Research of photovoltaic properties of cogeneration cylindrical photovoltaic module for hybrid solar panels

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Abstract. Solar energy is the most efficient and cleanest source of energy, as well as a cheap and eternal source of renewable energy. Improving the energy efficiency of solar panels will optimize their energy characteristics and operating modes, taking into account the load and solar radiation energy. The work is aimed at studying photosensitive structures based on porous Si and ZnO that are promising for solar energy. To increase the efficiency of solar panels, hybrid panels based on cogeneration photovoltaic modules of cylindrical shape cooled by liquid have been developed. This will open up the possibility of creating hybrid solar photovoltaic panels for simultaneous the generation of electricity and heat. A scheme for a hybrid solar panel device using a cooled cogeneration cylindrical photomodule based on ZnO/porous-Si/Si heterostructures is proposed. Using the PC1D program, the light characteristics of the manufactured structure (no-load voltage V_{OC}, short-circuit current I_{SC}, fill factor FF, and efficiency η) were calculated and the volt-ampere characteristics were plotted. The influence of porous-Si and ZnO layer thickness, texture, and doping level of the ZnO layer, as well as the effect of temperature on the performance of a ZnO/porous-Si/Si heterojunction solar cell was investigated in order to obtain a device with good conversion efficiency. It has been established that the energy conversion efficiency of a cogeneration cylindrical photomodule based on ZnO/porous-Si/Si heterostructures can reach 23.9 %. Keywords: Photo converter, porous silicon, computer modeling, ZnO film

1 Introduction

The energy problem is very urgent for all countries in the world today, and it is especially acute in Ukraine, which can only meet its needs by 35-40% with its own energy resources. Therefore, the issue of the energy saving is an urgent problem [1, 2]. One of the ways to solve this problem is to use alternative energy sources that convert wind, solar, etc. energy [3-5].

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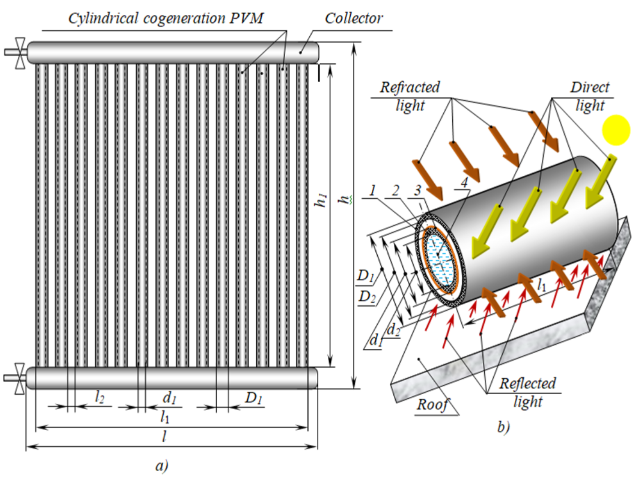
The use of solar energy and the possibility of creating large-scale production facilities for this promising industry require solving many fundamental scientific problems and applied tasks. The efficiency of solar energy use significantly depends on how accurately the design development took into account the patterns of solar radiation changes at the place of the proposed operation of the solar photovoltaic station (SPV) [6, 7].

It is known that with an increase in the specific power of solar radiation, the heating of the surface of the photovoltaic converter of a photovoltaic panel increases, which leads to a decrease in its efficiency. On a sunny summer day, the temperature of the solar photovoltaic converter system can reach 70-80 °C. This contradiction can be resolved by off taking heat from the solar photovoltaic converter system, which will lead to additional thermal energy that can be used for technological needs [8].

To increase the efficiency of the SPV, the Tavria State Agrotechnological University named after Dmytro Motornyi proposed to use hybrid panels based on cylindrical cogeneration photovoltaic modules (PVM) cooled by liquid instead of flat solar panels. This will open up the possibility of creating hybrid solar photovoltaic panels (HSPP) for the simultaneous generation of electricity and heat. The design scheme of the HSPP and solar absorption by a cogeneration PVM of cylindrical shape is shown in Fig. 1 [9, 10].



a) HSPP; b) cylindrical cogeneration PVM
1 – outer tube; 2 – inner tube; 3 – PVC; 4 – heat carrier

Fig. 1. Estimated scheme of HSPP and absorption of sunlight by cogeneration PVM

The PVM is produced with the use of borosilicate glass tubes T-300C with the following dimensional characters: outer tube – D_1 = 50 mm, wall thickness Δ = 2.5 mm, D_2 = 45 mm; inner tube – d_1 = 30 mm, wall thickness Δ = 2.5 mm, d_2 = 25 mm; length of the tubes h_1 = 1500 mm. The number of PVMs in HSPP is 14.

