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INCREASING THE EFFICIENCY OF FILM SOLAR CELLS BASED ON CADMIUM TELLURIDE

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Виконано аналіз втрат в вихідних параметрах сонячних елементів на основі телуриду кадмію, які зумовлені особливостями конструкції приладової структури і фотоелектричними процесами, які відбуваються в її об'ємі при поглинанні світла. Досліджено реалізовані підходи до підвищення коефіцієнта корисної дії фотоелемента на основі CdS/CdTe і їх результативність. Запропоновано шляхи підвищення ефективності таких плівкових сонячних елементів при удосконаленні способу отримання тильного контакту

Ключові слова: плівковий сонячний елемент, гетероструктура, телурид кадмію, вихідні параметри, тильний контакт

Выполнен анализ потерь в выходных параметрах солнечных элементов на основе теллурида кадмия, которые обусловлены особенностями конструкции приборной структуры и фотоэлектрическими процессами, происходящими в ее объеме при поглощении света. Исследованы реализованные подходы к повышению коэффициента полезного действия фотоэлемента на основе CdS/CdTe и их результативность. Предложены пути повышения эффективности таких пленочных солнечных элементов при усовершенствовании способа получения тыльного контакта

Ключевые слова: пленочный солнечный элемент, гетероструктура, теллурид кадмия, выходные параметры, тыльный контакт

1. Introduction

Solvinga complex set of energy-ecological problems in Ukraine is impossible without a large-scale use of alternative energy sources. Solar power engineering according to many predictions is one of the most promising sectors of renewable power engineering.

The lowest cost of the generated electrical energy is demonstrated by film solar cells (further denoted SC) based on cadmium sulfide and telluride. In addition, SC based on cadmium sulfide and telluride possess high degradation durability, which enlarges the scope of their application.

Thus, the film SC based on CdS/CdTe are an alternative to traditional solar cells based on Si and GaAs. However, their large-scale industrial production is held back by the low value of performance efficiency of experimental models. Low value of efficiency, despite high technological efficiency of contemporary vacuum methods of obtaining the films of cadmium sulfide and telluride, is caused to a considerable degree by the physical-technological problems of formation of low-ohmic back contacts to the base layers of p-CdTe. Thus, the relevance of conducting given research is predetermined by the need for further development of physical-technological base for obtaining electrical back contacts to film SC based on CdS/CdTe.

2. Literature review and problem statement

Solar cells based on crystalline silicon and thin films are the most widely used commercial technologies in the field of photovoltaic. However, a dominant position on the market is occupied by the solar cells based on crystalline silicon whose industrial output is 85 % of the world production volume of all photoelectric converters [1]. The main shortcoming of SC based on crystalline silicon is their high price as 50 % of the total cost is comprised of the silicon plate cost. In the course of fabrication of SC of this type, a high-quality raw material is used whose productionis energy-intensive at present. Furthermore, SC based on single-crystal and polycrystalline silicon are indirect-zonal conductors and, accordingly, have low absorption coefficient. That is why, for the effective use of solar radiation, thickness of the base layers must not be less than 200 µm [1]. In such instrument structures, a considerable decrease in efficiency is observed at the increase in temperature.

Solar cells based on CdTe are promising technologies under conditions of ground-based application [2]. The formation of such instrument structures is accomplished with lower energy costs of their production. In addition, technology of obtaining CdS/CdTe films is rapidly reproduced and makes it possible to form uniform thin films with area larger than 1 m^2, which have the highest theoretical performance efficiency coefficient among single-stage photoelectric converters – 29 % [3]. However, maximum experimental efficiency is 16,5 % and is registered for the SC based on heterosystem CdS/CdTe in the implementation of the back -barrier instrument structure [4], represented in Fig. 1.

