

Для задоволення потреби у альтернативній системі електрозабезпечення під час ліквідації та попередження надзвичайної ситуації в умовах пошкодження системи електропостачання досліджено плівкові сонячні елементи. З урахуванням високої деградаційної стійкості телуриду кадмію для дослідження було обрано двосторонньо чутливі сонячні елементи на основі CdS/CdTe з надтонким базовим шаром придатні для формування тандемних структур. Створення тандемних структур дозволяє збільшити коефіцієнт корисної дії за рахунок розміщення на фронтальній поверхні іншого фотоперетворювача. Проведено вимірювання світлових вольт-амперних характеристик сонячних елементів ITO/CdS/CdTe/Cu/ITO з товщиною базового шару 1 мкм, при одночасному освітленні з тильної та фронтальної сторін. Експериментально показано, що двостороннє освітлення дозволяє підвищити електричну потужність, що виробляєть-ся приладовою структурою, на 30 %.

Дослідження спектральних залежностей коефіцієнту пропускання показали, що приладові структури ITO/CdS/CdTe/Cu/ITO з товщиною базового шару 1 мкм в спектральному діапазоні (0,82–1,10) мкм мають середній коефіцієнт пропускання 0,58. Дослідження світлових вольт-амперних характеристик сонячних елементів Mo/CuInSe<sup>2</sup>/CdS/ZnO/ZnO:Al/Ni:Al/Ni показали, що розміщення на його фронтальній поверхні сонячного елемента ITO/CdS/CdTe/Cu/ITO призводить до зниження коефіцієнту корисної дії з 11,2 % до 6,0 %. Таке зниження, в першу чергу, обумовлене зменшенням густини струму короткого замикання з 25,9 мА/см<sup>2</sup> до 13,8 мА/см<sup>2</sup>. Однак, оскільки коефіцієнт корисної дії сонячного елемента ITO/CdS/CdTe/Cu/ITO становить 7,8 %, то апробовані тандемні фотоелектричні перетворювачі ITO/CdS/CdTe/Cu/ITO – Mo/CuInSe<sup>2</sup>/CdS/ZnO/ZnO:Al/Ni продемонстрували ефективність 13,8 %

**Ключові слова:** телурід кадмію, фотоелектричні перетворювачі, тандемні та двосторонньо чутливі приладові структури

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# INVESTIGATING AN ALTERNATIVE ELECTRICITY SUPPLY SYSTEM FOR PREVENTING EMERGENCIES UNDER CONDITIONS OF LIMITED CAPACITY

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## 1. Introduction

A side result of active scientific and technological progress has become the growth of emergencies due to accidents

and catastrophes of various nature including those of medical and biological character (COVID 19). Their complexity and complicated socio-economic implications actualize the issue of readiness of governance bodies, as well as their capa-

bilities, to prevent and eliminate them. In addition, in case the electricity supply is disrupted, each means of counteracting the emergency should be equipped with a rechargeable battery, which can renew its charge even in the absence of a conventional power supply. It is for such purposes that it is advisable to use non-traditional power sources, namely solar cells. However, a significant precondition for their use for this purpose is the low weight of instrument structures, which are highly effective and degradation resistant. Given this issue, it becomes necessary to focus on analyzing the prospects of using tandem and double-sided sensitive solar cells as an alternative power supply system to prevent emergencies in case conventional electrical systems are damaged. Considering the above, it is a relevant task to study the CdS/CdTe-based double-sided sensitive solar cells, as well as to use such instrument structures as part of tandem photovoltaic converters.

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## 2. Literature review and problem statement