In an effort to reduce the cost of production and increase the efficiency of solar cells, scientists resort to various manipulations with the structures of photovoltaic converters (PVC) 3 (Fig. 1) and the materials used in their production [11, 12]. The efficiency can be increased without increasing of the PVC. It can be done using PVC with anti-reflective coatings, which allow increasing the amount of light absorbed by the solar cell surface to significantly increase the efficiency of PVMs. Currently, the photovoltaic industry is dominated by anti-reflective coatings such as ITO, TiO_2, SnO_2, LiF, MgF_2, etc., but transparent conductive oxides (TCO) are the most widespread. In addition, recently, there have been studies that use porous semiconductors as anti-reflective coatings [13, 14].

Therefore, the issue of studying solar cells using both porous silicon layers and anti-reflective coatings *is relevant*.

The *aim of this work* is to perform numerical modeling and optimization of the functional characteristics of the PVC based on ZnO/porous-Si/Si heterostructures, as well as to study the influence of technological parameters on the characteristics of the structure.

2 Theoretical Background

The well-known transparent conductive oxides that are widely used as conductors and as emitters on a p-Si silicon substrate are CdO, SnO_2, and ITO [15-17]. However, some of them have certain disadvantages, such as shortages, high cost of the main ingredient, toxicity, and low stability. Zinc oxide ZnO has the least number of disadvantages, since it has a relatively large direct bandgap (3.3-3.4 eV) at room temperature, a high exciton binding energy of 60 MeV [18], low resistivity, Hall mobility of about 200 $cm^2\ V^{-1}\ s^{-1}$ [19], high transmittance for visible light, etc. As a result, ZnO is a promising transparent conductive oxide as an alternative to TCO and ITO.

In most applications, ZnO is used as a solar element conductive layer to absorb the maximum of incident light [20-22]. The study of solar element with ZnO as a TCO is not new, but there are still a number of unresolved issues. Thus, in [23], the authors studied the effect of the deposition temperature of the ZnO film on the solar element parameters of ZnO/Si. In [24], the electronic structure of the interface between a boron-doped oxygenated amorphous silicon "conductive layer" (a-SiOx:H(B)) and aluminum-doped zinc oxide (ZnO:Al) was investigated. Doped ZnO films (ZnO:Ga, ZnO:Al, ZnO:B, ZnO:In, etc.) also improve the optical properties of structures and solar element based on them [25,26]. Jiangnan Ding and others [27] report an increase in efficiency up to 17.13% when using unalloyed combined ZnO/ZnO:Al layers in heterostructured silicon solar elements. Results in [28] prove the improvement of the electrical and optical properties of Ga:ZnO films in relation to the unalloyed ZnO film, while the authors investigated the interface between the film and the Si substrate in order to identify specific problems that may prevent optimal electrical contact between them.

On the other hand, ZnO can be not only a conduct layer in a solar element, but also act as a part of the p-n junction separating photogenerated carriers in ZnO/p-Si based solar elements [29]. It is theoretically predicted that the Si/ZnO heterojunction solar element will have a conversion efficiency of up to 25% [30]. However, the vast majority of studies have shown that the efficiency of ZnO/Si solar element conversion largely depends on the properties of the interface between ZnO films and a silicon substrate [31].

Recently, porous nanomaterials and nanomaterials with special physical and chemical properties, such as porous silicon, have attracted special attention of researchers, used as independent coatings and buffer layers. For example, in [32], a periodic array of Si columns is used to form a n-ZnO/p-Si photovoltaic system by reducing the volume of the active material and maximizing optical absorption. The authors of [33] demonstrate an improvement in the efficiency (up to 18.97%) of c-Si/ZnO heterojunctions in the presence of trapezoidal c-Si pyramids on top of the c-Si active layer.

Although the experimentally fabricated solar elements in the works under study show efficiency below theoretically predicted values, modeling is an effective means of studying them, which allows to select the optimal layer parameters, optimize the design, study the interaction of cell layers, minimize interface defects between heterostructure layers, etc. without spending resources (materials, money) on the experimental selection of these parameters.

Software packages such as AFORS-HET, PC1D, AMPS-1D, SCAPS, etc. can be used to estimate the optimal numerical value of key photovoltaic parameters for a solar element.