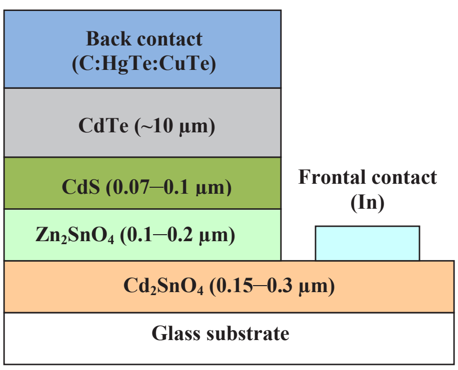


Fig. 1. Structure of back -barrier solar cell based on CdS/CdTe with performance efficiency=16,5 %

In order to achieve such high values of efficiency, the formation of SC represented in Fig. 1 was conducted on borosilicate glass [4], which is expensive in comparison with traditional SiO_2. The TCO ($In_2O_3SnO_2$) layer was replaced with the CTO (Cd_2SnO_4) layer [4], since conducting oxide Cd_2SnO_4 possesses better combination of optical and electrical properties and has higher transparency (higher than 90 %). The CdS thin films were deposited with the use of aqueous solution $Cd(C_2H_3O_2)_2$, $C_2H_3O_2NH_4$ $CS(NH_2)_2$ NH_4OH according to the technology described in [5]. Sedimentation of CdTe was performed by the method of sublimation in the closed volume. After putting on CdTe, the samples were exposed to the chloride treatment, which is a mandatory procedure at the formation of effective SC based on CdTe [6,7]. Without a chloride treatment, efficiency of SC based on CdTe is, as a rule, 5 %. It is accepted to assume that chloride treatment increases grain size of CdTe, it passivates their boundaries and contributes to effective adhesion between CdS and CdTe.

In order to use as a back contact, we put graphite paste HgTe:CuTe with the subsequent putting on silver paste and the antireflecting layer MgF_2.

However, despite the realized technologies, efficiency of the obtained samples is far from theoretical value. In connection with this, the formation of stable low ohmic back contacts is one additional major step in the fabrication of highly efficient SC based on CdTe/CdS [8].

A basic technological approach, which was realized by many authors, when creating the low ohmic contacts to SC based on CdS/CdTe is the formation of tunnel contacts [9–11]. The formation of ohmic contact to the base layers of p-CdTe under conditions of industrial production is not economical, since only platinum has the work of electrons output necessary for the formation of ohmic transition. That is why the tunnel contacts are traditionally formed to the layers of p-CdTe, using in this case thin films that contain copper or copper chalcogenide [9]. However, the diffusion of copper into the base layer leads to the degradation of the output parameters of film SC based on CdS/CdTe. Therefore, it is necessary to conduct comprehensive studies aimed at designing the backcontacts to the base layers of CdTe for the creation of highly effective, degradation resistant solar cells.

3. Goal and tasks of research

The purpose of this work is the development of physical-technological solutions for increasing efficiency of solar cells based on cadmium telluride.

To achieve the set goal, we formulated the following tasks:

– to analyze losses in the output parameters of the solar cells based on cadmium telluride, caused by the structural peculiarities of instrument structure and by the photoelectric processes that occur in it when illuminated;

– to analyze the realized approaches, aimed at increasing the efficiency of solar cell based on CdS/CdTe and their efficiency;

– to examine the effect of the physical-technological fundamentals of formation of the back contacts Cu/Au and the modes of operation of the solar cells ITO/CdS/CdTe/Cu/Au on their output parameters.

4. Results of research

4. 1. Analysis of losses in the output parameters of solar cells based on CdS/CdTe

A basic characteristic of any SC that is a semiconductor device for the conversion of solar energy into electrical is performance efficiency (η). Magnitude of η for any SC is calculated according to formula [10]:

$$\eta=(P_{nm}/P_i)\cdot 100\ \%=[P_{nm}/(P_i\cdot S_{sc})]\cdot 100\ \%, \qquad (1)$$

where P_{i^*} is the specific emission power at the photodetecting surface of SC; S_{sc} is the area of the SC photodetecting surface.

Power P_{nm} depends on three experimentally determined output parameters of SE by the following way:

$$P_{nm}=I_{sc}V_{oc}FF, \qquad (2)$$

where I_{sc} is the short-circuit current, V_{oc} is the open-circuit voltage, FF is the fill factor of the light BAX.

Therefore, for the calculation of efficiency of photoelectric converter, along with formula (1), the ratio is used:

$$\eta=[I_{sc}V_{oc}FF/(P_i*S_{sc})]\cdot 100\ \%. \quad (3)$$

As can be seen from expression (3), efficiency grows with an increase in each of three key output parameters of SC – I_{sc}, V_{oc} and FF, due to which it is necessary to analysis of losses of y these particular magnitudes.

