Methods of construction and features of operation of solar cells with luminescent coatings

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1. Introduction

Development of power sources based on solar radiation is an important direction in solving power supply issues in the absence of other energy resources (space objects, polar stations, non-stop pilotless aerial vehicles, etc.) and for the implementation of the green energy paradigm. Development of the second direction determines the need for methods of constructing effective and sustainable solar cells with high performance and service life.

Current developments in this field do not meet the needs of green energy: standard thin-film photo-cells based on polycrystalline silicon and similar structures, as well as new photovoltaic converters based on organic components, provide photoelectric conversion efficiency only at the level of 5-25%, while cascading Gallium arsenide-based structures are characterized by technological complexity, high cost, and include environmentally hazardous compounds.

This determines the relevance of studies to increase the efficiency of the photoelectric transformation of thin-film solar cells by depositing a luminescent coating on its surface, which, due to the phenomenon of Stokes shift, can change over the spectrum of solar radiation into the area of absorption of the photoelectric converter.

The analysis of recent studies and publications in this area included analysis of the development of solar cells based on crystalline, polycrystalline and nanocrystalline silicon [1-5], thin films of chalcogenides [6, 7], organic dyes and polymers [8-10], as well as cascade structures [11-13]. As a result of the analysis, the need to develop methods for the use of luminescent coatings in solar cells was pointed out, which allows to transfer the spectrum of solar radiation to the absorption region of the photoelectric converter [14, 15]. This approach is fundamentally new and for today the results of its application show low indicators of increasing the efficiency of the photoelectric transformation, as well as the typical problems for the operation of solar panels are indicated, which within the framework of this paper is allocated as an unsolved part of the general problem.

The goal of research, therefore, is to determine the optimal approach for the development of thin-film solar cells with a luminescent coating in view of increasing the efficiency of photoelectric converters of this class of elements while minimizing the cost and technological complexity of their construction and operation.

2. Determining efficiency of the photoelectric converter

The low efficiency coefficient of thin-film solar cells should first be related to the discrepancy of the solar radiation spectrum and the photoelectric converters absorption spectrum (Fig. 1).

