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Influence Of Operating Temperature On Efficiency Of Silicon Photovoltaic Devices

Kriukov Yu.A.[1], Zaitsev A.Ye.[1], Feshchenko A.A.[2], Gorshkov A.V.[2]

Moscow Region State Educational Institution for higher professional education
"Dubna International University for Nature, Society and Man" (Dubna State University)[1],
Joint Institute for Nuclear Research (JINR)[2]
e-mail: kua@uni-dubna.ru
[1]Dubna State University, 19 Universitetskaya St., Dubna, Moscow region, 141980,
[2]JINR, 6 Joliot-Curie St., Dubna, Moscow region, 141980

Abstract
The influence of operating temperature on efficiency of industrial samples of silicon photovoltaic devices has been investigated. It was shown that despite the high initial efficiency, the tests of the photovoltaic devices made in China carried out at higher operating temperatures have revealed a significant reduction of output parameters compared with the industrial analogs made in Europe. With the operating temperature increasing, an uncharacteristic decline in short-circuit current density was registered. As it was shown, the last is due not only to the inherent increase in the density of the diode saturation current, but also is the result of the reduction of shunt resistance.

Keywords: photovoltaic devices based on crystalline silicon, operating temperature, efficiency, output parameters, light diode characteristics.

1. Introduction

At the present time Chinese manufacturers became the largest importers of photovoltaic products across the world by ensuring increase of the efficiency coefficient (EC) of the industrial models of photovoltaic devices based on monocrystalline silicon (*Si*-PVD) up to 17-18% accompanied by considerable decrease of their cost [1]. A considerable part of the enterprises dealing with industrial production of photovoltaic modules in Russia use China-made device structures as initial photovoltaic converters. Moreover the products of Chinese manufacturers occupy the largest segment of imported photovoltaic modules in the Russian market. The Chinese manufacturers specify on the PVD both the EC and the following output parameters: offload voltage (U_{OL}), short-circuit current density (J_{SC}) and fill factor (*FF*) of light current-voltage characteristics (CVC) which are measured at the temperature of 25°C.

However in the process of *Si*-PVD operation with the specified level of efficiency just insignificant part of solar energy is used for electrical energy generation. The major part of solar irradiation is being transformed by the device structures into thermal energy. This results in increase of *Si*-PVD operation temperature thus causing their efficiency decline. Rather wide range of works was dedicated to the influence of temperature on the efficiency of single crystalline *Si*-PVD manufactured in European countries and Russia (see for example [2-4]). As a result physical mechanisms producing the effect of efficiency decline were established. At the same time no similar investigations of China-made *Si*-PVD are being performed (with some minor exceptions) [5]. Therefore an investigation of temperature influence on the efficiency of photovoltaic processes in China-made *Si*-PVD should be considered to be an urgent task for scientific research having great practical importance.

2. Routine of experiment

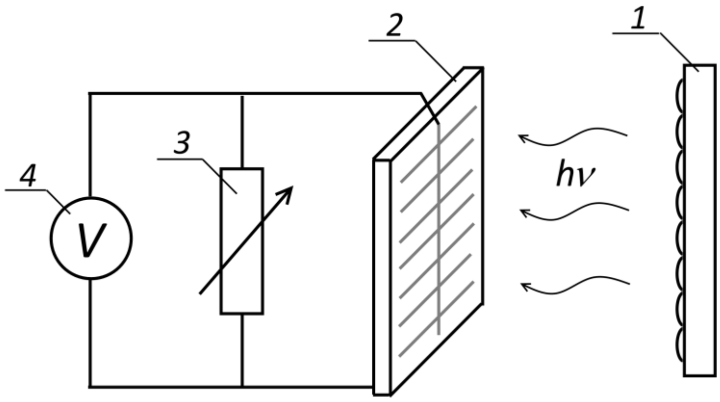
Based on the analogue circuit of PVD the below given light diode characteristics are quantitative parameters of photovoltaic processes which take place in such device structures while the same are illuminated with light: photocurrent density (J_{PH}), diode saturation current density (J_0), diode ideality factor (A), series resistance (R_S) and shunt resistance (R_{SH}) rated per unit area of PVD. Relationship between the PVD efficiency and the light diode characteristics is implicitly described by the theoretical light CVC of PVD [6]:

