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Analysis Of Possibilities For An Efficiency Improvement For Industrial Silicon Photovoltaic Devices

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Abstract
The ways for increasing the efficiency of silicon photovoltaic devices made in China up to over 20% have been researched. Computer simulation revealed that the implemented in such solar cells lifetime of non-equilibrium charge carriers which is 520 microseconds does not limit the possibility of increasing their efficiency over 20%. It was shown that the growth in the photocurrent density up to 43.1 mA/cm2 leads to the increase in the photovoltaic device efficiency up to 20.1%, while the reduction in the density of the diode saturation current to 3.1·10-14 A/cm2 is a cause of the efficiency increasing up to 20.4%. Simultaneous changes in these diode characteristics increase efficiency up to 23.1%. In this article we propose the physical and technological approaches for the increasing the photocurrent density and for the reducing the diode saturation current density in the ready-made photovoltaic devices.

Keywords: photovoltaic devices based on monocrystalline silicon, efficiency, output parameters, light diode characteristics.

1. Introduction

Extensive use of the most widespread photovoltaic devices (PVD) based on crystalline silicon is mainly prevented by the necessity to ensure competitiveness of electric energy generated by such device structures as compared to the traditional electric power sources [1]. This could be achieved by the cost reduction of 1 Watt of peak capacity by means of increasing the solar energy conversion ratio (efficiency coefficient - EC) and decrease of their production technology cost [1].

Currently the western companies have developed and implemented design and technology concepts of PVD based on crystalline silicon (DTC of *Si*–PVD) with the efficiency of more than 20% under the conditions of industrial production [2-4]. Commercialization of such DTC in Russia requires technical re-equipment of the domestic electronics-sector enterprises dealing with serial production of PVD based on crystalline silicon through purchase of expensive high-technology equipment which does not have comparable domestic counterparts.

At the present time the leading Chinese companies reduce the cost of *Si*–PVD with the EC of 18% by more than 1.4 times due to abrupt enlargement of investments in production development, and in the nearest three years their cost will be again reduced by 1.3 times [5]. Therefore use of Chinese-made *Si*–PVD as initial device structures would have economical practicability. Meanwhile the analysis of photovoltaic conversion efficiency in such device structures for the purposes of studying the possibilities to advance the EC of the ready-made Chinese PVD to the level of more than 20% should be deemed the issue of current concern.

2. Routine of experiment

Under the industrial production conditions the output *Si*-PVD parameters (namely offload voltage (U_{OL}), short-circuit current density (J_{SC}), fill factor (FF) of light current-voltage characteristic (CVC) and efficiency coefficient (EC) are determined at time of in-process inspection by means of analytical treatment of the light CVC. Nevertheless these parameters describe technical capabilities of a device and do not have unambiguous connection with photovoltaic processes which determine operation of PVD. That's why light diode characteristics giving unambiguous determination to a single-diode model of *Si*-PVD should be analyzed along with the output parameters [6]. Such diode characteristics include photocurrent density (J_{PH}), diode saturation current density (J_0), ideality factor (A), shunting (R_{SH}) and series (R_S) resistance rated per unit area of *Si*-PVD. Relationship between the PVD efficiency and the light diode characteristics is implicitly described by the light CVC of PVD [6]:

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

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 output parameters, the light diode characteristics and the EC of PVD may be determined by approximating experimental values I_L и U_L by theoretical expression (1). Analytical treatment of the light CVC of PVD under investigation was performed by means of a PC with use of a designed program. The program supposes transformation of the analytic expression for the light CVC (1) into the following expression:

$$J_L = A_0 - A_1 U_L - A_2 \exp(A_3 U_L + A_4 U_L), \quad (2)$$

where

$$A_0 = \frac{(J_{PH} + J_0)R_{SH}}{R_S + R_{SH}},\ A_1 = \frac{1}{R_S + R_{SH}},$$

$$A_2 = \frac{J_0 R_{SH}}{R_S + R_{SH}},\ A_3 = \frac{e}{AkT}, A_4 = \frac{eR_S}{AkT}.$$