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The solar cells considered in this work are the cadmium telluride-based film solar cells that show prospects for further research [1, 2]. Papers [3, 4] report the results of studying the initial parameters and the diode characteristics of such instrument structures. It is shown that such solar cells have not yet reached their theoretical maximum but they demonstrate high values of degradation stability [5]. The authors of works [5, 6] suggest the production of solar cells based on CdS/CdTe using the electrochemical method. However, the application of this method also did not make it possible to improve the effectiveness of such instrument structures. The authors of [7] reported a study into the degradation stability and showed that such solar cells are adapted exactly for the solar insolation observed in Ukraine. However, the theoretical maximum efficiency could also not be achieved. One way to increase the effectiveness of SC is to build tandem (cascading) structures, an example of which is described in [8], as well as double-sided structures in which two or more base layers of different  $E_g$  (the width of the forbidden zone) are used, but such instrument structures were not investigated when using cadmium telluride. Such an approach makes it possible to effectively convert incident solar radiation over a wide spectral range. Paper [9] proposed, with respect to the size of the forbidden zone, building the tandem structures by using the film solar cells based on CdTe and CuInSe<sub>2</sub> since it is known that  $E_g$  for CdTe is 1.46 eV [4] and  $E_g$  for CuInSe<sub>2</sub> – 1.10 eV [8]. However, the cited works did not perform experimental studies of such tandem structures. Up to now, the construction of tandem and double-sided sensitive instrument structures with a base layer of CdTe was prevented by the lack of effective transparent rear contacts and the inappropriate thickness of the base layer of a solar cell based on CdTe. The issue of building transparent rear contacts for p- CdTe was considered in [10] and was resolved and described in detail in [11, 12], but the tandem structures were also not investigated in the cited works. The authors of [13] reported research aimed at reducing the thickness of the base layer to 1  $\mu\text{m}$ . As shown in paper [13], the ITO/CdS/CdTe/Cu/ITO solar cells with a base layer thickness of 1  $\mu\text{m}$  demonstrate high degradation stability. In addition, the authors of the paper indicated that the

reduction of the base layer thickness makes it possible to consider the investigated solar cells as part of tandem instrument structures and as the double-sided sensitive solar elements. However, no such studies have been conducted yet. However, no such studies have been revealed until now.

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## 3. The aim and objectives of the study

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The aim of this study work is to build and investigate SC with a thin base layer made from CdTe under double-sided irradiation and as part of tandem photovoltaic converters. This would make it possible to increase the efficiency of the instrument structure through the more effective absorption of incident radiation.

To accomplish the aim, the following tasks have been set:

- to investigate the efficiency and output parameters of ITO/CdS/CdTe/Cu/ITO SC under double-sided irradiation;
- to investigate the spectral dependences of the collection factor of ITO/CdS/CdTe/Cu/ITO SC at different shifting voltages;
- to investigate the efficiency and output parameters of ITO/CdS/CdTe/Cu/ITO SC within the tandem photo converters.

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## 4. Materials for building, and methods for studying, the ITO/CdS/CdTe/Cu/ITO film solar cells

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For the present research, we fabricated a series of SC using the method of thermal evaporation applying the vacuum installation UVN67 with modified internal equipment. The design of the installations is given in [12]. In order to form a high-quality rear contact, the samples of ITO/CdS/CdTe were subjected to “chloride” treatment [14]. The procedure of the “chloride” treatment was carried out according to the procedure described in detail in work [13]. After the “chloride” treatment, the samples were exposed to annealing in the air in a closed volume. The air annealing was carried out at a temperature of 430 °C for 25 minutes. We applied the ITO films (oxides of indium and tin) by the method of non-reactive magnetron spraying at the direct current in the vacuum installation VUP-5M, using the original material-saving magnetron [14]. The length of a discharge gap, which is the distance between the magnetron and the substrate, was 70 mm. The power consumption of the magnetron was 0.2 W/cm<sup>2</sup>. The substrate temperature ( $T_s$ ) was 300 °C. The initial pressure in the vacuum chamber was  $3 \times 10^{-5}$  mm Hg, the operating pressure of the argon-air mixture in the process of spraying –  $(2.1\text{--}2.6) \times 10^{-2}$  mm Hg. For pressing the targets of ITO, containing 95 % by weight of indium oxide and 5 % by weight of tin oxide, a special press was made. It should be noted that magnetron spraying is an effective method of obtaining all transparent electrodes [15, 16]. This is due to the high degree of accuracy of transferring the target’s composition to the substrate, the reproducibility and manageability of the magnetron spraying process [17]. The procedure of analytical processing of light volt-ampere characteristics is described in detail in work [13]. The irradiation, which was used in studying the film solar cells both from the frontal and rear sides, is 1,000 W/m<sup>2</sup>.

**5. Results of studying the experimental samples of ITO/CdS/CdTe/Cu/ITO**

**5.1. Results of studying the output parameters of the ITO/CdS/CdTe/Cu/ITO SC under double-sided irradiation**

In order to quantify the impact of double-sided irradiation on the efficiency of electric energy generation, the comparative studies of CdS/CdTe/Cu/ITO were carried out under irradiation from the rear and front sides and at simultaneous irradiation (Fig. 1).