The losses of short-circuit current (J_{sc}) in SE are caused by the following processes:

– reflection of solar radiation from the surface of instrument structure;

– absorption of solar radiation in the photoelectric-inactive layers;

– absorption of light in the area of contacts.

Short-circuit current density is determined by the following analytical expression:

$$J_{sc}=\int_{\lambda_{min}}^{\lambda_{max}} Q_E(\lambda)J_{solar}(\lambda)d\lambda, \quad (4)$$

where $Q_E(\lambda)$ is the coefficient of quantum efficiency, J_{solar} is the solar radiation intensity.

The losses that correspond to each of the processes described above can be calculated with the use of the following expression:

$$J_{loss}=\int_{\lambda_{min}}^{\lambda_{max}} F(\lambda)J_{solar}d\lambda, \quad (5)$$

where $F(\lambda)$ is the partial reflection or absorption for each wavelength.

The sum of losses and values of quantum efficiency (Q_E) must equal unity for all wavelengths.

Basic physical mechanisms that specify losses in the magnitude of open-circuit voltage are investigated insufficiently at present. It is assumed that V_{oc} is limited by the prevailing mechanism of the current flow. A current-voltage characteristic of typical solar element is described as follows [10]:

$$J\approx J_0\exp\left[\frac{q(V-V_{p-n})}{AkT}\right]-J_{ph}, \quad (6)$$

where J_{ph} is the density of photocurrent, J_0 is the density of diode current of saturation, V is the voltage drop on SC, V_{p-n} is the height of potential barrier, q is the electron charge, k is the Boltzmann constant, T is the temperature of solar element, A is the coefficient of ideality of diode.

Density of diode current of saturation (J_0) depends on particular acting mechanism that dominates at the passage of direct current. Let us assume that processes in the solar cells based on CdTe are mainly controlled by volumetric recombination and, therefore, J_0 can be expressed as:

$$J_0=qpv_r, \quad (7)$$

where p is the concentration of holes and v_r is the recombination velocity. Thus, V_{oc} can be represented in the form:

$$V_{oc}=V_{p-n}-\frac{AkT}{q}\ln\left(\frac{qpv_r}{J_{ph}}\right). \quad (8)$$

Expression, which connects the height of potential barrier and the width of the forbidden zone (E_g), takes the form:

$$V_{p-n}=\frac{E_g}{q}-\frac{kT}{q}\ln\left(\frac{N_v}{p}\right), \quad (9)$$

where N_v is the effective density of states in the valence band.

Thus, for A=2:

$$V_{oc}=\frac{E_g}{q}-\frac{kT}{q}\ln\left(\frac{q^2N_vpv_r^2}{J_{ph}^2}\right). \quad (10)$$

Independent of the components, V_{oc} decreases with an increase in the recombination velocity. Thus, a decrease in recombination must contribute to an increase in V_{oc}. The ratio of recombination velocity to thermal velocity is expressed as (v_r/v_h), where $v_h\approx10^7$cm/s and is used as a primary recombination parameter for the analysis of losses of voltage.

For the analysis of losses in the magnitude of fill factor of the light current-voltage characteristic (FF), an empirical expression is used that determines dependence of FF on the open-circuit voltage (V_{oc}) of coefficient of ideality of diode (A), series resistance (R_s) and shunt conductivity (G).

In the absence of series resistance and shunting conductivity, expression for FF can be represented as in [11]

$$FF_0=\frac{v_{oc}-\ln(v_{oc}+0.72)}{v_{oc}+1}, \quad (11)$$

where

$$v_{oc}=\frac{qV_{oc}}{AkT}. \quad (12)$$

In the presence of series resistance (R_s), expression for the fill factor of the light current-voltage characteristic (FF_s) is converted as follows

$$FF_s=FF_0(1-R_s/R_{ch}). \quad (13)$$

where $R_{ch}=V_{oc}/J_{sc}$ is the characteristic impedance.

