T)$. In this case, realization of the meter of temperature dependences is considerably simpler and requires minor costs.

2. BASIC RELATIONS FOR THE TEMPERATURE DEPENDENCES OF THE SOLAR CELL PARAMETERS

As all semiconductor devices, SE are temperature-sensitive. Increase in the temperature decreases the band gap of semiconductor and influences the majority of the parameters of semiconductor material. Decrease in the band gap with temperature increase can be considered as the increase in the energy of electrons in the valence band; therefore, less energy is necessary now for the transition into free state. As a result of the decrease in the band gap, output characteristics of SE become worse.

The open-circuit voltage V_{OC} is the parameter of SE which mostly depends on the temperature increase.

Open-circuit voltage V_{OC} is decreased with the temperature increase due to the temperature dependence of the current I_0 (Fig. 1). The value of I_0 for the *p-n*-transition is determined by the correlation

$$I_0 = qA \frac{Dn_i^2}{LN_D} \, ,$$

where q is the electron charge; D is the diffusion coefficient of minority charge carriers; L is the diffusion length of minority charge carriers; N_D is the impurity concentration (doping level); n_i is the concentration of intrinsic charge carriers.

The majority of the parameters in the represented equation also depend on the temperature, however, the most significant influence is connected with the concentration of intrinsic charge carriers n_i. Concentration of intrinsic charge carriers depends on the band gap energy (concentration of intrinsic charge carriers increases with the decrease in the band gap) and energy of charge carriers (energy increases with temperature growth). Equation for the concentration of intrinsic charge carriers is written as

$$n_i^2 = 4\left(\frac{2\pi kT}{h^2}\right)^3 \left(m_e^* m_h^*\right)^{3/2} \exp\left(-\frac{E_{G0}}{kT}\right) = BT^3 \exp\left(-\frac{E_{G0}}{kT}\right),$$

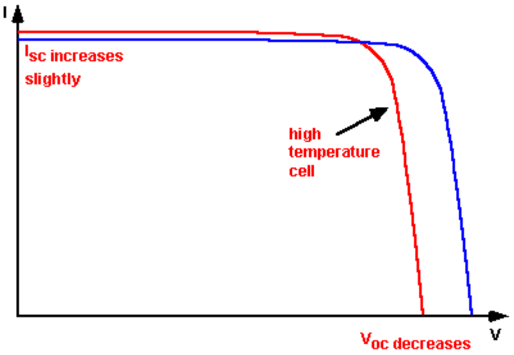


Fig. 1 – Temperature influence on the CVC of SE

where T is the temperature; h is the Planck constant; k is the Boltzmann constant; m_e and m_h are the electron and hole effective masses, respectively; E_{G0} is the band gap which is linearly extrapolated to absolute zero; B is the temperature-independent constant.

Substituting this equation into the preceding expression for I_0 and assuming that temperature dependences of other parameters can be neglected, we obtain

$$I_0 = qA\frac{D}{LN_D}BT^3\exp\left(-\frac{E_{G0}}{kT}\right) \approx B'T^{\gamma}\exp\left(-\frac{E_{G0}}{kT}\right),$$

where B' is the temperature-independent constant. Constant γ is used instead of the number 3 for the inclusion of possible temperature dependences of other parameters of the material.

Influence of I_0 on the open-circuit voltage V_{OC} can be estimated by the substitution of equation for I_0 into equation for V_{OC}

$$V_{OC} = \frac{kT}{q}\ln\left(\frac{I_{SC}}{I_0}\right) = \frac{kT}{q}\left[\ln I_{SC} - \ln I_0\right] =$$

$$= \frac{kT}{q}\ln I_{SC} - \frac{kT}{q}\ln\left[B'T^{\gamma}\exp\left(-\frac{qV_{G0}}{kT}\right)\right] =$$

$$= \frac{kT}{q}\left(\ln I_{SC} - \ln B' - \gamma\ln T + \frac{qV_{G0}}{kT}\right),$$

where $E_{G0} = qV_{G0}$. Under the condition that dV_{OC}/dT does not depend on dI_{SC}/dT, dV_{OC}/dT can be found as

$$\frac{dV_{OC}}{dT} = \frac{V_{OC} - V_{G0}}{T} - \gamma\frac{k}{q}.$$

The given equation shows that temperature sensitivity of SE depends on the open-circuit voltage. Thus, SE with higher voltage depend less on the temperature.