Through use of expression (2) and experimental values J_L and U_L, by means of variation of values of the above coefficients A_0, A_1, A_2, A_3, A_4 the program performs the best approximation of the experimental data $I_L = I_L(U_L)$ of the curve described by the transformed theoretical expression (2). Usually analytical treatment ensures mean square deviation less than 10^{-8} which corresponds to the fractional error for determination of the output parameters and the light diode characteristics at the level not exceeding 1%. After evaluating the specified coefficients which ensure the best approximation the following output parameters of PVD are determined: J_{SC}, U_{OL}, *FF*, EC. The light diode characteristics R_S, R_{SH}, A and I_0 are calculated with use of the determined coefficients A_0, A_1, A_2, A_3, A_4. The light CVC of PVD were measured with the aid of a laboratory bench by means of illuminating of the device structures with a solar simulator under terrestrial conditions with the luminous flux power of 100 mW/cm^2. A halogen lamp with the power of 500 W switched to a stabilized power module was used as a source simulating solar irradiation.

The efficiency of photovoltaic processes (i.e. of generation, diffusion, drifting, division and gathering) being generated under the action of light from a non-equilibrium charge carrier greatly depends on their lifetime. That's why at time of *Si*-PVD efficiency analysis we determined the lifetime of non-equilibrium charge carriers in the investigated device structures by the method of offload voltage drop [7].

Study of the spectral dependence of the coefficient of quantum efficiency $Q(\lambda)$ allows to analyze integral efficiency of the photovoltaic processes depending on incident radiant energy [7]. Therefore such investigations are also necessary for optimization of *Si*-PVD DTC. There is a functional relationship between short-circuit current I_{SC} and $Q(\lambda)$ value which can be described by the following formula given significant high shunt resistance R_{SH} [7]:

$$I_{SC} = e\int_0^{\lambda_{PT}} Q(\lambda)\cdot N(\lambda)d\lambda - I_D, \tag{3}$$

where λ - light wavelength; λ_{PT} - photoelectric threshold; $N(\lambda)$ – rate of photons arrival at PVD surface; I_D – PVD diode current.

In practice the intensity of solar irradiation arriving at the surface of a solar cell under the conditions of the experimental value of series resistance of the device structure ensures $I_D << I_{SC}$, therefore formula (3) will be converted into the following:

$$I_{SC} = Q(\lambda)\cdot N(\lambda). \tag{4}$$

The value of $N(\lambda)$ in (4) may be expressed through intensity of light $I_{LI}(\lambda)$ arriving at the surface of PVD:

$$Q(\lambda) = \frac{I_{SC}(\lambda)\cdot E(\lambda)}{eS\cdot I_{LI}(\lambda)}. \tag{5}$$

In the course of study of the spectral dependence of photoresponse *Si*-PVD was placed on the output slit of a double monochromator, I_{SC} was measured while the incident radiation wavelength was smoothly changed, after which the value of $Q(\lambda)$ was calculated with use of formula (5). Light intensity $I_{LI}(\lambda)$ is a characteristic of the used light source, i.e. in this case of the incandescent lamp with the power of 500 W.

3. Results and discussions

3.1 Experimental investigations of the industrial silicon photovoltaic devices

The most efficient industrial models of Chinese-made *Si*–PVD were used for the investigation. There were measured the light CVC for 10 device structures. The results evidence that their EC falls within the range from 17.7 % to 18.4%. The light current-voltage characteristic of *Si*–PVD with the representative value of EC of 18.1% was selected for analysis (Fig. 1, curve 1). The analytical treatment of the light CVC allowed determining the output parameters and the light diode characteristics of *Si*-PVD (see Table).