When series resistance (R_s) and shunt conductivity (G) are essential, expression for the fill factor of the light current-voltage characteristic (FF_{s+sh}) takes the form:

$$FF_{s+sh}=FF_s\left[1-\frac{(v_{oc}+0.72)FF_s}{v_{oc}/(R_{ch}G)}\right]. \quad (14)$$

According to expression (14), it is absolutely obvious that the decrease of R_s and G will correspond to the increase in the value of FF_{s+sh}.

4. 2. Analysis of the realized approaches to the reduction of losses in the output parameters of solar element based on CdS/CdTe

For the reduction of solar radiation reflection from the surface of instrument structure, design of contemporary film SE based on CdS/CdTe usually includes the SnO_2 layers, which, at the surface resistance of the order of magnitude 10 Ohm/ð, have coefficient of transmission at the level of 80 %.

An alternative to the traditional SnO_2 layer is the application as the frontal transparent electrode of the conducting oxide Cd_2SnO_4, which possesses better combination of optical and electrical properties. The Cd_2SnO_4 layers have higher transparency (higher than 90 %), which is achieved through decreasing their thickness to 0,1 μm, since their surface resistance is about3 Ohm/ð, which is several times lower than that of the traditional electrodes SnO_2 [12–14]. Thus, the use ofCd_2SnO_4 contributes to the reduction in losses J_{sc} to the level 0,62 of mA/cm^2, as a result of absorption in the spectral range (300–800) nm, while for the traditional SnO_2 layers such losses compose (2,8–1,3) mA/cm^2 [15].

An essential negative effect on magnitude J_{sc} is also exerted by the recombination of non-equilibrium charge carriers, generated under the action of photons in the spectral interval (300–520) nm in the CdS layer. A decrease in the recombination level can be achieved by reducing the thickness of the CdS layer, however this leads to the reduction of values V_{oc} and FF. Paper [16] proposed to use a buffer layer of ZTO that ensures interdiffusion with the CdS layer in the process of formation the structure. With the interdiffusion that proceeds at temperature of annealing 600 °C in the Ar of He presence, a penetration of approximately 3–5 % of Cd into the ZTO layer is observed and approximately 2–3 % of Zn into the CdS layer. Diffusion at a lower temperature of annealing 420 °C during 15 minutes in the presence of $CdCl_2$ also indicates a significant amount of distributed Cd and Zn in the ZTO and CdS layer, respectively.

Thus, consumption of the CdS layer in the process of interdiffusion contributes to:

– reduction in the absorption of photons with the energy that exceeds the width of the forbidden band CdS;

– growth in the quantum efficiency >75 % for the photons with the wavelength larger than 400 nm;

– decrease of losses J_{sc} by 1,0–1,3 mA/cm^2.

In this case, values of V_{oc} and FF remain constant.

At present, a required technological operation when fabricating highly effective film solar cells based on CdS/CdTe is the "chloride" thermal treatment [17]. The processes that occur as a result of interphase interaction of $CdTe$-$CdCl_2$ predetermine growth in the size of grains of cadmium telluride and cadmium sulfide, as well as an increase in the life cycle of non-equilibrium charge carriers [18]. However, the stresses on the boundary of division of TCO/CdS that appear as a result of grain growth can substantially deteriorate the adhesion of these layers and contribute to the formation of "bulges". The use of the ZTO (Zn_2SnO_4) buffer layer decreases the stresses, which occurred in the crystal lattice, providing for a good adhesion [19]. The application of optimum "chloride" thermal treatment and the use of the ZTO buffer layer makes it possible to reduce the value of density of saturation diode current J_0 to 10^{-11}–10^{-9} A/cm^2 and coefficient of ideality of diode A to 1,6–2, while for the traditional film solar cells based on CdS/CdTe, $J_0>10^{-9}$ and A>2. The application of this approach makes it possible to decrease losses J_{sc}, caused by the boundary recombination.