$$J_L = -J_{PH} + J_0\left\{\exp\left[\frac{e(U_L - J_L R_S)}{AkT}\right] - 1\right\} + \frac{U_L - J_L R_S}{R_{SH}}, \qquad (1)$$

where J_L – density of current flow under load; e – electron charge; k - Boltzmann constant; T - solar cell temperature; U_L – voltage drop under load.

The analysis of expression (1) shows that the PVD efficiency grows with the increase of J_{PH}, R_{SH} and with the decrease of J_0, A, R_S. The value of photocurrent density which is a quantitative measure of the efficiency of the processes of generation and diffusion of non-equilibrium charge carriers is determined by the number of photons arriving to the base layer, quantum efficiency of photoeffect and lifetime of non-equilibrium charge carriers in the base layer. The value of ideality factor and the value of diode saturation current density which give quantitative evaluation to the efficiency of the process of non-equilibrium charge-carriers partition in *Si*-PVD are being controlled by the recombination rate in the zone of space-charge cloud and by the separating barrier energy structure. Shunt resistance is included in the analogue circuit of PVD in order to take into account the influence of low electrical resistance of local parts of the device structure and its end faces on the photovoltaic processes efficiency. Series resistance of PVD the value of which determines the efficiency of the non-equilibrium charge carriers gathering process depends on electrical conductivity of the base and the interfacing layers of PVD, contact resistance and the recombination rate of non-equilibrium charge carriers at the rear and front contacts.

The authors of the work used a specially designed program for analytical treatment based on approximation of experimental light currency-voltage characteristics (CVC) with the aid of theoretical expression (1) for determination of the output parameters and the light diode characteristics of *Si*-PVD. The light CVC of PVD were measured under load while the device structures where illuminated with a solar simulator under terrestrial conditions with the luminous flux power of 100 mW/cm^2. A measuring bench with the design shown on Fig. 1, switches on a LED illuminator (Fig 1, b) with MPU control operating as a source imitating solar irradiation. At time of the light CVC measurements a resistive load bank with six decades of the corresponding values was used as load resistance (R_L). It gives an opportunity of precise variation of the value of R_L within the range of $0.01 \le R_L \le 1000$ Ohm at time of measurement of PVD CVC under load. Registration of U_L voltage drop at load resistance was performed by means of a digital multimeter Mastech MS8226 DMM. Initial determination and control over measurement of radiation power at the frontal surface of *Si*-PVD under investigation were made with use of a reference *Si*-PVD with the known short circuit current value located near the *Si*-PVD under investigation. Correspondence between the actual value of I_{SC} of the reference *Si*-PVD and its rated value under the conditions of irradiation power of 100 mW/cm^2 was achieved by means of changing the distance between the *Si*-PVD and a radiating element of the LED illuminator. After that the *Si*-PVD under investigation was connected to the measurement circuit.



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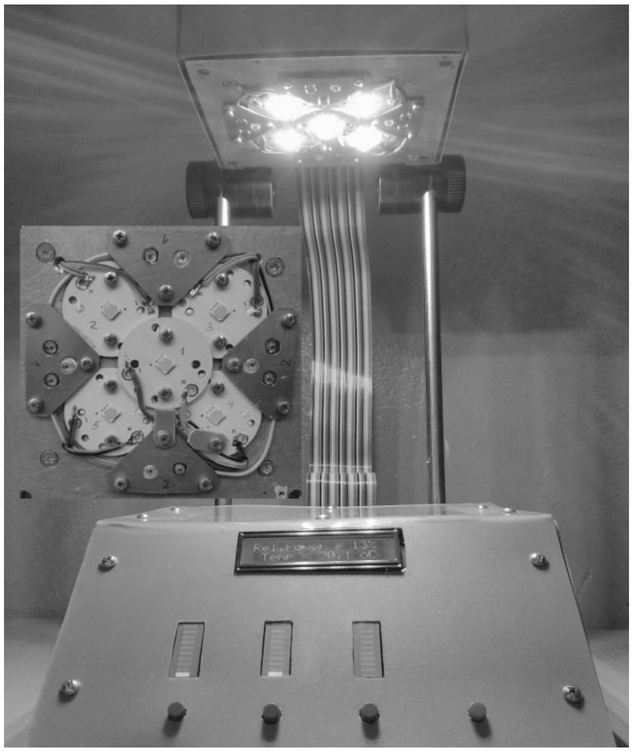