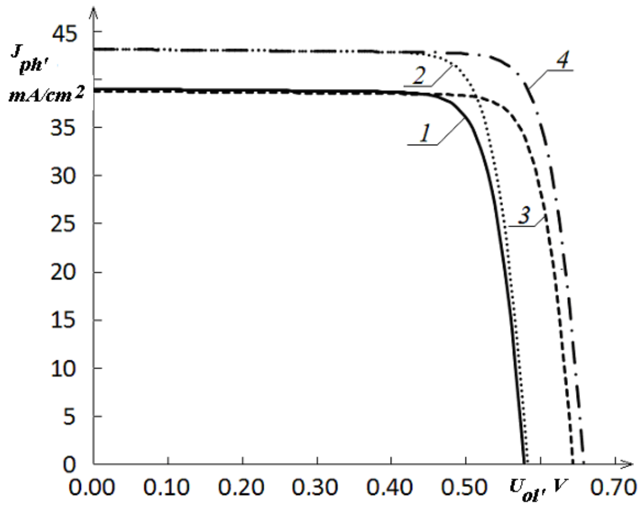


Fig. 1. Light current-voltage characteristics *1* – initial, J_{PH}=39.0 mA/cm^2, J_0=5.4·10^{-13} A/cm^2, EC=18.1%; *2* – theoretical CVC at J_{PH}=43.1 mA/cm^2, J_0=5.4·10^{-13} A/cm^2, EC=20.1%; *3* – theoretical CVC at J_{PH} =39.0 mA/cm^2, J_0=3.1·10^{-14} A/cm^2, EC=20.4%; *4* – theoretical CVC at J_{PH} =43.1 mA/cm^2, J_0=3.1·10^{-14} A/cm^2, EC=23.1%.

The study of the output parameters and the light diode characteristics was supplemented by the study of lifetime. Judging from offline voltage drop (see Fig 2, a) it was established that the lifetime of non-equilibrium charge carriers made 520 μs. The results of study of the spectral dependence of the coefficient of quantum efficiency (Fig. 3, curve 1) show that the spectral range of *Si*-PVD photosensitivity made 0.42-1.20 μm. The maximum value of $Q(\lambda)$ was observed within the spectral range of 0.90-1.10 μm, starting from 0.80 μm $Q(\lambda)$ significantly decreases.

3.2 Modeling of the influence of the non-equilibrium charge carriers lifetime on the efficiency of industrial silicon photovoltaic devices

Since the value of EC of the investigated industrial models was lower than the efficiency of the best European industrial models which exceeds 20% we've performed computer-aided numerical modeling of the parameters of the investigated *Si*-PVD in order to find the ways of EC enhancing. A free-available program *PC*1*D* 5.9 developed by New South Wales University (Australia) was used for this purpose. An electronic model of PVD was built by means of the mentioned software. Such parameters of the master silicon chip of a photovoltaic device as bandgap, specific inductive capacitivity, intrinsic concentration of charge carriers, the value of electron and hole mobility were included in *PC*1*D* 5.9 software. Besides the following characteristics of the investigated PVD were taken into account at time of modeling:

- the *p*-type master chip impurity level which made $1.5{\cdot}10^{16}$ cm^{-3};
- the width of n^+-layer (0.1 μm), of p^+-layer (1.15 μm), the average impurity level of the same at *erfc*-distribution (10^{20} cm^{-3} and 10^{18} cm^{-3} correspondingly);
- the width of antireflection coating of Si_3N_4 (53 nm);
- the height of relief of chaotically textured frontal surface-(3 μm);
- the recombination rate at the frontal and the back surfaces (S_n=S_p= 10^3) m/s;
- series and shunt resistances which were determined by the analytical treatment of the experimental light CVC (see Table).

PVD operation modeling was performed for its temperature of 25^{o}C in the irradiation mode *AM*1.5*G*, at that irradiancy of the frontal surface made 1000 W/m^2. The non-equilibrium charge carriers lifetime which was changed within the range from 10 to 1000 μs was a variable in this model.

The analysis of the obtained data (Fig. 2, b) shows that starting form the lifetime value of 300 μs its further increase does not have influence on the efficiency coefficient. Since the investigated industrial models were characterized by the experimental lifetime of 520 μs a conclusion can be drawn that the master chip quality should not be considered to be a factor limiting the efficiency coefficient of the investigated *Si*–PVD at the level of 18%.

3.2 Modeling of the influence of light diode characteristics on the efficiency of industrial silicon photovoltaic devices

The analysis of expression (1) shows that the growth of J_{PH}, R_{SH} and the decrease of J_0, A, R_S are accompanied by the PVD efficiency increase. Nevertheless is would be more useful to establish quantitative interrelation between the efficiency of the device structure and its light diode characteristics in order to identify physical mechanisms determining the EC of PVD. It allows defining predominant light diode characteristics change of which along with change of *Si*-PVD DTC causes change of the EC of PVD. As a result we'll have an opportunity to decrease considerably the extent of the following experimental investigations aimed at determination of physical pattern of DTC influence on *Si*-PVD efficiency. That's why the work included modeling of the influence of change of each of PVD light diode characteristic on the efficiency with the aid of the designed software program. At that all PVD light diode characteristics are fixed except one and the chosen light diode characteristic adopts a value from within the selected range of values. On the basis of the set of light diode characteristics as specified in expression (1) the program calculated theoretical light CVC and determined the efficiency coefficient. After that the next value of light diode characteristics from the selected interval was chosen and the next theoretical light CVC was calculated, the result of calculation was used for the efficiency coefficient determination. As a result we've obtained theoretical dependence of the efficiency coefficient from change in the selected range of one diode characteristic while the other diode characteristics remained fixed. Similar modeling was repeated for each light diode characteristic of PVD. By analyzing theoretical dependences of the EC on change of the light diode characteristics we evaluated quantitative contribution of change of each light diode characteristic in possibility to reach the EC above 20%.

