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Features of Photoelectric Processes in CdS/CdTe Thin Film Heterosystems with Nanoscale Layers in Back Contacts

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A comparative study of the influence of the solar radiation intensity level on the output parameters and light diode characteristics of solar cells (SCs) based on the CdS/CdTe heterosystem with different types of back contact has been carried out. It is shown that the studied SCs obtained by vacuum thermal evaporation method have the maximum efficiency under illumination conditions of 60 % AM1.5. The presence of a maximum is caused by a decrease in the fill factor of the light *I-V* characteristic due to a decrease in the shunt resistance, while the short-circuit current and open-circuit voltage increase with increasing illumination. In the case of solving the problem with a decrease in the shunt resistance, it can be expected that the tendency to an increase in the efficiency with increasing illumination level can be continued in the region of concentrated radiation. It is shown that not only the back contact material, but also the nature of the interphase interaction of the back contact with the base CdTe layer has a determinative influence on the illumination dependence of the series resistance of these SCs obtained by vacuum thermal evaporation method. The observed nonmonotonic dependence of the diode saturation current density on the illumination level is associated with two competing physical mechanisms. One mechanism assumes the traditional increase in the diode saturation current due to an increase in the concentration of nonequilibrium charge carriers generated by light, and the other one determines a decrease in the diode saturation current due to the filling of traps, which leads to an increase in the charge carrier lifetime.

Keywords: Cadmium sulphide, Cadmium telluride, Output parameters, Solar cell, Light diode characteristics.

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1. INTRODUCTION

Currently, due to the low material and energy consumption, thin film device structures compete silicon crystalline solar cells (SCs) [1-3]. The most promising among thin film device structures are SCs based on CdS/CdTe heterosystems [4-6]. The output parameters of SCs are short-circuit current density (J_{sc}), open-circuit voltage (U_{oc}), fill factor (*FF*) of the load light current-voltage (*I-V*) characteristic and, ultimately, the efficiency (η). All output parameters are determined by the light *I-V* characteristic under standard test conditions (STC): the luminous flux power is 1000 W/m^2, the spectral composition of the radiation corresponds to the AM1.5 solar spectrum in terrestrial conditions, the temperature of the SC is 25 °C. Exactly the output parameters measured under STC, as well as the price of an SC, are analyzed by the customer when choosing an SC. However, STC are practically not found in real-life conditions since the luminous flux power of 1000 W/m^2 can be achieved only in southern latitudes. In mid-latitudes in summer, the luminous flux is usually 800 W/m^2 and in winter it decreases to 450 W/cm^2. Therefore, the output parameters must also be assessed under real operating conditions, i.e., at different illumination levels.

When SCs are illuminated, the conversion of solar energy into electrical energy is carried out as a result of a number of physical processes: generation, diffusion, drift, separation and collection of nonequilibrium charge carriers. According to the SC equivalent circuit [7], the quantitative characteristics of photovoltaic processes are the light diode characteristics of a SC: photocurrent density (J_{ph}), diode saturation current density (J_0), diode ideality factor (A), series resistance (R_s), shunt resistance (R_{sh}) calculated per unit area of SC.

Based on the above, the study of the illumination effect on the output parameters and light diode characteristics of thin film SCs based on the CdS/CdTe heterostructure is relevant not only for large-scale terrestrial applications of such SCs, but also for understanding the physical laws that determine the efficiency of the photovoltaic processes occurring in them.

2. EXPERIMENTAL

In this study, SCs based on the CdS/CdTe heterostructure were obtained by the method of vacuum thermal evaporation in a vacuum installation, which is a prototype of industrial installations. Evaporation of CdS and CdTe films was carried out in a single technological cycle from graphite evaporators. The fabrication of a superstrate configuration of the SC based on the CdS/CdTe heterostructure was carried out according to the technical procedures described in detail in [8].

The *I-V* characteristics were measured at a luminous flux power from 10 to 100 mW/cm^2 using a laboratory stand based on a 4145A semiconductor analyzer (manufactured by Hewlett Packard). The measurements were controlled by a computer. A 50 W halogen lamp connected to a stabilized power supply was used as a solar radiation source. Two probe systems were used as contacts to the current-collecting electrodes of the SC, each consists of two electrically isolated probes, rigidly fixed at a distance of 0.5 mm from each other. To control the quality of the probe connection, three

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voltage levels were sequentially applied to two adjacent probes of each contact system: 0.1, 0.2 and 0.3 V before the start of measurements, and the flowing currents were recorded. Based on the results of these measurements, the electrical resistance of that part of the SC current-collecting electrode, which was located between the probes, was calculated. So that the contact resistance does not affect the measurement results of the light *I-V* characteristics when pressing the probes, the measured electrical resistance should not exceed 1-2 Ohm. In this case, the value of the measured resistance is determined by the resistance of that part of the SC current-collecting electrode, which is located between the probes.