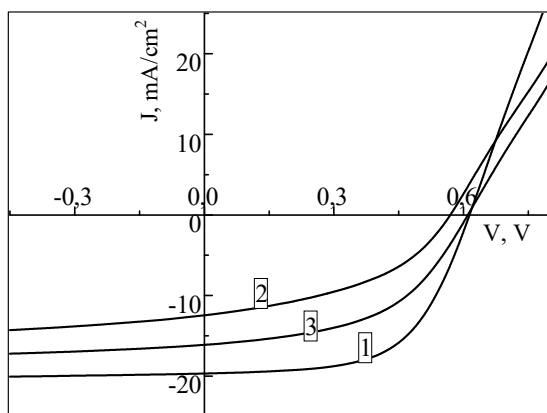


Fig. 1. Light current-voltage characteristic of CdS/CdTe/Cu/ITO current-voltage characteristic: 1 – under irradiation on the rear side; 2 – under irradiation on the frontal side; 3 – under simultaneous irradiation on the rear and frontal sides

The analytical processing of the light current-voltage characteristic of the examined samples produced the output parameters under different irradiation variants, which are given in Table 1.

Table 1  
Output parameters of ITO/CdS/CdTe/Cu/ITO SC under different irradiation variants

| SC output parameters             | Direction of irradiation |                  |                              |
|----------------------------------|--------------------------|------------------|------------------------------|
|                                  | on the frontal side      | on the rear side | simultaneously on both sides |
| $J_{sc}$ , (mA/cm <sup>2</sup> ) | 19.6                     | 12.5             | 32.4                         |
| $V_{oc}$ , (mV)                  | 620                      | 570              | 610                          |
| FF, rel. units                   | 0.59                     | 0.44             | 0.50                         |
| $\eta$ , %                       | 7.17                     | 3.13             | 9.88                         |

Note: \* – output parameters of the theoretical light current-voltage characteristic, obtained by adding two experimental light current-voltage characteristic at the rear side illumination

As seen in Table 1, at the irradiation on the rear side, there is a significant decrease in the magnitudes  $J_{sc}$  and  $V_{oc}$ , which is accompanied by a significant decrease in efficiency. However, simultaneous irradiation on both sides demonstrates high results of the output parameters.

**5.2. Results of studying the spectral dependences of the collection factor of the ITO/CdS/CdTe/Cu/ITO SC at different shifting voltages**

In order to analyze the possibility of using the designed SC based on ITO/CdS/CdTe/Cu/ITO in tandem instru-

ment structures, we studied the spectral dependences of the collection factor at various shifting voltages and different directions of irradiation. Based on the acquired spectral dependences, we analyzed the influence of the region of the spatial discharge of a rear contact on the efficiency of photovoltaic processes in the basic layer of SC based on ITO/CdS/CdTe/Cu/ITO (Fig. 2).