The results of modeling show that the increase of shunt resistance and the decrease of series resistance given fixed values of the other diode characteristics of *Si*-PVD with the EC of 18.1 % does not results in significant efficiency growth (Fig. 4 a, b). Thus the increase of shunt resistance from R_{SH} = 1000 Ohm·cm^2 to R_{SH} = 4000 Ohm·cm^2 results in the efficiency growth by 0.1 %. The decrease of series resistance from R_S = 0.45 Ohm·cm^2 to R_S = 0.1 Ohm·cm^2 results in the efficiency growth by 0.5 %.

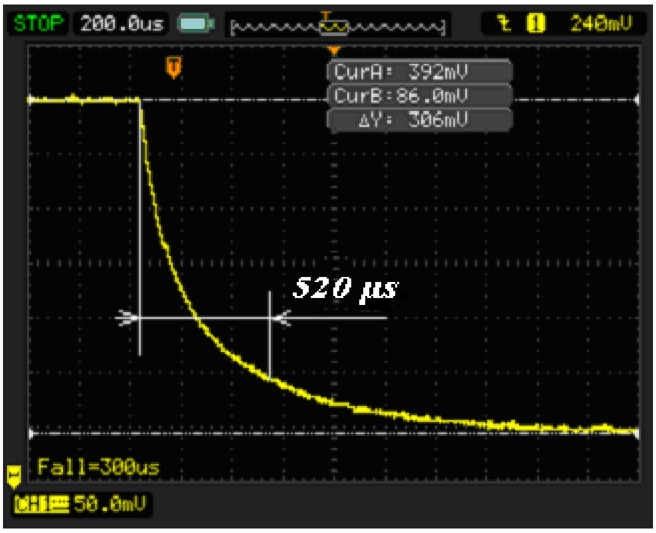
Significant efficiency growth with the other fixed diode characteristics may be achieved either due to photocurrent density increase or due to diode saturation current density decrease (see Fig. 4, c, d). Thus 1.1-fold photocurrent density increase, i.e. from J_{PH} = 39.0 mA/cm^2 to J_{PH} = 43.1 mA/cm^2 results in the growth of efficiency up to 20.1% (see Table). The diode saturation current density decrease from $J_0 = 5.4{\cdot}10^{-13}$ A/cm^2 to $J_0 = 3.1{\cdot}10^{-14}$ A/cm^2 allows to enhance the EC up to 20.4 % (see Table). Mathematical modeling showed that simultaneous growth of $J_0 = 3.1{\cdot}10^{-14}$ A/cm^2 and J_{PH} = 43.1 mA/cm^2 results in the EC increase up to 23.1% (see Table).

According to the experimental data (see Fig. 3) the short-wavelength limit of photosensitivity of the investigated models of *Si-PVD* makes 0.42 μm, that's why the device structures do not transform ultraviolet spectrum. Therefore the growth of photocurrent density of the investigated *Si-PVD* may be achieved by applying a luminescent coating onto the surface of the ready-made device structure. Such coating will absorb photons in the ultraviolet spectrum and generate photons in the infrared solar spectrum. The luminescent coating based on lead sulphide quantum dots applied by a cost-efficient chemical method will be the most appropriate for the industrial models of *Si-PVD* [8]. Such quantum dots absorb light in the spectral range from 0.30 to 0.40 µm and generate photons with the wavelength of about 1.05 µm [8] which corresponds to the range of maximum experimental values of quantum efficiency of *Si*-PVD studied in this work (Fig. 3). According to the modeling results presented in work [8] use of such luminescent coating theoretically will allow to increase the original short-circuit current density by more than 1.1-1.2 times which as the results of investigations carried out by us show is sufficient for achievement of the EC of over 20% by the Chinese industrial *Si*-PVD.