There are two theoretical approaches in order to increase open-circuit voltage. The first approach implies an increase in the concentration of holes (acceptors) in the CdTe layer to values 2×10^{17} cm^{-3}. It is necessary to note that at present, for a typical SC based on CdTe, the concentration of acceptors in the base layer is three orders of magnitude lower and is 2×10^{14} cm^{-3}. In this case, a decrease in the width of the depletion region at the increased concentration of charge carriers contributes to the growth of diffusion length of the minority charge carriers, and, therefore, ensures an increase in their life cycle, which will contribute to the increase in V_{oc}. Furthermore, an increase in the concentration of charge carriers leads to an increase in the height of potential barrier whose magnitude limits a maximally accessible value of open-circuit voltage. However, with an increase in the concentration of charge carriers, surface-recombination rate at the heterojunction of CdS/CdTe can limit growth of open-circuit voltage, caused by intensification of the process of gathering nonequilibrium charge carriers generated under the action of light in the base layer. In addition, to actually reach the required concentrations of charge carriers at the existing approaches to the reduction of specific resistance is impossible. At present, reducing specific resistance is conducted at the "chloride" treatment, as a result of which, shallow acceptor levels are generated that are the defective complexes Cl_{Te}-V_{Cd}. With an increase in the chlorine concentration, there occurs an evolution of energy structure of the base layer, the result of which is that an increase in the concentration of the defective complexes described above does not occur, but the isoelectronic traps $2Cl_{Te}$-V_{Cd} are formed, which contribute to the increase in specific resistance of the base layer [20].

The second approach is in the formation ofp – and – n structure with the concentration of holes in the CdTe layer of 2×10^{13}. In this case, inner field is propagated throughout the entire thickness of CdTe and the barrier that appears in this case, called an "electronic reflector", limits recombination velocity at the back surface. Without the increase in the barrier of conductivity band, voltage is somewhat lower than the voltage at the typical concentration of charge carriers of 2×10^{14} cm^3 in CdTe, but even with an undemanding electronic reflector (0,2 eV), voltage V_{oc} must increase considerably. One of the possibilities for creating such a barrier involves adding a layer of ZnTe [21] or other material with extended break in the conductivity band. Potential difficulty, however, is in the fact that any recombination in CdTe/ZnTe or a contact with a reflector may be a threat to the positive effect of "electronic" reflection [22].

In order to increase fill factor of the light current-voltage characteristic (FF), it is necessary to ensure reduction in R_s and increase in R_{sh}. One of the methods of reducing R_s is the replacement of the traditional alloyed SnO_2 layer with theCd_2SnO_4 layer, which has a lower value of specific resistance, caused by the high value of mobility (μ=54,5 $cm^2/(V\cdot s)$) and by the high level of concentration of charge carriers n=$8,94\times10^{20}$ cm^{-3} with the retention of its transparency, which is two times larger than that in the SnO_2 layer.

An increase in R_{sh} can be realized by introduction into the contact area of TCO/CdS of the unalloyed ZTO (Zn_2SnO_4), of thickness about 0,1–0,2 μm. With a decrease in thickness of the CdS layer for the purpose of enhancing J_{sc}, small windows appear in it, through which a contact between TSO and p-CdTe and the p-n junction is shunted. A high-ohmic layer of ZTO with optical width of forbidden band (~3,6 eV) prevents the occurrence of defective heterojunction of TCO/CdTe. By implementing the approaches described above, authors of paper [23] managed to increase the FF value to the level of 77,34 %.

An analysis we conducted revealed that the majority of directions for increasing the efficiency of SC based on cadmium telluride have been implemented in practice; however, it appeared impossible to reach theoretical maximum. Increasing the efficiency of SC due to the optimization of back contacts is paid insufficient attention to. In connection with which, it is necessary to examine in detail the peculiarities of the formation of low ohmic back contacts to the base layers of SC based on CdS/CdTe.

4. 3. Formation of low ohmic back contacts to the base layers of SE based on CdS/CdTe

The efficiency of work, as well as degradation stability of SC based on CdS/CdTe, depend on the material and the method of obtaining a back contact. Schottky barrier is formed when putting a metallic film on the CdTe surface layer. As electron affinity of CdTe is very large, only metals with the work function>5,7 eV form ohmic contacts. Platinum has the largest work function (5,5 eV). But using this material is economically inexpedient.