Short-circuit current I_{SC} slightly increases with the temperature, since band gap energy E_G decreases and more photons have energy sufficient for the generation of electron-hole pairs.

Simplified temperature dependence of FF for silicon is defined by the following equation:

$$\frac{1}{FF}\frac{dFF}{dT} \approx \left(\frac{1}{V_{OC}}\frac{dV_{OC}}{dT} - \frac{1}{T}\right).$$

Influence of the temperature on the maximum output power is realized by the equality

$$P_{M\,\mathrm{var}} = \frac{1}{P_M}\frac{dP_M}{dT} \approx \frac{1}{V_{OC}}\frac{dV_{OC}}{dT} + \frac{1}{FF}\frac{dFF}{dT} + \frac{1}{I_{SC}}\frac{dI_{SC}}{dT}.$$

3. DEVELOPMENT OF THE DEVICE FOR MEASURING THE TEMPERATURE COEFFICIENTS OF THE SOLAR CELL PARAMETERS

Device for measuring the temperature coefficients of SE parameters (short-circuit current I_{SC}, open-circuit voltage V_{OC} and output load power P_M) includes two basic components, namely, meter of the output characteristics of SE and instrument table for fastening of the photoconverter contacts.

Digital meter (Fig. 2) consists of the following: temperature meter (instrument range of 55-125 °C); voltage meter (measuring ranges of the open-circuit voltage V_{OC} from 0 to 999 mV and from 0 to 100 V with measuring resolution of 0.1 mV); current meter (measuring ranges of the short-circuit current I_C from 0 to 999 μA and from 0.01 to 10 A with measuring resolution of 0.1 μA); interface module; voltage regulator module.

In Fig. 3 we illustrate the general view of the instrument table for fastening of the FC contacts.

Electrical-insulating material – lavsan turbonit, which is the most suitable by the temperature characteristics, is used for the working surface of instrument table.

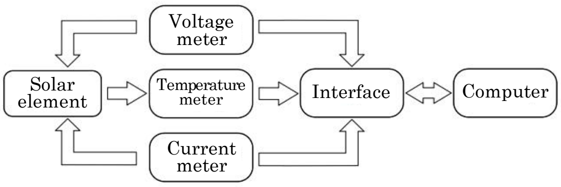
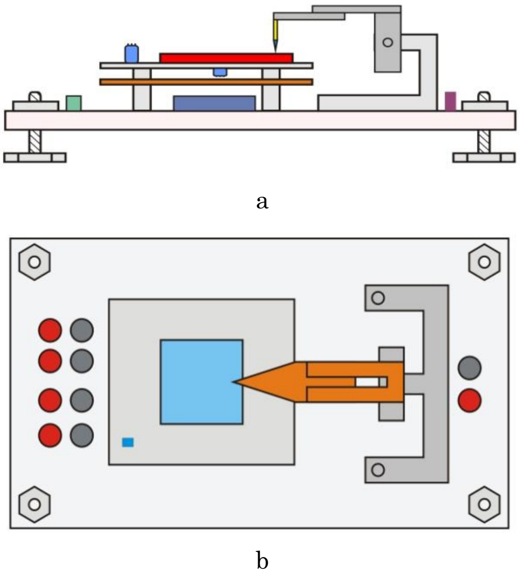


Fig. 2 – Block diagram of the digital meter



a

b

Fig. 3 – Draft of the device for measuring the temperature coefficients of SE (side view (a) and top view (b)): 1 – insulating surface; 2 – controlled racks; 3 – probe; 4 – instrument table; 5 – solar element; 6 – temperature sensor; 7 – racks of the vertical probe displacement; 8 – shift knob

The probe moving along the vertical axis is used for closing the front contact. Halogen lamp of the power of 500 W with adjustable lifting height is applied as the simulator of solar radiation.