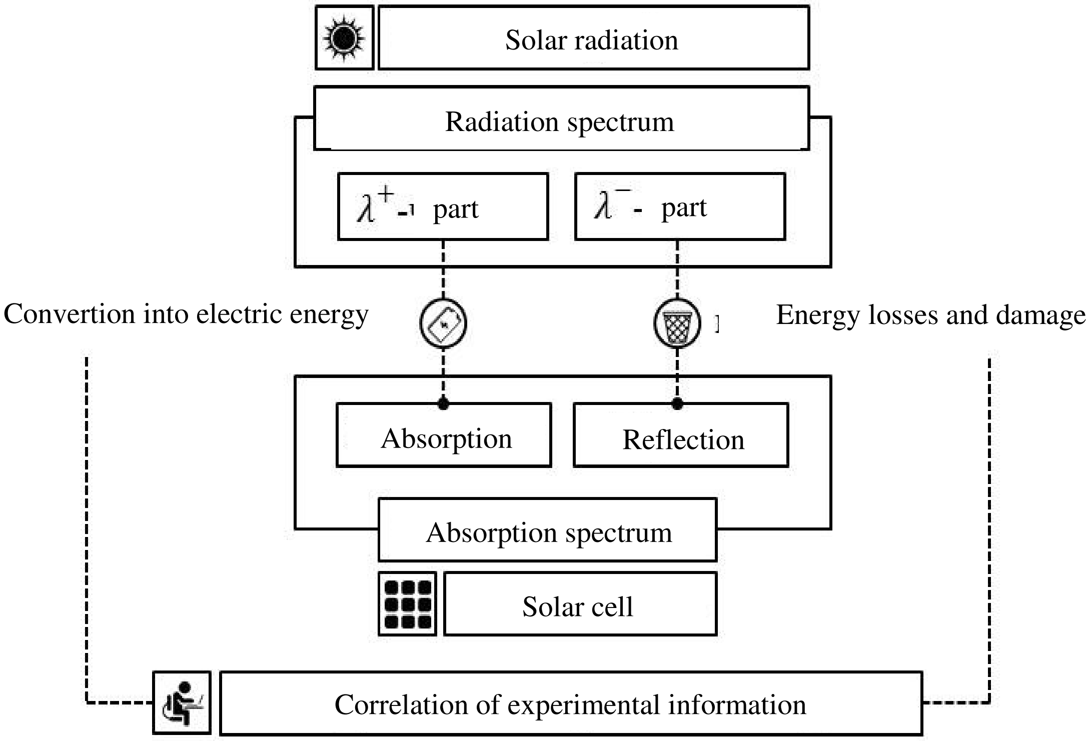
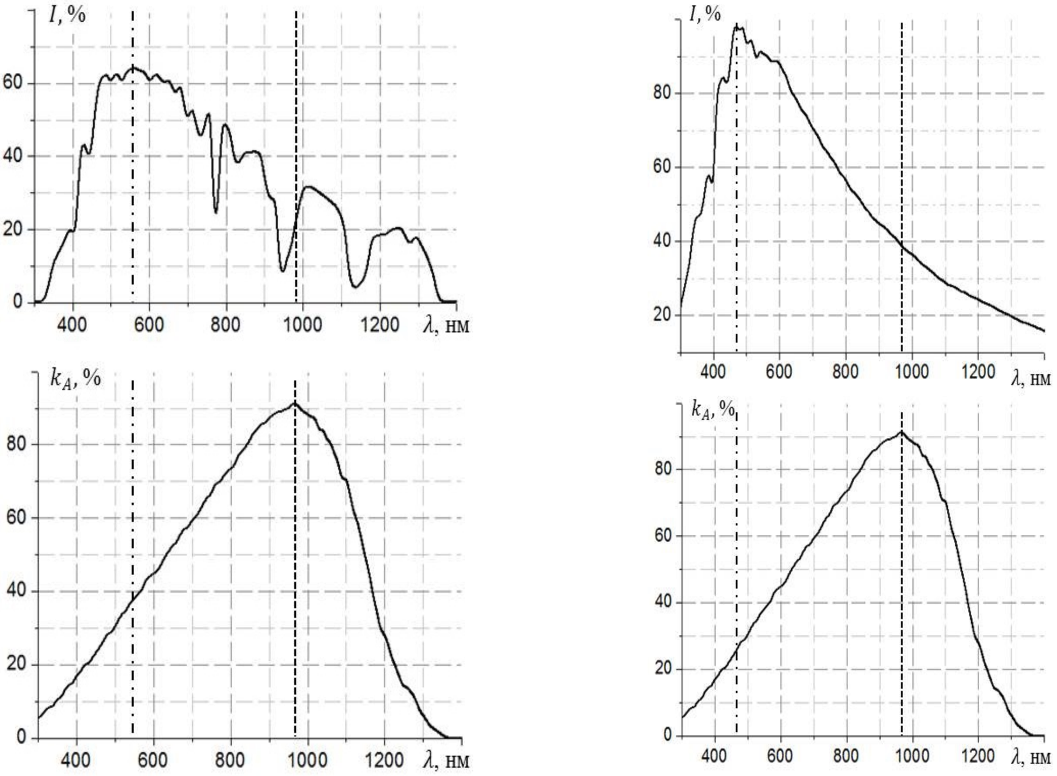


Fig. 1. Basic scheme for determining efficiency of a solar cell.