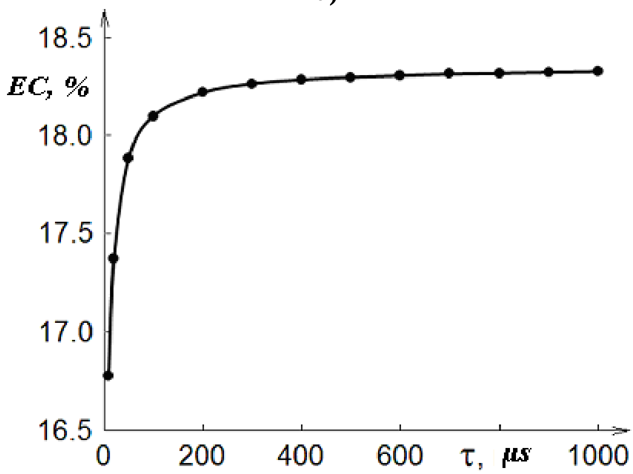
The diode saturation current density decrease may be achieved by application of plasmonic coatings onto *Si*-PVD surface or by treatment of these devices under the magnetic field conditions. According to data from the literature sources (see for example [9]) plasmonic coatings allow to implement a new method of photon capture optimization by means of metallic nanoparticles applied onto the PVD surface. Generation of non-equilibrium charge carriers only in p zone near homojunction may be ensured by excitation of plasmon-polariton waves which allows decreasing the diode saturation current density. Magnetic treatment of *Si*-PVD in the constant magnetic field which according to data from literary source [10] has an effect on electrically-active native defects and defective complexes inside a silicon slab will also theoretically give an opportunity to decrease the diode saturation current density by means of reorganization of energy structure of the group of electrically-active native point defects in the zone of homojunction of the device structure.

Table 1. Output parameters and light diode characteristics of *Si*-PVD obtained as a result of the experiment and modeling practices.

Output parameters and light diode characteristics	Experimental model	Modeling of J_0 influence	Modeling of J_{PH} influence	Modeling of J_{PH} and J_0 influence
J_{SC}, mA/cm^2	39.0	39.0	43.1	43.1
U_{OL}, mV	578	643	583	658
FF, rel. units	0.80	0.82	0.80	0.82
η, %	18.1	20.4	20.1	23.1
J_{PH}, mA/cm^2	38.8	39.0	43.1	43.1
R_S, Ohm·cm^2	0.45	0.45	0.45	0.45
R_{SH}, Ohm·cm^2	1013	1013	1013	1013
A, rel. units	0.9	0.9	0.9	0.9
J_0, A/cm^2	$5.4\cdot10^{-13}$	$3.1\cdot10^{-14}$	$5.4\cdot10^{-13}$	$3.1\cdot10^{-14}$



a)



b)

Fig. 2. Study of the lifetime of non-equilibrium charge-carriers in industrial models of *Si*-PVD (a) and modeling of influence of the lifetime on their efficiency coefficient (b).

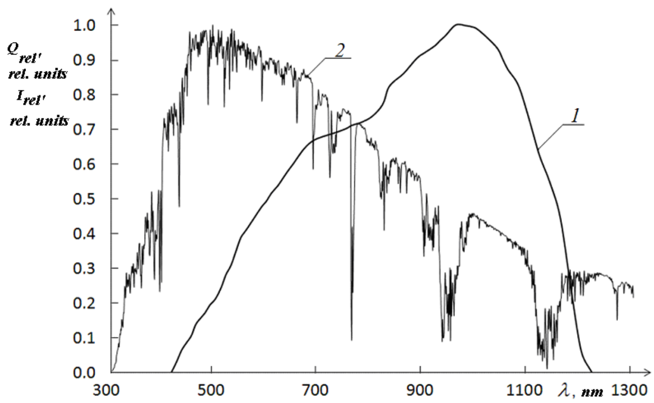


Fig. 3. Spectral dependences of the quantum efficiency coefficient of *Si*-PVD *1* – *Q*(λ) *Si*-PVD; *2* – solar spectrum *AM1.5G.*