For example, in [34, 35], the authors obtained an efficiency of η = 24.8% by simulating in the PC1D program a solar cell based on a ZnO/Si heterostructure at a base thickness of 400 μm, an emitter thickness of 20 μm, a doping concentration of 1.1 × 1017 cm^{-3} in the base and a doping concentration of 5.1 × 1016 cm^{-3} in the emitter. A slightly lower photovoltaic conversion efficiency of 20.23% was achieved by modeling for a c-Si solar element of a pyramidal-textured front surface using ZnO nanorod arrays as an antireflective layer [36]. In addition, simulations in the PC1D program demonstrate that the photovoltaic property for these solar elements is much better than for c-Si solar elements without a ZnO layer.

Thus, some scientific papers propose to use ZnO as a conductive or anti-reflective layer of a solar cell to improve efficiency, there are known scientific studies that report the use of ZnO as an n-layer in heterostructured silicon solar elements, there are also known studies that use a periodic array of Si columns as a buffer layer, but there are not many studies on the use of ZnO as an n-layer, and antireflective coating using an intermediate layer of porous-Si simultaneously for the solar cell.

3 Research Methods

The study used the analysis of scientific literature on improving the efficiency of a photovoltaic converter for use in cogeneration PVMs of cylindrical shape, which are the main structural element of the HSPP, which will allow simultaneously generating electrical and thermal energy and stabilizing the temperature of the solar cell. To simulate the main characteristics of a photovoltaic converter based on the ZnO/porous-Si/Si heterostructure, we used the freely available computer program PC1D [37]. This software allows you to relate the electrical characteristics of a semiconductor device to its topology.

4 Results and Discussion

The results of the simulation using the PC1D software product allowed us to obtain numerical values of the no-load voltage V_{OC} and the short-circuit current I_{SC}. The values of the filling factor FF and efficiency η were theoretically calculated using the formulas [37-42]:

$$FF = \frac{P_{max}}{V_{OC} \cdot I_{SC}}, \ \eta = V_{OC} \cdot I_{SC} \cdot FF.$$

The simulation was performed by varying the thickness of the ZnO layer and the thickness of the porous-Si layer by fixing the latter in order to study the role of each parameter on the cell performance. In the first case, the thickness of the porous silicon layer was fixed at 0.2 μm, in the second - 500 μm, while the thickness of the ZnO coating varied from 10.0 nm to 2.0 μm. The thickness of the silicon substrate remained unchanged.

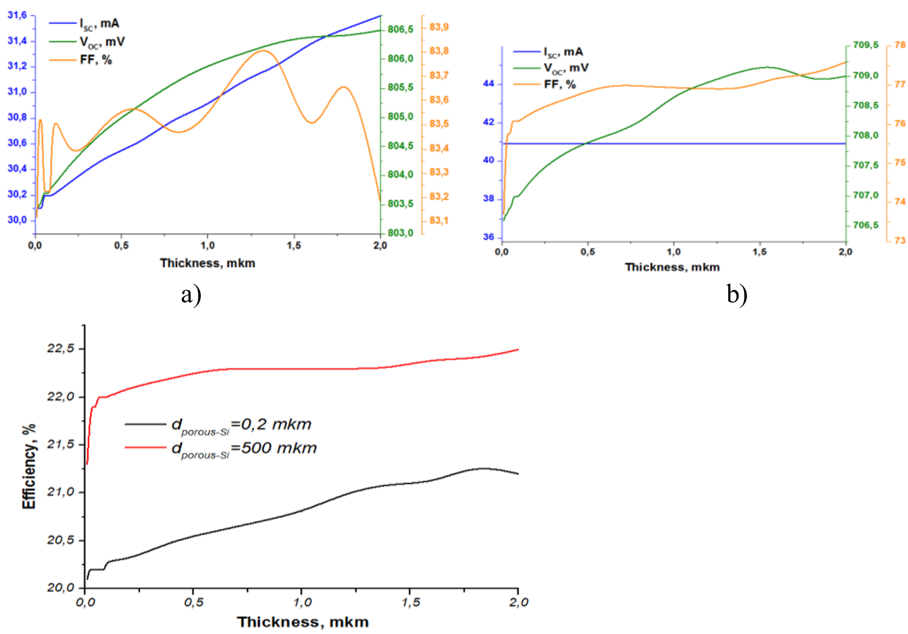
The electrical and optical parameters of the materials used in this simulation (Table 1) were selected from the databases of software packages for a solar element modeling and the scientific literature [43-45].