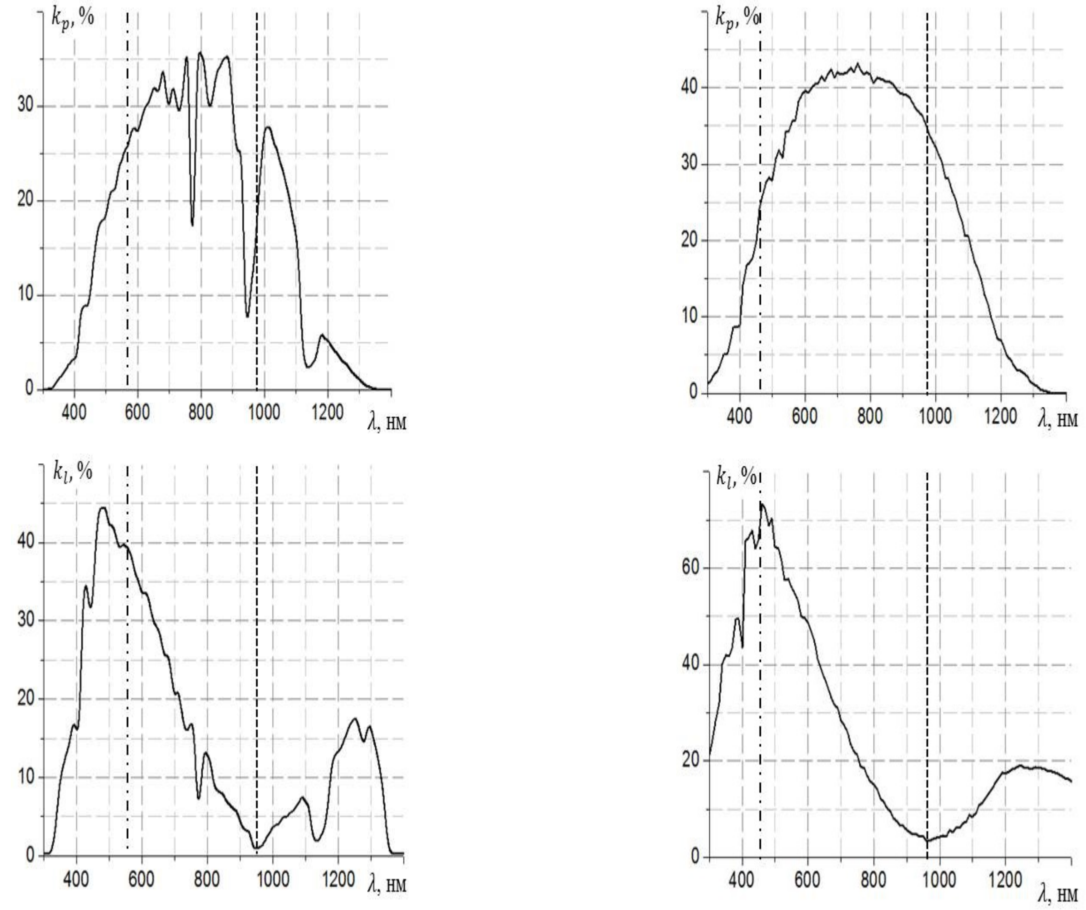
Let us divide the absorption spectrum of solar radiation into a long-wave and short-wave part (they are indicated in Fig. 1 as λ^+ and λ^-, respectively). While the λ^+ region of the spectrum is absorbed by a solar cell, and in accordance with the coefficient of the photoelectric transformation it creates electric energy at its output, the λ^- region is reflected from the solar cell, in addition, its high-energy photons partially damage the element.



(a) (b)

Fig. 2. The spectra of solar radiation and absorption of poly-Si.

Thus, at the mathematical level, efficiency of a solar cell can be determined by correlating solar energy absorbed by a photoelectric converter and energy losses. Fig. 2 shows the spectra of solar radiation and absorption spectra of polycrystalline silicon (poly-Si), which is the basis for most modern thin-film photoelectric converters. At the same time, in Fig. 2-a the absorption spectrum of polycrystalline silicon correlates with the spectrum of solar radiation in the Earth's atmosphere at the sea level, and in Fig. 2-b absorption of air is not taken into account, therefore, this graph is relevant for the analysis of the solar cells use peculiarities on space objects and stratospheric aircrafts. In both cases, it can be seen that the polycrystalline silicon absorption peak corresponds to the region of infrared (IR) radiation, while the peak of solar radiation corresponds to the yellow-green part of the visible range and partially covers the near ultraviolet (UV) region.



(a) (b)

Fig. 3. Correlation of efficiency coefficient and losses for poly-Si structures.