Aluminum substrate providing a good thermal and electric contact as well as an optimal temperature distribution over the object surface is used as the back contact. Heating of SE is controlled by means of the nichrome coil.

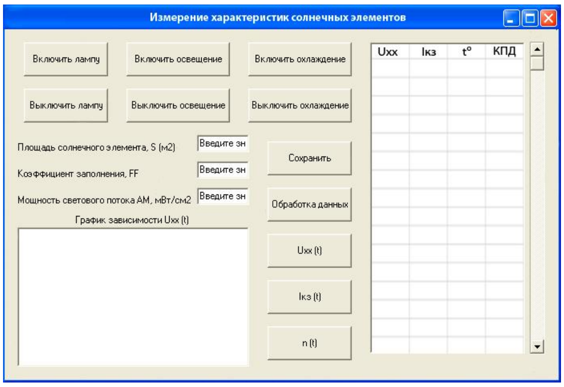
Temperature sensors are attached by heat sink compound to the substrate for better contact and temperature measurements with the error not more than ± 0.2 ºC. All leads are attached to the measurement unit of SE characteristics for the transmission and processing of the obtained values.

Before starting the measurements, it is necessary to heat the halogen lamp of the power of 500 W and choose intensity of the light radiation corresponding to AM 1.5 by means of the change in the distance between radiator and studied PC. Calibration of the measuring system relative to the standard SE is carried out at the temperature of SE of 25 °C. Efficiency is calculated by the following formula:

$$\eta = \frac{I_{sc} \cdot V_{oc}}{P_{ph} \cdot S} FF ,$$

where I_{SC} is the short-circuit current; V_{OC} is the open-circuit voltage; FF is the filling factor; P_{ph} is the luminous power; S is the area of SE.

Measurements are carried out in the temperature range from 25 °C to 80 °C according to GOST 28976-91. At the increase in the PC temperature by 1 °C, the data which is read from microcontrollers is aggregated into database on a personal computer, processed and stored in the program. Using the data table, program builds the dependences $I_{SC}(T)$ and $V_{OC}(T)$, and $\eta(T)$ as well. As a result, the data archive is generated and stored on a personal computer. Application window of the program is represented in Fig. 4.



Площадь солнечного элемента, S (м2) Введите зн

Коэффициент заполнения, FF Введите зн

Мощность светового потока AM, мВт/см2 Введите зн

Fig. 4 – Application window of the program

4. EXPERIMENTATION, DESCRIPTION AND ANALYSIS OF THE RESULTS

SE of the HIT type – heterojunction with intrinsic thin layer *a*-Si:H (Fig. 5) with high conversion efficiency – is used for the investigations [3]. This is possible due to the inclusion of undoped thin layer *a*-Si:H from both sides of *c*-Si plate for the passivation of defects on its surface that decreases the recombination of minority carriers and, correspondingly, increases the conversion efficiency of SE. The maximum conversion efficiency for HIT SE is equal to 23.9% [8].

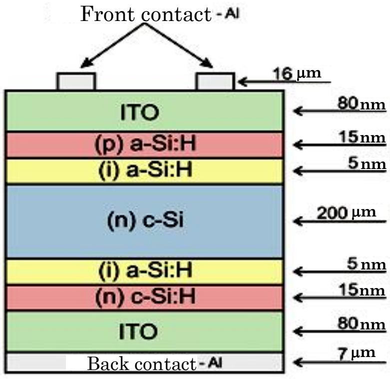


Fig. 5 – Structure of the HIT SE

The studied SE was placed on the aluminum substrate. Temperature was measured by using sensors, one of which was placed on the aluminum substrate and another contacted with SE from backside. Sensor leads were attached to the control unit for the transmission of the test signal and temperature values to the indicator. Irradiance in the working plane of the simulator is adjusted in such a way that short-circuit current of the standard SE at the temperature of 25 ± 5 °C corresponds to its calibrated value. Measurement of the short-circuit current I_{SC} and open-circuit voltage V_{OC} of the studied SE was done in the steady-state thermal conditions at the temperature close to the minimum of the specified temperature range (25 °C). Measurements were carried out at the temperature higher than the air temperature; therefore, one can neglect the possibility of moisture condensation on active surfaces of the studied and standard elements. During the investigation, temperature of the studied SE was increased by 5 °C and measurements of I_{SC} and V_{OC} were repeated in the range of 25-80 °C.