Table 1. Solar element modeling parameters

Parameter	The value for the layer		
	ZnO	Si	porous-Si
Electron affinity, eV	4.0	4.05	4.05
Dielectric constant	9.0	11.9	1.6
Band gap width, eV	3.3	1.124	2.05

Electron mobility, $cm^2\ V^{-1}\ s^{-1}$	100	1107	30
Hole mobility, $cm^2\ V^{-1}\ s^{-1}$	25.0	424.6	2.0
Doping concentration of acceptors, cm^{-3}	0	$1{\cdot}10^{16}$	varies
Doping concentration of donors, cm^{-3}	varies	0	0

1. Influence of ZnO and porous-Si layers thickness on the electrophysical properties of a solar element. The thickness of the ZnO layer determines the amount of radiation entering the silicon layer of the photovoltaic converter, so it is advisable to study the effect of the thickness of the ZnO and porous-Si layers on its electrical properties. In Fig. 2 shows the changes in the short-circuit current I_{SC}, opencircuit voltage V_{OC}, fill factor FF, and efficiency at different values of the ZnO film thickness and porous-Si layer.



c)

a) short-circuit current I_{SC}, open-circuit voltage V_{OC}, filling factor FF at the thickness of the porous layer $d_{porous-Si}$ = 0.2 μm;
b) short-circuit current I_{SC}, open-circuit voltage V_{OC}, filling factor FF at the thickness of the porous layer $d_{porous-Si}$ = 500 μm;
c) the efficiency of the PVC at different values of the thickness of the disturbed layer.

Fig. 2. Dependence of optoelectric parameters of ZnO/porous-Si/Si heterostructure on different values of ZnO film thickness

It was found that the highest efficiency of 22.5 % was obtained for ZnO with a thickness of 2 μm, i. e., the efficiency increases when the thickness of the ZnO coating increases to 1.8 μm and decreases with further increase in thickness, indicating the optimal thickness for better performance. The result is expected, since the absorbed photons are directly proportional to the thickness of the active layer. However, a further increase in the thickness of the active layer causes the recombination of free charge carriers, which contributes to a decrease in efficiency [46]. It is noted that the values of the filling factor of ~10% differ significantly for the thicknesses of the disturbed silicon layer under consideration. In the second case (Fig. 1, b), the value of the short-circuit current does not change within a given thickness range.

2. The influence of the doping level of the ZnO layer on the electrophysical properties of a solar element. A significant part of the light is absorbed by the surface of the solar element, which leads to a high generation rate, so the effect of the concentration of alloying impurities should be studied in detail. During the simulation, the thickness of the ZnO layer was 2.0 µm, for the porous Si layer - 200 nm, the rest of the parameters corresponded to those indicated in Table. 1. The modeling results are shown in Fig. 3.

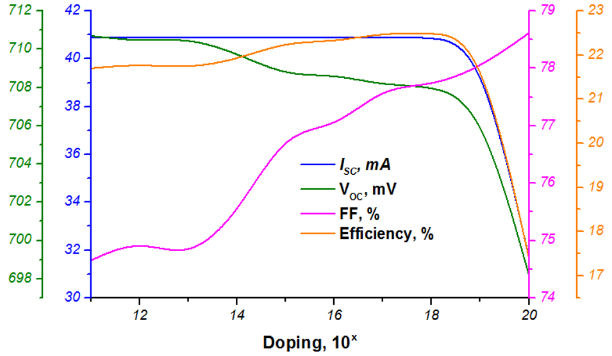


Fig. 3. Dependence of optoelectrical parameters of ZnO/porous-Si/Si heterostructure on the level of doping of ZnO coating

According to Fig. 3 high concentration of doping in the ZnO layer leads to a decrease in overall efficiency due to lower light transmission, absorption, and higher recombination rate [47]. However, at doping values of 10^{12}-10^{16} cm^{-3}, the efficiency of the solar element also decreases, which is most likely due to a decrease in the drift velocity and an increase in the resistance of the structure. Thus, at high values of doping concentration and ZnO film thickness, light hardly penetrates the silicon substrate, which affects the generation of the charge carrier and leads to a decrease in device efficiency. The maximum efficiency is achieved at a donor doping concentration of ~10^{18} cm^{-3}.

3. Effect of ZnO layers texturing on the electrophysical properties of the solar element. The efficiency of ZnO/Si heterojunction a solar element can be improved by maximizing the roughness of the ZnO surface on silicon micropores. An important technique for reducing light reflection is surface texturing, and therefore, we modeled the ZnO/porous-Si/Si photovoltaic converter at texturing angles in the range of 40-85° (Table 2).