It should be separately noted that high energy losses (Fig. 3) in this case will be related not only to the width of the spectral region that is not absorbed by the photocell, but also to the fact that the reflected part of the solar radiation is a high-energy component. The exact definition of energy losses associated specifically with the inconsistency of the spectra of solar radiation and the absorption of the photoelectric converter is possible through the integral analysis of spectra by numerical methods. Its results are presented in Fig. 3 (Fig. 3-a in the presence of the Earth's atmosphere and Fig. 3-b in the open space conditions), the largest losses correspond to the high-energy part of the solar radiation spectrum.

3. Application of a luminescent coating on a solar cell

In order to solve the stated problem, it was proposed to use an auxiliary luminescent layer on the surface of a solar cell, which has to be transparent for wavelengths corresponding to the absorption spectrum of the photoelectric converter, but at the same time to absorb the light outside this range, changing its wavelength thus to increase the efficiency of a solar cell [14, 15].

Thus, for example, if for most thin-film solar cells, in particular polycrystalline silicon cells, the absorption spectrum lies in the IR region and in the long-wavelength of the visible spectrum, while the maximum intensity of the solar radiation falls at shorter wavelengths, and a large part of it lies in the near UV range region, then in the proposed design a thin film of Stokes luminophor absorbs in the UV and the short-wave part of the spectrum, but at the same time it luminesces and allows passage in the range of IR and long-wavelength part of the visible spectrum.

The problem that needs to be addressed in applying this approach is the amorphism of luminescent radiation, which means that half of the luminescent radiation will be lost on account of a planar structure of a solar cell.

In addition, it should be borne in mind that transfer of the spectrum of radiation by a luminophore is not ideally effected: the part of λ^+ region of the spectrum is also absorbed, luminophor has the quantum luminescence output and the absorption coefficient, which depends on λ and is less than 100% (Fig. 4).