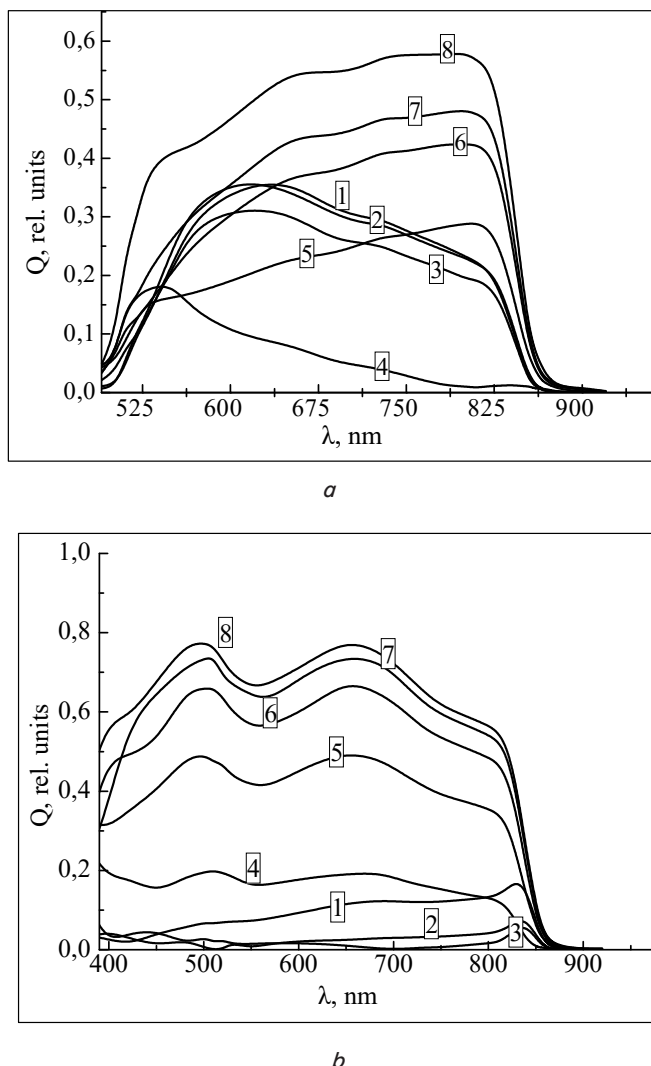


Fig. 2. Spectral dependences of collection factor of the CdS/CdTe/Cu/ITO SC with a thickness of the base layer of 1 μm at various shifting voltages (1 – 0 V, 2 – 0.5 V, 3 – 0.6 V, 4 – 0.7 V, 5 – 0.8 V, 6 – 0.9 V, 7 – CE 1.1 V, 8 – 1.2 V): a – under irradiation on the frontal side; b – under irradiation on the rear side

To quantify the contribution of incomplete absorption to the reduction of the photocurrent density, we investigated the light current-voltage characteristic of CdS/CdTe/Cu/ITO with a thickness of the base layer of 1 μm when illuminated on the rear side (Fig. 3).

The output parameters of SC from the analytical treatment of light current-voltage characteristic are given in Table 2.

In carrying out such studies, we placed on the frontal side, under the irradiation on the rear side, a mirror, which allowed the radiation passed through the SC to be directed again to the base layer from the frontal side. Thus, we have experimentally analyzed the loss of electrical power, gener-

ated by SC, due to the incomplete absorption of light when illuminated from the rear side.

Table 2

The output parameters of CdS/CdTe/Cu/ITO SC with a thickness of the base layer of 1 μm under different irradiation variants

| SC output parameters             | Direction of irradiation |              |         |
|----------------------------------|--------------------------|--------------|---------|
|                                  | rear                     | rear-frontal | frontal |
| $J_{sc}$ , (mA/cm <sup>2</sup> ) | 12.5                     | 14.1         | 19.7    |
| $V_{oc}$ , (mV)                  | 570                      | 571          | 666     |
| FF, rel. units                   | 0.44                     | 0.43         | 0.60    |
| $\eta$ , %                       | 3.1                      | 3.4          | 7.8     |

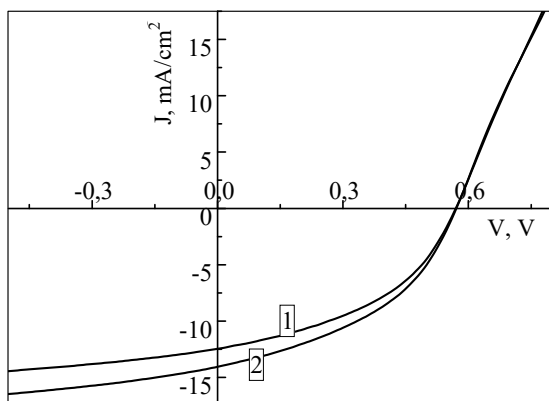


Fig. 3. Light current-voltage characteristic of CdS/CdTe/Cu/ITO SC: 1 – irradiation on the rear side, 2 – rear-frontal irradiation

5.3. Results of studying the output parameters of ITO/CdS/CdTe/Cu/ITO SC as part of tandem SC

We have verified the designed ITO/CdS/CdTe/Cu/ITO SC as part of the tandem SC with a narrow band layer based on copper diselenide and indium. Such solar cells were produced at the Swiss Institute of Technology. The Mo/CuInSe<sub>2</sub>/CdS/ZnO/ZnO:Al/Ni:Al/Ni SC were made on glass substrates and had a frontal configuration. The lighting of such instrument structures is enabled on the side of a ridge Ni contact. The light current-voltage characteristic of such instrument structures were studied when the illuminated surface hosted an ITO/CdS/CdTe/Cu/ITO SC with a base layer thickness of 1 μm and the efficiency 7.8 % (Fig. 4).