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Fig. 1. Diagram of a laboratory bench for measurement of the full-load light CVC (a) and appearance of a LED illuminator the connection of which demonstrates location of LEDs on the radiating element (b): *1* – LED illuminator; *2* – investigated PVD; *3* – resistive load bank; *4* – multimeter for measurement of voltage drops at load resistance

3. Results and discussions

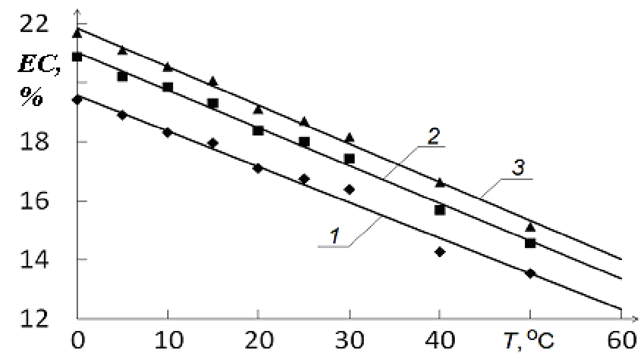
3.1 Experimental investigations of the influence of temperature on the output parameters and the light diode characteristics of silicon photovoltaic devices

For the investigation were chosen single crystalline China-made *Si*-PVD with the representative values of the efficiency coefficient which corresponded to the minimum (1-16.7%), average (2-18.0%) and maximum (3-18.7%) values for the device structures available at the market (see Table). The light CVC under load were measured for the chosen samples at the temperatures from 0^{o}C to 50^{o}C. The following analytical treatment of the experimental light CVC allowed determining the output parameters and the light characteristics of *Si*-PVD.

Table 1. The output parameters and the light diode characteristics of the investigated *Si*-PVD as determined on the basis of their light CVC at the temperature of 25°C

Output parameters and light diode characteristics	Sample		
	1	2	3
J_{SC}, mA/cm^2	35.5	38.8	39.0
U_{OL}, mV	582	578	597
FF, rel. units	0.81	0.81	0.81
EC, %	16.7	18.0	18.7
J_{PH}, mA/cm^2	35.5	38.8	39.0
R_S, Ohm·cm^2	0.53	0.45	0.45
R_{SH}, Ohm·cm^2	1560	1490	1680
A_i, rel. units	0.86	0.90	0.90
J_0, A/cm^2	$2.9 \cdot 10^{-13}$	$2.4 \cdot 10^{-13}$	$2.4 \cdot 10^{-13}$

The results of analysis show that the growth of temperature causes almost linear decrease of the efficiency coefficient in all investigated samples (Fig. 2, a). At that the coefficient of decrease which describes relative change of the EC at temperature change by 1 degree was almost the same for the investigated samples and made 0.7%/°C. The values of offload voltage and short circuit current density also demonstrate reduction with operating temperature increase (Fig. 2, b, c). Experiments proved that the light CVC fill factor remains almost unchanged with the temperature growth (Fig. 2, d).
The analysis of the light diode characteristics shows that the registered EC decrease is accompanied by the diode saturation current density growth (Fig. 3, a) and the shunt resistance decrease (Fig. 3, b). Besides the serial resistance value reduction was also registered (Fig. 3, c).