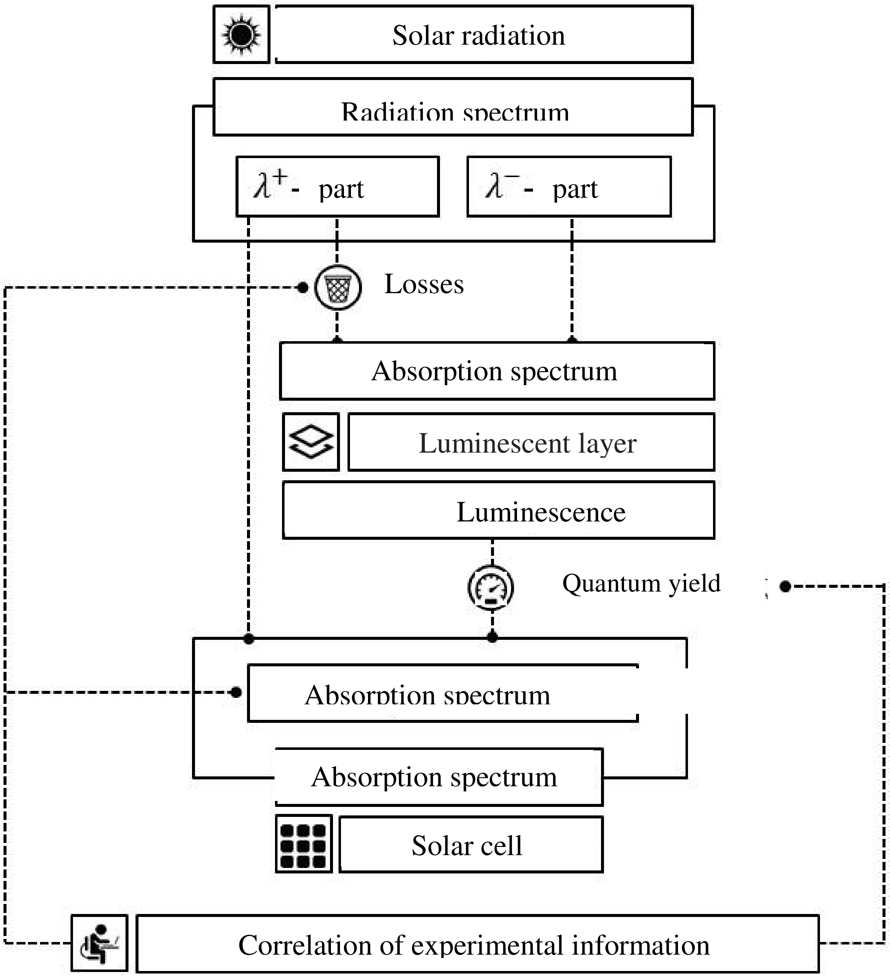


Fig. 4. Operational scheme of a solar element with a luminophor layer.

As a result, the efficiency coefficient increase for a solar cell with luminophor will be 0.1-1%, which does not justify the cost of applying an additional layer.

4. Development of a relief solar luminescent element

One of the basic approaches that can be used in solving the low efficiency problem of a luminescent coating of a solar cell is the creation of a relief or microrelief structure of a photoelectric converter [14, 15], the variant of which is presented in Fig. 5.

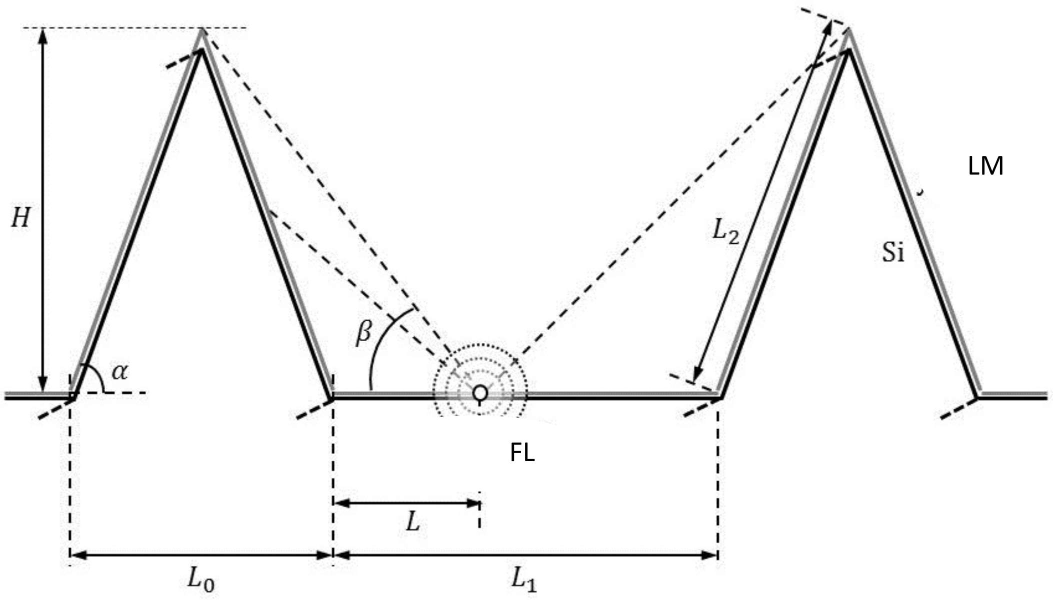


Fig. 5. Relief surface of a photocell with luminescent coating.

A mathematical model that allows determining the optimal parameters of such a structure (ratio of L_1, L_2, α values) is based on the equation for the average energy value:

$$\left[\begin{array}{l} \overline{\Delta E} = \dfrac{\int_{\lambda^-}^{\lambda^+}\left(\int_0^{L_1}\Delta E_1\left(I_L(\lambda), k_A(\alpha, \lambda)\right) + \int_0^{L_2}\Delta E_2\left(I_L(\lambda), k_A(\alpha, \lambda)\right)\right)}{2} \\ I_L(\lambda) = I_0(\lambda)\cdot k_Q(\lambda)\cdot k_{LA}(\lambda) \end{array}\right. ,$$

ΔE is obtained from one element of the structure which is obtained as the average of the sum of the integral values of the L_1 and L_2 elements energies and the length of the element and the wavelength (from λ^- to λ^+ as minimum and maximum values, respectively). Here, $k_A(\alpha,\lambda)$ is the coefficient of absorption of polycrystalline silicon, depending on the wavelength and the incident angle of the beam, $I_L(\lambda)$ is the intensity of the luminescent radiation, which includes the intensity of the solar radiation $I_0(\lambda)$, the quantum yield coefficient $k_Q(\lambda)$ and the luminophore absorption coefficient $k_{LA}(\lambda)$.