Table 2. Change in the optoelectric parameters of the ZnO/ porous-Si/Si heterostructure when the surface texturing angle of the PVC is changed

Texture angle, degrees	Amperage, I_{SC}, mA	Voltage, V_{OC}, mV	Fill factor FF, %	Efficiency, %
40	40.9	708.7	76.6	22.2
45	40.9	708.7	76.6	22.2
50	40.9	708.7	76.9	22.3
55	40.9	708.7	76.9	22.3
60	41	708.7	76.7	22.3
65	41	708.7	77.1	22.4
70	41.1	708.6	76.9	22.4
75	41.1	708.4	77.3	22.5
80	41.2	708.3	77.4	22.6
85	41.3	708	77.6	22.7

The analysis of the change in the optoelectric parameters of the ZnO/porous-Si/Si heterostructure depending on the angle of the PVC surface texturing (Table 2) shows that the solar energy conversion efficiency reaches its maximum value at an angle of 85° due to a decrease in light reflection from the front surface and light trapping in the solar element. An increase in the number of photons that can be absorbed by the solar element leads to a higher short-circuit current density. Thus, due to the surface texturing, the heterojunction area increases, which leads to the appearance of more electron-hole pairs during illumination and increases the efficiency of the PVC (Fig. 4).

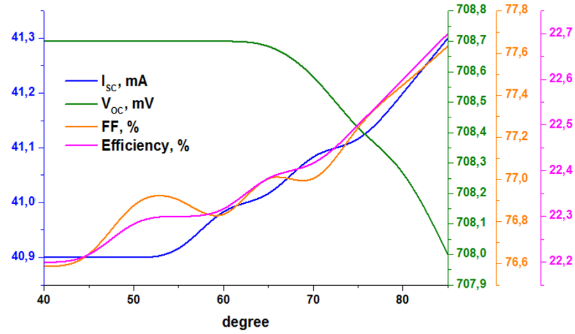


Fig. 4. Dependence of optoelectric parameters of the ZnO/porous-Si/Si heterostructure on the angle of texturing of the photovoltaic converter surface

4. The effect of the solar element temperature on electrophysical properties. Operating temperature is significantly to a certain extent affects the efficiency of PV modules and, accordingly, the efficiency of the HSPP. In order to study this effect, the photovoltaic parameters of the ZnO/porous-Si/Si heterostructure were modeled at different temperatures in the range from 280 K to 340 K. The obtained values are shown in Fig. 5.

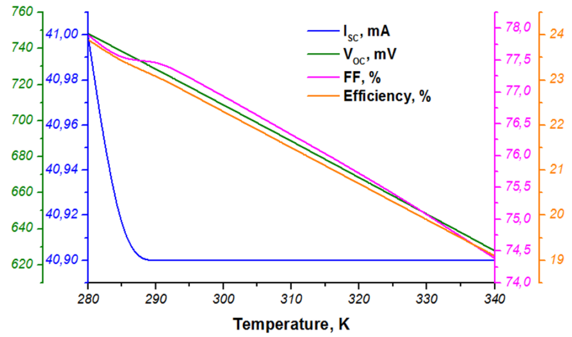


Fig. 5. Optoelectrical parameters of the photovoltaic converter based on ZnO/porous-Si/Si heterostructure at different temperature values

Fig. 5 demonstrates that the temperature increase significantly affects the performance of PV modules, leading to a decrease in efficiency. The best efficiency value is achieved at 280 K, where the FF fill factor is almost 78%. The effect of temperature is the result of the inherent characteristics of silicon solar elements - voltage increase with temperature decrease.

5 Conclusions

The photovoltaic parameters of the heterostructured ZnO/porous-Si/Si solar element have been investigated using the PC1D program. The effect of the thickness of ZnO and porous-Si layers on the electrophysical properties of the solar element has been studied. It was found that the highest efficiency of 22.5 % can be obtained for ZnO with a thickness of 2 μm and at a porous-Si thickness of 500 μm. An increase in the doping concentration in the ZnO layer leads to a decrease in the overall efficiency of the device due to a decrease in light transmission. The maximum efficiency is achieved at a donor doping concentration of ~1018 cm^{-3}. The study of the surface texture of the solar element shows that the solar energy conversion efficiency reaches a maximum value of 22.7% at an angle of 85º due to the reduction of light reflection from the front surface and light trapping in the solar element. It was also found that an increase in temperature from 280 K to 340 K leads to a 4.8% decrease in efficiency. The best efficiency value of 23.9% is achieved at 280 K.

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