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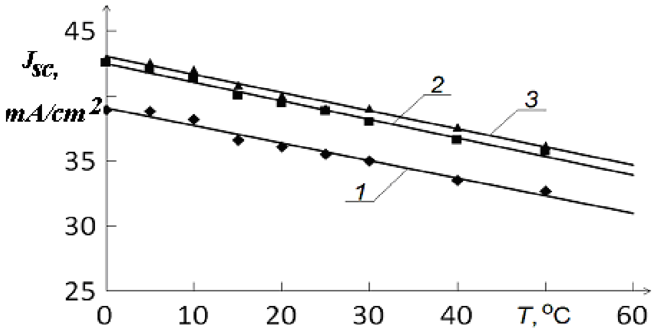

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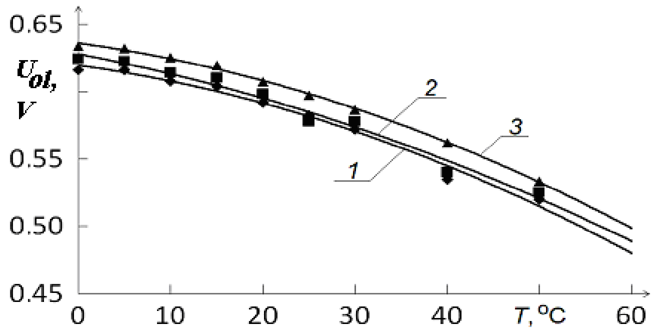

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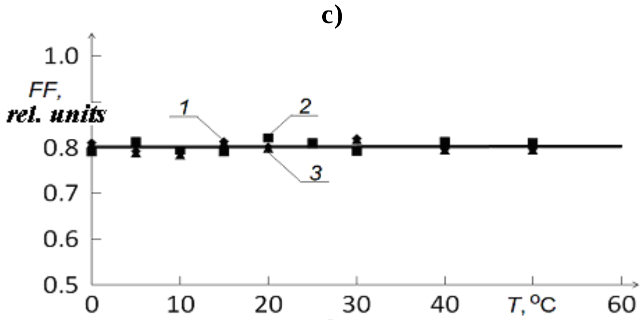
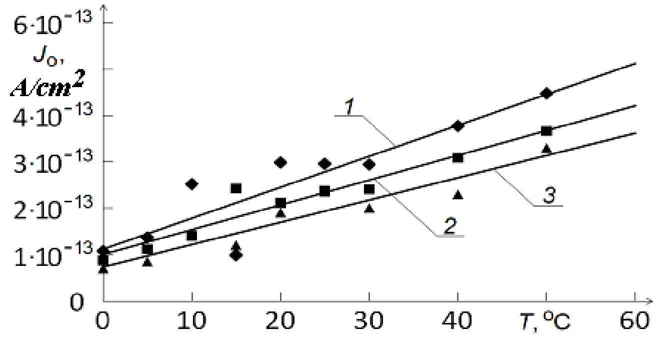


d)

Fig. 2. Influence of operating temperature on the efficiency coefficient (a), short circuit current density (b), off-load voltage (c) light CVC fill factor (d) of the investigated *Si*-PVD: *1* – sample 1 with the EC =16.7 % at the temperature of 25°C *2* – sample 2 with the EC =18.0 % at the temperature of 25°C *3* – sample 3 with the EC =18.7 % at the temperature of 25°C



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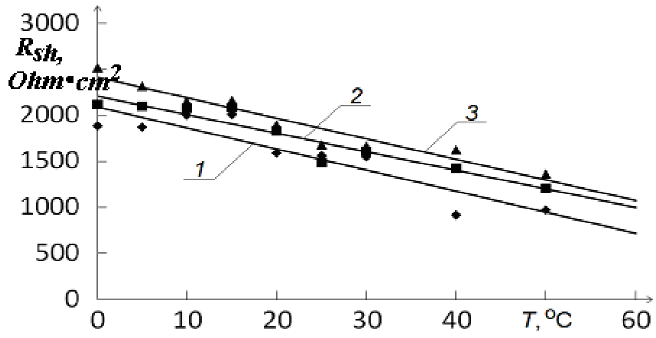