That is why a tunneling junction is traditionally used as a back contact. For this purpose, etching of CdTe is performed at the back surface for the formation of excess of elementary Te [23]. The following step is putting on the CdTe surface a semiconductor or semimetal with low width of forbidden band in the form of thin buffer layer (~10 nm) with the subsequent putting on a layer of metallization. Base film heterosystems CdS/CdTe were deposited by the method of thermal vacuum evaporation in a single technological cycle.

The formation of the film back contacts, which are the film heterostructure Cu/Au of nano-dimensional thickness, was also accomplished by this method. Putting on the back contacts of the ITO films (oxides of indium and tin) was conducted by the method of nonreactive magnetron dispersion by direct current using original material-saving magnetron. Before putting on the back contacts, the surface of cadmium telluride was etched in the 5 % solution of bromine in methanol for 10 seconds. Then the layers of copper, thickness 12 nm, and the film of gold, thickness 50 nm, were applied by the method of thermal condensation without heating the substrate to the base layer surface. After this, the annealing was carried out in the air at temperature 200 °C for 30 minutes. In this case, in the previous 10 minutes, laboratory sample was heated to the indicated temperature of annealing. In addition to the laboratory samples with standard technological operations, in the course of formation of back contacts, we analyzed SE, the design of whose backcontacts lacked the layer of copper, and which, after obtaining the film heterosystem Cu/Au, were not annealed.

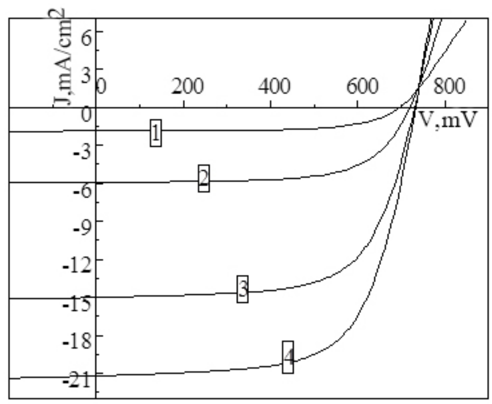
In order to explore the influence of a nano-dimensional layer of copper in the design of back contact on the efficiency of photoelectric processes in the film SC ITO/CdS/CdTe, we measured light current-voltage characteristics. The measurements were conducted for a series of samples with different constructive solutions of back contact at power of lighting from 10 mW/cm^2 to 100 mW/cm^2 (100 mW/cm^2 corresponds to the standard regime of lighting AM1).

5. Discussion of results of research

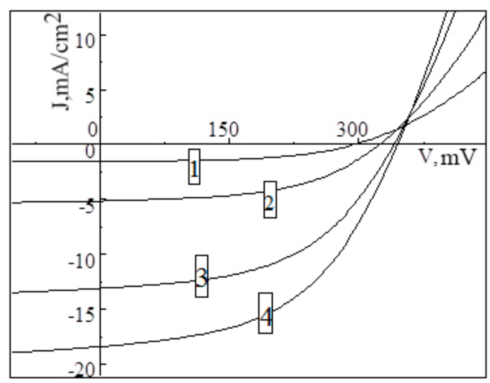
An examination of SC based on CdS/CdTe with two types of back contacts (Cu/Au and Au) demonstrated that in the absence of a copper layer, the efficiency of SE is limited at the level of 3,1 %. An introduction into the composition of a back contact of the copper layer leads to an increase in efficiency by 10,4 % at power of lighting 1000 W/m^2, which is caused, first of all, by the large value of open-circuit voltage and fill factor of the light current-voltage characteristic.

A dependence of short circuit current density on the level of lighting for both types of contacts is of traditional linear character (Fig. 2, *a*). In this case, SC with the back contact containing copper, at emission power of 70 mW/cm^2,demonstrates maximum efficiency value, and for the instrument structures with the Au back contact, efficiency slightly grows with an increase in lighting.