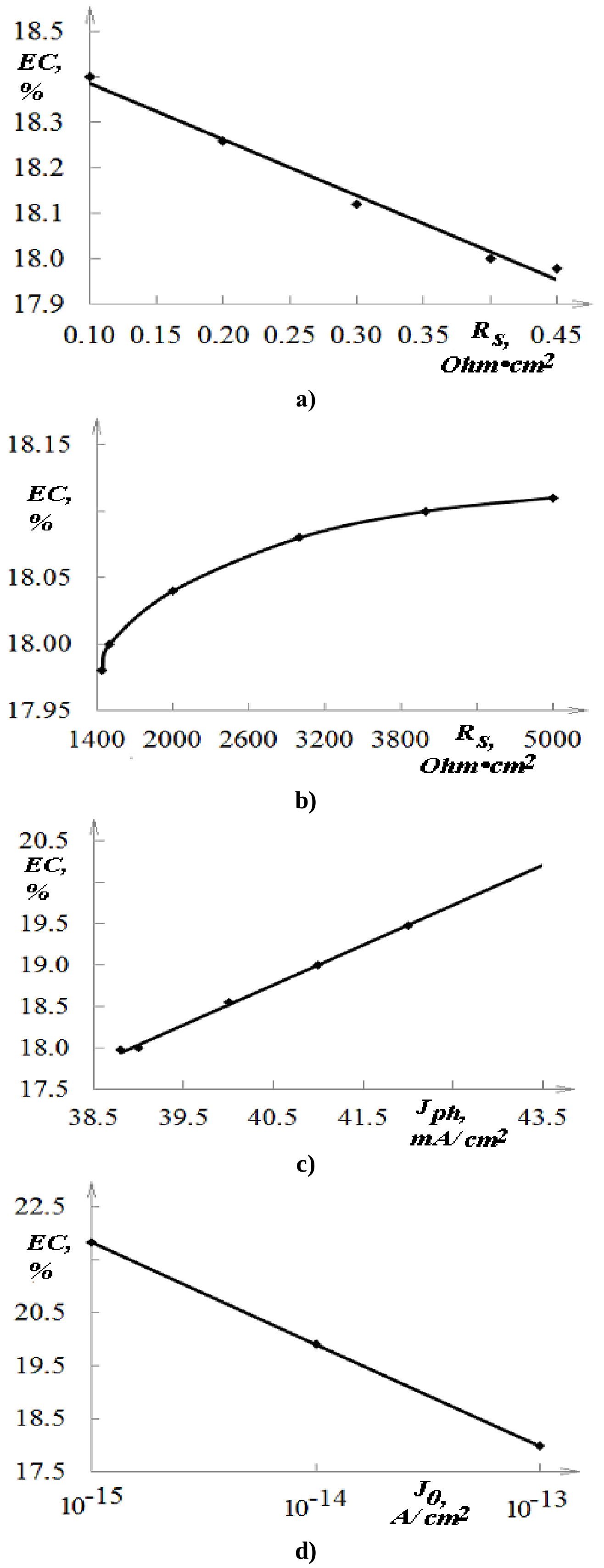


Fig. 4. Modeling of influence of series resistance (a), shunt resistance (b), photocurrent density (c) and diode saturation current density (d) on the *Si*-PVD efficiency coefficient.

4. Conclusions

The results of investigation demonstrated that the lifetimes of non-equilibrium charge carriers which were realized for the industrial *Si*-PVD and made 520 µs did not limit the possibility to increase the EC of the devices to the level of more than 20%. The achieved values of series and shunt resistances of the industrial models of *Si*-PVD which make 0.45 Ohm·cm^2 and 1000 Ohm·cm^2 correspondingly do not require further optimization. It was shown that the increase of photocurrent density from 39.0 mA/cm^2 to 43.1 mA/cm^2 in the industrial *Si*-PVD while the other diode characteristics remained unchanged resulted in the growth of the devices efficiency up to 20.1 %. In order to ensure the similar photocurrent density it is necessary to apply luminescent coatings containing lead sulphide quantum dots on the surface of a ready-made device structure. It was established that the decrease of diode saturation current density from $5.4 \cdot 10^{-13}$ A/cm^2 to $3.1 \cdot 10^{-14}$ A/cm^2 in the industrial *Si*-PVD with the other diode characteristics unchanged resulted in the growth of efficiency up to 20.4%. Application of plasmonic coatings or treatment of the device structures in magnetic field is a possible physico-technological approach allowing to decrease the diode saturation current density of a ready-made PVD. Simultaneous increase of the photocurrent density and the diode saturation current density up to the above specified values allows the EC growth up to 23.1%.

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