For the analysis of the experimental temperature dependences of the output parameters V_{OC} and I_{SC} we use the known equation of SE CVC

$$V = \frac{AkT}{e} \ln\left(\frac{I_{ph} - 1}{I_0} + 1\right)$$

and derivative dV/dT in the form of [9]

$$\frac{dV}{dT} = \frac{V}{T} - \frac{AkT}{eI_0} \cdot \frac{dI_0}{dT} + \frac{AkT}{e} \cdot \frac{1}{I_{ph} - 1} \frac{d(I_{ph} - 1)}{dT} .$$

Photocurrent I_{ph} in the third term weakly depends on the temperature, since $I_{ph} = eK_c g_0 S\eta$, where K_c is the integral collection coefficient; η is the quantum yield; S is the area of SE; g_0 is the number of photons absorbed per time unit.

Collection coefficient K_c depends on the diffusion length of minority charge carriers L

$$K_c = f(L) , \; L = \sqrt{D\tau} ,$$

where D is the diffusion coefficient; τ is the lifetime.

In this case, $D \sim \sqrt{T}$, and τ weakly depends on the temperature.

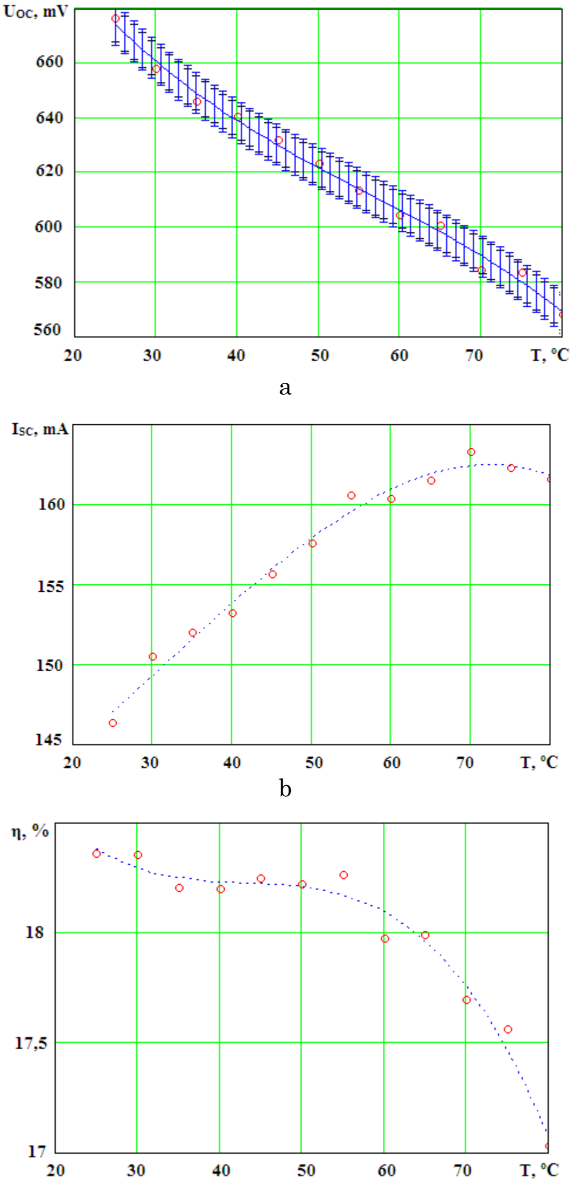
With account of the known dependence of the saturation current I_0 on the temperature, the second term under the condition $A = 1$ takes the form

$$-\frac{AkT}{eI_0}\cdot\frac{dI_0}{dT} = -\frac{kT}{e}\cdot\frac{E_g}{kT^2} = -\frac{E_g}{eT}.$$