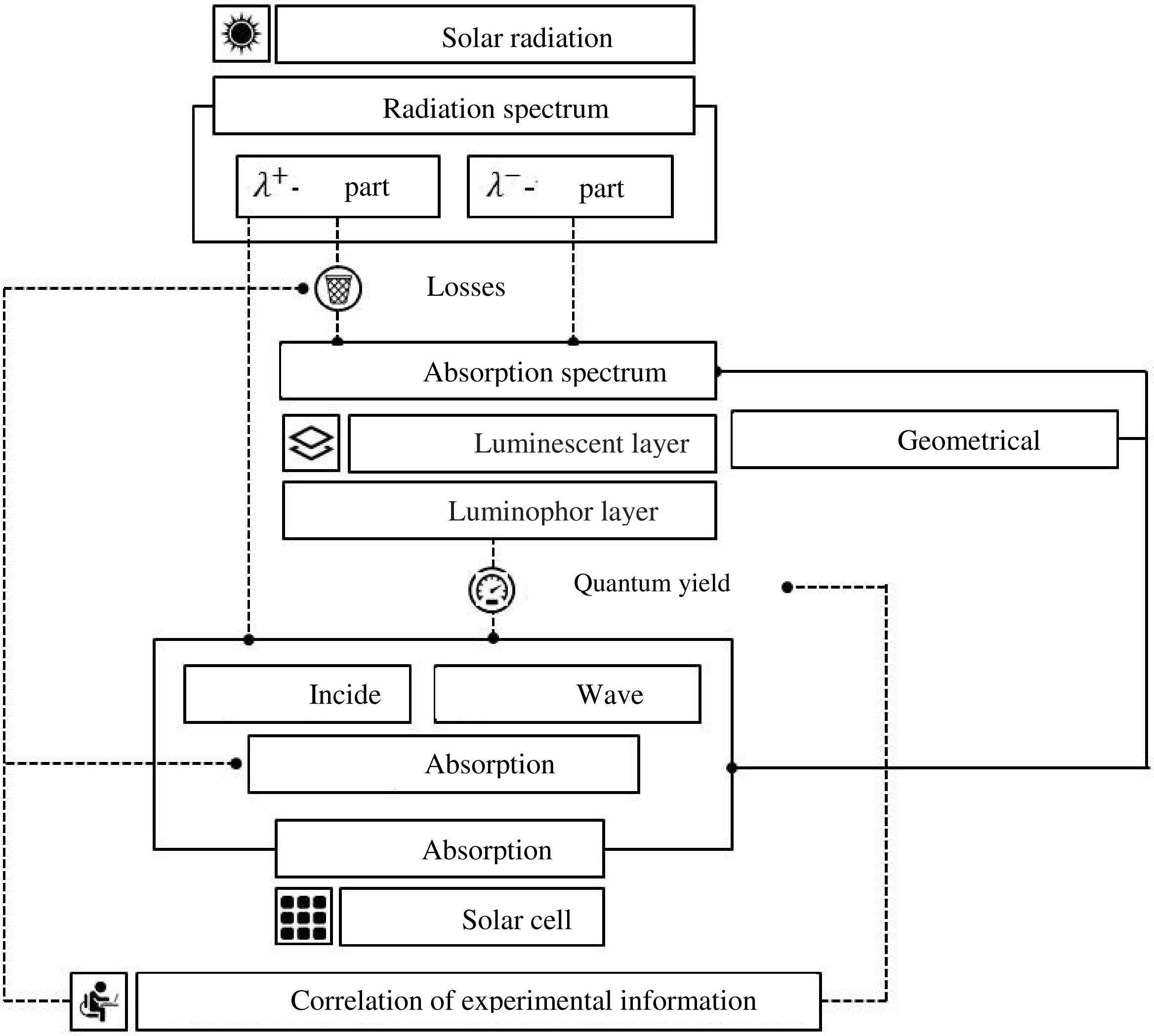


Fig. 6. Operational scheme of a relief luminescent solar cell.