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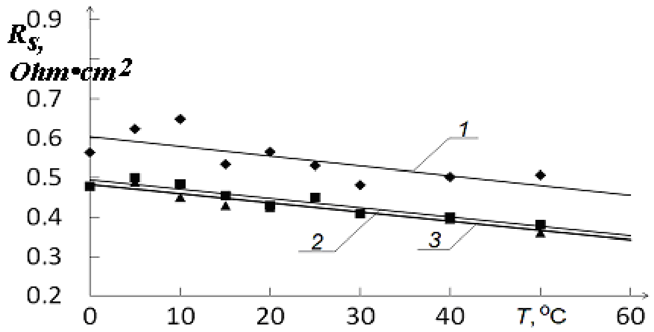

c)

Fig. 3. Influence of operating temperature on diode saturation current density (a), shunt (b) and series (c) resistances of the investigated *Si*-PVD *1* – sample 1 with the EC =16.7 % at the temperature of 25°C *2* – sample 2 with the EC =18.0 % at the temperature of 25°C *3* – sample 3 with the EC =18.7 % at the temperature of 25°C

3.2 Analysis of physical mechanisms of operating temperature influence on the output parameters and the light diode characteristics of silicon photovoltaic devices

The obtained results may be only partially commented within the context of conventional formulation of the operating temperature influence on the efficiency of photovoltaic processes in *Si*-PVD which is generally described in [7]. Conventional assumptions which comply with the experimental investigations of *Si*-PVD state that the growth of temperature causes increase of diffusion distance of non-equilibrium charge carriers in single-crystalline silicon. This is due to no change or growth of the diffusion coefficient and increase of the lifetime of minority charge carriers with the growth of temperature. The growth of the minority charge carriers diffusion distance results in the increase of the short circuit current density with the temperature increase. But this influence is insignificant and makes about 0.07%/°C. The reduction of offload voltage significantly exceeds the growth of short circuit current density and makes 0.4%/°C. More smooth form of the light CVC under the conditions of the raised temperature results in the decrease of the light CVC fill factor. In general the operating temperature increase results in the relative decrease of the *Si*-PVD efficiency with the coefficient of 0.5 %/°C.

According to the experimental data obtained by us the China-made *Si*-PVD demonstrate higher relative decrease of the EC making 0.7 %/°C. At that the short circuit current density reduces and the light CVC fill factor remains almost unchanged.

The existing physical representations suppose that the diode saturation current density is the most important light diode characteristic which controls change of the PVD output parameters with the operation temperature change. A theoretical expression for the diode saturation current density (without consideration of shunt and series resistances) will be as follows [2]:

$$J_0 = C \cdot T^3 \cdot \exp - \frac{qE_g}{kT} \qquad (2)$$

where C – parameter, q – electron charge, E_g – band gap, k – Boltzmann constant.

Work [2] showed that at $C{\cdot}T^3 = A = 1.5{\cdot}10^8$ mA·cm^{-2} there was observed the best correspondence between the experimental temperature changes of the output parameters and their theoretical dependences. Since A is a constant the exponential growth of the diode saturation current density is indicative of the fact that thermally activated growth of the charge carriers concentration is a basic physical mechanism of J_0 increase. As far as it was established that the experimental dependences $J_0(T)$ of the samples investigated by us are not linearized within the coordinates lnJ_0-$1000/T$ the above specified mechanism is not one and only variant. The registered unconventional decrease of the short circuit current density (Fig. 2, c) is indicative of existence of another physical mechanism reducing the efficiency of the investigated *Si*-PVD along with the conventional one.

The analysis of the light diode characteristics shows that anomalously high decrease of the EC and reduction of the short circuit current density can be explained not only by the growth of the diode saturation current density but also by the registered shunt resistance decrease. Current running along the areas with high conductivity reduces the contribution of photocurrent to short circuit current and is a supplementary physical mechanism causing the EC decrease.