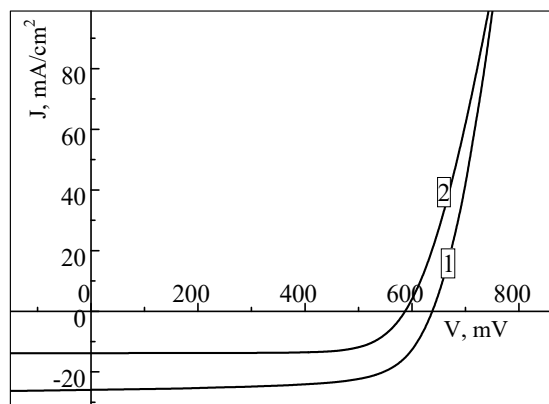


Fig. 4. Light current-voltage characteristic of Mo/CuInSe<sub>2</sub>/CdS/ZnO/ZnO:Al/Ni:Al/Ni SC: – (1) and when ITO/CdS/CdTe/Cu/ITO is placed at its frontal surface – (2)

The output parameters of the characteristic samples of Mo/CuInSe<sub>2</sub>/CdS/ZnO/ZnO:Al/Ni:Al/Ni SC and a tandem ITO/CdS/CdTe/Cu/ITO – Mo/CuInSe<sub>2</sub>/CdS/ZnO/ZnO:Al/Ni:Al/Ni photoelectric converter are given in Table 3.

Table 3

Output parameters of solar cells in a tandem structure

| SC parameters                    | CuInSe <sub>2</sub> | CuInSe <sub>2</sub> /CdTe | CdTe |
|----------------------------------|---------------------|---------------------------|------|
| $J_{sc}$ , (mA/cm <sup>2</sup> ) | 25.9                | 13.8                      | 19.7 |
| $V_{oc}$ , (mV)                  | 634                 | 590                       | 666  |
| FF, rel. units                   | 0.68                | 0.74                      | 0.60 |
| $\eta$ , %                       | 11.2                | 6.0                       | 7.8  |

As shown by Table 3, placing the ITO/CdS/CdTe/Cu/ITO solar cell at the surface of Mo/CuInSe<sub>2</sub>/CdS/ZnO/ZnO:Al/Ni:Al/Ni results in a significant decrease in the effectiveness of the latter.

6. Discussion of results of studying the ITO/CdS/CdTe/Cu/ITO SC under double-sided irradiation and as part of a tandem photoelectric converter

The parameters and the efficiency of the instrument structure ITO/CdS/CdTe/Cu/ITO SC were analyzed, which were obtained from the analytical processing of light current-voltage characteristic. It was determined that the resultant light current-voltage characteristic of the SC when illuminating on both sides is not the sum of light current-voltage characteristic when illuminated from the rear and front sides (Fig. 1).

However, double-sided illumination makes it possible to improve the efficiency of the instrument structure by 43 % (Table 1) This reduces the area of the corresponding single-sided SC and that, in turn, makes it possible to expand the scope of their application in case of emergency prevention in the event of a limited deployment area.

The spectral dependences of the collection factor of the ITO/CdS/CdTe/Cu/ITO SC under different shifting voltages were analyzed. It was determined that in the absence of a shifting voltage a maximum on spectral dependence is observed at the wavelength 0.65 μm, then there is a decline of photoresponse so that the area under the spectral dependence decreased by 20 %.

Since the area under the spectral dependence of the coefficient of quantum efficiency is proportional to the short-circuit current density, the efficiency of the instrument structure also decreased by 20 relative %. Such a significant decrease in the effectiveness of photovoltaic processes can probably be due to either the adverse effect of the surface recombination on the rear contact or the incomplete absorption in the base layer because of the small thickness of the base layer.

An analysis of Table 2 reveals that if the radiation that has passed through the SC when illuminated on the rear side is directed to the frontal surface, it leads to an increase in electric power by 0.3 mW/cm<sup>2</sup>. The increase in efficiency is due to the increased short-circuit current density on 1.6 mA/cm<sup>2</sup> at constant values for the idling voltage and the fill factor of light current-voltage characteristic. As regards the short-circuit current density in the radiation on the frontal side, an increase in the original parameter is 8 %.



Thus, we have experimentally demonstrated that in reducing the efficiency of photovoltaic processes the contribution of incomplete absorption of light in the base layer in the region of its photosensitivity almost coincides with the negative contribution of the rear contact.