Then

$$\frac{dV}{dT} = \frac{V}{T} - \frac{E_g}{eT} = -\frac{E_g - eV}{eT}.$$

Since $E_g > eV$ always, voltage temperature coefficient will be negative, and the output voltage of PC decreases with the temperature increase. Using the experimentally obtained temperature dependences I_{SC} and V_{OC} (Fig. 6) for HIT SE, we have calculated the temperature coefficients for these parameters.



a

b

c

Fig. 6 – Temperature dependences of the open-circuit voltage V_{OC} (a), short-circuit current I_{SC} (b), and efficiency (c)

Mathematical models based on the regression analysis were developed and confidence intervals by the Student's criterion were calculated for the temperature dependences of SE parameters. In Fig. 6 dots represent the experimental data, and dashed line is the results of approximation by the following regression models:

$$V_{OC} = 7{,}826\cdot10^{2} - 6{,}068T + 8{,}117\cdot10^{-2}T^{2} - 4{,}844\cdot10^{-4}T^{3}$$

$$I_{SC} = 1{,}383\cdot10^{2} + 1{,}905\cdot10^{-1}T + 8{,}603\cdot10^{-3}T^{2} - \\ -9{,}151\cdot10^{-5}T^{3}$$

$$\eta = 2{,}001\cdot10 - 1{,}218\cdot10^{-1}T + 2{,}802\cdot10^{-3}T^{2} - 2{,}174\cdot10^{-5}T^{3}.$$

Confidence intervals by the Student's criterion for the third-order regression were the following: $V_{OC}(T)$ – 0.23% (Fig. 6a); $I_{SC}(T)$ – 0.39%; $\eta(T)$ – 0.4%.

As seen from Fig. 6, with the increase in the temperature of SE from 25 °C to 80 °C (ΔT = 55 °C) open-circuit voltage decreases from 677 to 568 mV (Fig. 6a) and efficiency – from 18.36% to 17.03% (Fig. 6c). Here, difference between the air and SE temperatures was changed from 0 °C to 55 °C. Based on the results of the performed experiment it was determined that temperature coefficients of the open-circuit voltage are equal to $\Delta V_{OC}/\Delta T$ = – 1.97 mV/°C; of the short-circuit current – $\Delta I_{SC}/\Delta T$ = 0.28 mA/°C, efficiency – $\Delta\eta/\Delta T$ = – 0.024 %/°C.

Comparison of the temperature coefficients of conversion efficiency of different HIT SE (see Fig. 7) was carried out after the experiment.

Due to the comparison it is determined that if operating in the temperature range from 25°C to 80 °C, HIT SE obtained in ISFH (Germany) (blue squares) has almost the same temperature coefficient of conversion efficiency as HIT obtained by Sanyo [10] (black circles).

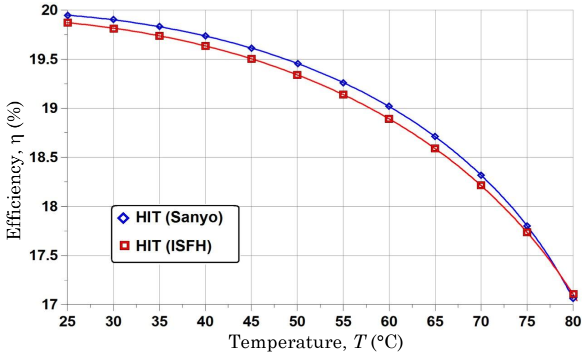


Fig. 7 – Dependences of the efficiency on the temperature for different PC types

5. CONCLUSIONS

As seen from the performed experiments and calculations, temperature coefficient for the open-circuit voltage is negative, and, therefore, temperature growth leads to the drop in V_{OC}, and, correspondingly, to the decrease in the efficiency and power loss.

Results obtained using the meter of temperature coefficients of the output photoelectric parameters of SE agree well with the data of previous investigations [11]. Therefore, device for measuring the temperature coefficients of the output photoelectric parameters of SE corresponds to the requirements of GOST 28976-91 and can be applied for further investigations.

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