The model object for calculations was nanostructured pyrazoline luminophores, which were synthesized for use in optical recording systems. This class of luminescent dyes of the visible range is characterized by a high level of quantum yield of luminescence $\mathrm{k_Q} = 75 - 80\%$ and a significant width of a Stokes shift ($\Delta\lambda_S = 150 - 250$ nm), which allows the solar luminescence of the UV spectrum and the short-wave portion of the visible range to be transmitted to the long-wavelength of the visible range. The introduction of pyrazoline phosphors into the zeolite matrix for the purpose of breaking the monolithic dye into nano-sized particles led to the fact that some of the forbidden electronic transitions in its structure became partially resolved. Said that, the experiment showed an increase in the level of the main luminescence peak which increased after additional laser annealing in the infrared range, which, according to theoretical considerations, confirmed by subsequent experiments, contributed to the penetration of the luminophor in smaller pores of zeolite (Table 1).

Table 1

Optical parameters of nanostructured luminescent coating

Luminophor	Stokes shift	Luminescence peak increase	
		before annealing	after annealing
59M	245 nm	27%	61%
59HM	250 nm	19%	43%
59HC	210 nm	28%	47%
53SC	170 nm	45%	63%

Table 2

Optimal parameters of the relief structure of a solar cell

Luminophor	L_2/L_1	α	$\overline{\Delta E}/E_{\Sigma}$
59M	0,67	40°	4,7 %
59HM	1,11	45°	5,6 %
59HC	0,53	32°	3,6%
53SC	0,63	35°	3,8%

Table 2 shows the results of computer simulation that was conducted to determine the optimal parameters of the structure of the solar cell. As can be seen from Table 2 the optimal architecture of a solar element with a luminescent coating requires the creation of relief structures with a significant angle of inclination. With a significant period of use, such structures are largely contaminated, which offset the benefits of increasing the efficiency. Thus, the necessary stage of development of this class of solar panels is the construction of automatic cleaning systems.

5. Cleaning system for relief elements of solar panels

The basic model of the cleaning complex for relief elements of solar panels is presented in Fig. 7

It includes a correction system at the level of acidity and alkalinity of deionized water, which serves to clear optical surfaces [16, 17] and consists of the following functional nodes:

- power source for an electrochemical reactor (1);
- deionized water reservoir for further feeding to an electrochemical reactor (2);
- electrochemical reactor with interelectrode space (3);
- collector of water with a reduced level of acidity (4);
- collector of water with an increased level of alkalinity (5);
- sensory module for measuring a reduced level of acidity (6);
- sensory module for measuring an increased level of alkalinity (7);
- collector of water with a reduced level of acidity (8)
- collector of water with an increased level of alkalinity (9);
- pulse generator for sensor (10).

The liquid for cleaning optical surfaces should be an insulator to exclude local current pulses. The advanced model also includes an input pipeline to the electrochemical reactor and devices for controlling the flow rate of the liquid.

A basic prototype was created to test the feasibility of this scheme, including an electrochemical reactor in which electrode cores have working zones separated by a neutral membrane located symmetrically between two electrodes.