In the case of direct shift, the area of the spatial charge of the main separating barrier where the electric field exists that accelerates the electron motion is decreased. This leads to a decrease in the efficiency of harvesting the non-equilibrium charge carriers, generated under the influence of light, due to the reduction of the semiconductor region where their drift in the electric field occurs. The increase in effectiveness is seen experimentally in the analysis of spectral dependences. With the increase in voltage, there is a decrease in  $Q(\lambda)$  over the entire spectral range of photosensitivity. Thus, the greatest decrease is observed for the non-equilibrium charge carriers generated under the influence of photons from the long-wave part of the spectrum. The depth of light absorption increases with the growth of wavelength, which leads to distancing the active generation region from the separating barrier area. There is also an increase in the negative impact exerted on the collection factor by the volumetric recombination in the diffusion of charge carriers from the field of generation to the separating area.

At a voltage of 0.7 V, corresponding to the idling voltage, the photosensitivity becomes zero as the external electric field becomes equal to the internal field of the separation barrier. Since these electric fields have the opposite content, the process of separation of non-equilibrium carriers stops. With further growth of the displacement voltage, the voltage drop is carried out on the rear diode enabled in the opposite direction. Therefore, the non-equilibrium charge carriers are separated by the rear diode. The result is a change in the shape of the spectral dependence of photoresponse. The greatest contribution to the creation of photoresponse is provided by the non-equilibrium charge carriers generated under the action of photons from the long-wave part of the spectrum, as the region of their generation is located near the separation area. When illuminated on the rear side (Fig. 2, *b*), a maximum on the spectral dependence is observed at absorbing the photons from the long-wave region of the spectrum, which testifies to the high surface recombination on the rear contact. Indeed, the non-equilibrium charge carriers when illuminated from the rear side are generated near the rear surface. If this surface is characterized by the high-speed surface recombination, the contribution of charge carriers, generated near the rear surface, to the photoresponse is minimized, which is experimentally observed.

With the growth of the shifting voltage, the energy structure of the rear contact is being optimized and there is a growth of the depletion region, which causes an increase in the photoresponse over the entire spectral range of photosensitivity.

An analysis of the output parameters of the tandem structure ITO/CdS/CdTe/Cu/ITO – Mo/CuInSe<sup>2</sup>/CdS/ZnO/ZnO:Al/Ni : Al/Ni shows that the absorption of part of the incident radiation in the ITO/CdS/CdTe/Cu/ITO SC results in the decreased efficiency of the Mo/CuInSe<sup>2</sup>/CdS/ZnO/ZnO:Al/Ni : Al/Ni SC, from 11.2 % to 6.0 %. Such a reduction of efficiency occurs due to the reduction of short-circuit current density, from 25.9 mA/cm<sup>2</sup> to 13.8 mA/cm<sup>2</sup>.

At the same time, the idling voltage is reduced slightly while the fill factor of the light current-voltage characteristic increases. The obtained results agree well with the spectral dependence of the transmittance of ITO/CdS/CdTe/Cu/ITO SC, shown in Fig. 2, since the short-circuit current density linearly depends on the intensity of the incident radiation while the idling voltage depends on it logarithmically.

It should be noted that despite the substantial reduction in the effectiveness of the Mo/CuInSe<sup>2</sup>/CdS/ZnO/ZnO:Al/Ni : Al/Ni SC at its darkening by the ITO/CdS/CdTe/Cu/ITO SC, the efficiency of the tandem structure significantly higher than those of such SC separately, and is 13.8 %.

Thus, by building a tandem structure it was possible to increase the efficiency of the instrument structure to 13.8 %. Studies in the future may address the development of structural and technological solutions to further improve efficiency.

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## 5. Conclusions

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1. We have investigated the ITO/CdS/CdTe/Cu/ITO SC with a thickness of the base layer of 1 μm at different irradiation variants. It has been established that the double-sided illumination makes it possible to increase the efficiency of the instrument structure by 43 %.

2. Studying the loss of electrical power, generated by the ITO/CdS/CdTe/Cu/ITO SC, due to the incomplete absorption of light when illuminated from the rear side, showed a decrease in efficiency when changing the direction of irradiation, from 7.8 % to 3.1 %.

3. The construction of the ITO/CdS/CdTe/Cu/ITO – Mo/CuInSe<sup>2</sup>/CdS/ZnO/ZnO:Al/Ni : Al/Ni tandem structure has made it possible to obtain an instrument structure with the efficiency of 13.8 %.

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