Light current-voltage characteristic of SE at different lighting powers are given in Fig. 2.



a



b

Fig. 2. Light current-voltage characteristic of solar cells at different lighting levels (1 — 10 mW/cm^2; 2 — 30 mW/cm^2; 3 — 70 mW/cm^2; 4 — 100 mW/cm^2): *a* — ITO/CdS/CdTe/Cu/Au, *b* — ITO/CdS/CdTe/Au

An analysis of light diode characteristics demonstrates that for SC with the Cu/Au back contact, at an increase in lighting, a traditional increase in density of photocurrent (Table 1) is observed, which is caused by the growth of concentration of non-equilibrium charge carriers with an increase in density of the flow of incident photons. With an increase in lighting, shunting resistance decreases, which is caused by an increase in specific conductivity of the base layer. The magnitude of series resistance practically does not depend on the lighting. This indicates that a predominant contribution to the magnitude of series resistance of instrument structure is made by the back and frontal contact resistance.

We also explored effect of annealing at temperature 200 °C for 30 minutes on the output characteristics of SC with the Cu/Au back contact.

Table 1

Influence of the level of lighting on the output parameters and the light diode characteristics of ITO/CdS/CdTe/Cu/Au

Parameters and characteristics	P_r, mW/cm^2									
	10	20	30	40	50	60	70	80	90	100
J_{sc}, mA/cm^2	1,9	3,8	5,94	8,3	10,3	12,8	15,0	17,0	19,5	21,2
V_{oc}, mV	697	711	719	720	728	727	729	731	727	731
FF	0,66	0,67	0,67	0,67	0,67	0,663	0,66	0,66	0,66	0,66
Efficiency, %	8,7	9,1	9,49	10	10	10,29	10,37	10,23	10,36	10,19
J_{ph}, mA/cm^2	1,87	3,8	5,95	8,4	10,3	12,8	15,1	17,0	19,5	21,3
R_s,Ohm·cm^2	<1	<1	<1	<1	<1	1,3	1,3	1,4	1,6	1,6
R_{sh}, Ohm·cm^2	8250	4420	2390	2400	1280	1010	894	741	694	623
A	2,9	2,9	2,8	2,8	2,7	2,6	2,6	2,5	2,5	2,5
J_0, 10^{-7}A/cm^2	1,3	2,2	2,7	2,7	2,6	2,2	2,6	2,1	1,8	1,9

Table 2

Effect of annealing of back contacts on the output parameters of SC ITO/CdS/CdTe/Cu/Au

Output parameters	V_{oc}, mV	J_{sc}, mA/cm^2	FF	Efficiency, %
Before annealing	322	20,2	0,41	1,6
After annealing in the air	723	22,2	0,54	8,8

It is established that before the annealing, the efficiency in the instrument structures is limited at the level of 2 %. A determining contribution to the limitation in efficiency is made by low values of open-circuit voltage. The obtained results indicate that only annealing in SC with the Cu/Au back contact leads to the formation of effective tunnel contact. According to the literature data [24], this is caused by interphase interaction between the film of copper and the near-surface layer of tellurium, which leads to the formation of the degenerate semiconductor $Cu_{2-x}Te$. Without the layer of degenerate semiconductor in the instrument structures with the Cu/Au back contact, as well as for SC with the Au back contact, the regime of open diode is realized, which limits the magnitude of open-circuit voltage.

6. Conclusions

1. An analysis of losses in the output parameters of SC based on cadmium sulfide and telluride demonstrated that for increasing the efficiency of instrument structure, it is necessary to reduce recombination velocity of the minority charge carriers in the volume of photoelectric converter, to decrease series resistance and the level of shunt conductivity.

2. The basic directions towards increasing the efficiency of SE based on CdS/CdT through increasing V_{oc} and J_{sc} have already been realized; however, increasing the efficiency via a growth in FF of the light current-voltage characteristic, by reducing series resistance when creating the low ohmic back contacts, is paid insufficient attention to.

3. A main approach when creating the low ohmic back contacts is the formation of tunnel contacts that contain copper, the formation technology of which implies, before putting on the electrode, performing chemical etching when there is the Te layer formed with the annealing being a completing stage, which leads to the formation of the $Cu_{2-x}Te$ phase that is the degenerate conductor of the p-type. It was experimentally established that in the absence of the copper layer at the back surface or in the absence of the annealing process after formation of back contact, the efficiency of the film ITO/CdS/CdTe/Cu/Au SC is limited at the level of 3–4 % due to the work of instrument structure in the regime of "open diode". In the course of formation of quality Cu/Au tunnel contact, the efficiency of SC increases to 10,4 %.

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