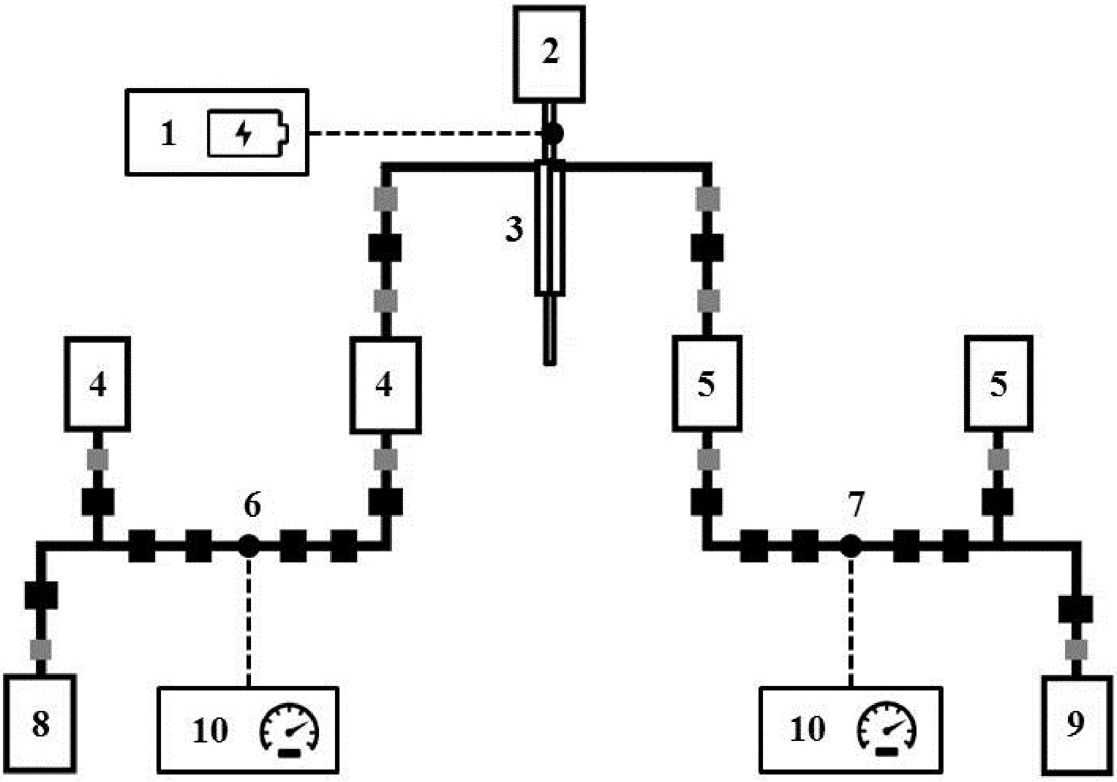


Fig. 7. Model of the cleaning system for relief solar cells.

One of the important principles of efficiency in electrode cores is the treatment of deionized water in the outflow. In this case, the distance between the working surfaces of the electrodes was about 3 mm, and the thickness of the membrane and the width of the fluid flow was 1 mm. This allowed to raise the current density to 100 A/cm2 and, accordingly, helped to make electrochemical correction of acidity and alkalinity of water in accordance with the parameters of the dielectric. It should be noted that the liquid at the output of the system is divided into two streams, therefore, for the processing of solar cells, it is possible to apply water both with a high alkaline effect and water with a high acidic effect. Furthermore, the preparation and water treatment stage is technologically simple, there are typical structural materials and components used in the system, so it can be installed in a small utility room or laboratory. In an electrochemical reactor, the system of directing the current to the cathode and anode of the electrode core is from a single source, thus, under the conditions of the same active surface of the electrodes, a phenomenon of proportional correction of the liquid parameters in two directions occurs (both in terms of acidity and alkalinity).

Conclusions

The analysis showed that the main factor of the low efficiency of converting solar energy into electric energy for single-film photoelectric converters is the discrepancy of absorption spectra of a solar cell and solar radiation. Methods of applying a luminescent coating to a solar cell was considered, characterized by a Stokes shift and allowing transfer of the solar radiation spectrum to the absorption region of the photoelectric converter. Herewith, it was indicated on the possibility of increasing the effectiveness of this approach in the construction of relief structures on the basis of solar elements. As a result of the work, optimal parameters of the architecture of a relief luminescent solar cell for the photoconductor based on polycrystalline silicon are calculated. The technology of cleaning these structures based on a system of applying deionized water with a controlled level of acidity and alkalinity is proposed.

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