Since the investigations gave an opportunity to establish experimentally high rate of the *Si*-PVD efficiency coefficient decrease, rather high initial output parameters of these devices are being downplayed in the process of their use. High rate of the efficiency coefficient decrease caused by the operating temperature growth conditions advisability of use of the China-made *Si*-PVD as a part of a photovoltaic thermal module (PVTM) which is a hybrid of PVD and a solar collector. PVTM ensures cooling of a silicon device structure due to heat medium circulation. Depending on the necessary production requirements there were elaborated three main operating modes of PVTM [8]: ensuring the maximum efficient electric energy production; ensuring the maximum efficiency of heat energy; and ensuring the maximum overall efficiency. Russian scientists in [9] have developed designs of the devices which ensure the possibility of heat removal from the PVD frontal surface to atmosphere and from the rear surface to a circuit with heat medium in order to obtain the maximum electric power. Absence of air gap between PVD and a translucent coating is the key design feature of the module consistent with the mentioned operation mode. In this operation mode heat medium temperature in the circuit should not exceed 35°C. At that the liquid being heated by the module has low temperature therefore its further heating is necessary which conditions the need in additional equipment installation. Thus for example such operation mode of PVTD is being ensured by a combined system of hot water supply, heating and conditioning based on a heat pump unit and PVTM [10].

4. Conclusions

The investigation of the influence of operating temperature on the efficiency of silicon photovoltaic devices made in China showed that the growth of operating temperature conditioned relative decrease of the efficiency coefficient at the rate of 0.7 %/C which was significantly higher as compared to the device structures produced in Russia or Europe and was caused by unconventional reduction of short current circuit density.

It was demonstrated that the decrease of the efficiency of the silicon photovoltaic devices was caused not only by the conventional diode saturation current density growth but also by the shunt resistance decrease.

The identified temperature dependence of the efficiency coefficient evidences reasonability of the photovoltaic devices use as a part of design of a photovoltaic thermal plant which along with a heat pump unit is a constituent of a combined hot water supply, heating and conditioning system.

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References

1. **Bye G., Ceccaroli B.** Solar grade silicon: Technology status and industrial trends // Solar Energy Materials & Solar Cells. 2014. V. 130. P. 634–646.
2. **P. Singh, Ravindra N.M.** Temperature dependence of solar cell performance — an analysis // Solar Energy Materials & Solar Cells. 2012. V. 101. P.36–45.
3. **Singh P, Singh S N, Lal M**. Temperature dependence of I-V characteristics and performance parameters of silicon solar cell // Solar Energy Materials & Solar Cells. 2008. V. 92. P. 1611–1616.
4. **Radziemska E.** Effect of temperature on dark current characteristics of silicon solar cells and diodes // International Journal Energy Res. 2006. V. 30. № 2. P.127–134.
5. **Cai W., Chao F., JinLong T., DeXiong L., SiFu H., ZhiGang X.** The influence of environment temperatures on single crystalline and polycrystalline silicon solar cell performance // Physics, Mechanics & Astronomy. 2012. V. 55. № 2. P. 235–241.
6. **Möller H.J**. Semiconductors for solar cells. Boston: Artech House, 1993.
7. **Afanasiev V.P., Terukov Ye.I., Sherchenko A.A.** Silicon-based thin-film solar cells. Publishing house of Saint Petersburg Electrotechnical University: "LETI".2012.
8. **Kharchenko V.V., Nikitin B.A., Tikhonov P.V.** Selection of parameters of a photovoltaic thermal module // Renewable and small-scale power generation 2012: collected works of the IX International Annual Conference. M. 2012. P. 292-297.
9. **Tikhonov P. V.** Substantiation of parameters of a photovoltaic thermal module // Thesis paper for the academic degree of Candidate of Science (Engineering) in specialization 05.14.08 - power installations based on renewable energy sources. Moscow. 2014. 142 p.
10. **Tikhonov P. V., Kharchenko V.V.** Electric power systems based on cogeneration photovoltaic and thermal modules and thermal pumps // Works of the 7th International Scientific and Technical Conference. Part 4: Renewable energy sources. Local energy resources. Ecology. M: Public scientific institution “All-Russia Research Institute for use of electric power in farming”. 2010. P. 275-279.