The relationship between the SC efficiency and the light diode characteristics is implicitly described by the theoretical light *I-V* characteristic of the SC [7]:

$$J(U) = -J_{ph} + J_0\{\exp[e(U - J(U)R_s)/(Ak_BT)] - 1\} + (U - J(U)R_s)/R_{sh}, \quad (1)$$

where J is the density of the current flowing through the load, e is the electron charge, k_B is the Boltzmann constant, T is the temperature of the SC, U is the loading voltage.

To calculate the diode parameters in this work, we did not use an approximate method for finding these parameters only from the sections of the *I-V* characteristic near the points of short circuit and open circuit, as is often done, for example in [9, 10]. This method gives rather differential resistance values near these points. Therefore, the use of these values as series and shunt resistances, and then the found saturation current and the diode ideality factor, can differ greatly from the values that provide the best approximation of the experimental *I-V* characteristic by expression (1). In addition, measurements of the experimental light *I-V* characteristics near these points have the greatest error. Therefore, the calculation of the diode parameters was carried out by solving the following system of equations:

$$J(0) = J_{sc};\ J(U_{oc}) = 0;\ J(U_m) = J_m;$$
$$dP/dJ\,|_{(U_m,\,J_m)} = 0, \quad (2)$$

where U_m and J_m are the voltage and current at the point of maximum power, $P = JU$ is the SC generated power. This system is solved by the developed computer program. Since there are four equations and five unknown parameters, one of the diode parameters remains free. This parameter is varied until the minimum value of the root-mean-square error of approximating the experimental curve by expression (1) is reached. The values of U_m, J_m, J_{sc}, U_{oc} also vary, they are never known exactly due to the presence of an error and discreteness of the process of measuring the *I-V* characteristic points. This variation method turns out to be more effective than direct variation of the diode parameters, because when five diode parameters are unknown, an adequate variation range can be predicted in advance only for the photocurrent and ideality factor.

Ultimately, the average value of the absolute deviation of the theoretical expression (1) from the experimental points of the *I-V* characteristic is usually 0.5-1 %. When using this equipment, which provides a sufficiently smooth experimental curve for measuring the *I-V* characteristic, the deviation value is probably related to how expression (1) is applicable to the description of a SC. Note that the diode characteristics found in this way are "integral" (i.e., they are parameters for the entire *I-V* characteristic curve (1)). These characteristics more closely correspond to the equivalent circuit in comparison with the characteristics obtained using the method of evaluating these parameters from separate parts of the *I-V* characteristic. The error in determining the output parameters and light diode characteristics is determined not only by the quality of the approximation, but also by the error in measuring the light *I-V* characteristic. The total error in measuring operating voltages (U_p) and currents (U_p/R)-$\varepsilon(U_p)$ is determined by the step of changing the voltage supplied to the SC (ΔU_p): $\varepsilon(U_p) = (\Delta U_p/U_p)^2$. Calculations show that this source of error is significant when measuring the *I-V* characteristics for SCs with low efficiency. When measuring highly efficient instrument structures, this error is about 1 %.

3. RESULTS AND DISCUSSION

The *I-V* characteristics depending on the illumination level in the range from 10 to 100 % AM1.5 were studied for serial samples of the following designs: 1) with nanoscale Cu layer in glass/FTO/CdS/CdTe/Cu/Au back contact and 2) without nanoscale Cu layer in glass/FTO/CdS/CdTe/Au back contact. The typical *I-V* characteristics of these samples are shown in Fig. 1.

When analyzing the change in the shape of the *I-V* characteristic depending on the illumination, it can be noted that with an increase in the illumination, not only the *I-V* characteristic is shifted down the current axis, as is commonly believed, but the *I-V* characteristic is also stretched along this axis. This is especially clearly seen for a sample with a low efficiency and a pronounced effect of the back contact on the *I-V* characteristic. For a sample with an efficiency of 10 %, it can also be seen that by simply shifting the *I-V* characteristic downward, it is impossible to come from points of the *I-V* characteristic at an illumination of 10 % to points of the *I-V* characteristic at an illumination of 100 % AM1.5.

The dependences on the illumination of the output characteristics and the light diode parameters of SCs are shown in Fig. 2 and Fig. 3, respectively.

The efficiency, measured at STC, of the SC glass/FTO/CdS/CdTe/Cu/Au is 10.0%. The efficiency of the SC glass/FTO/CdS/CdTe/Au, in the design of which there is no nanoscale copper interlayer, reaches only 3.14 % (Fig. 2d). From the graph of the efficiency versus illumination for glass/FTO/CdS/CdTe/Cu/Au and glass/FTO/CdS/CdTe/Au SCs (Fig. 2d), it can be seen that, in accordance with the formula $\eta = U_{oc}I_{sc}FF/P_s$, the efficiency grows rapidly in the illumination range from 10 to 60 % AM1.5, and then slowly decreases.

Let us consider the dependences of the output characteristics of glass/FTO/CdS/CdTe/Cu/Au and glass/FTO/CdS/CdTe/Au SCs on different illumination levels. The short-circuit current dependence shown in Fig. 2a has a linear nature, increasing in the same way as for crystalline SCs with an increase in the illumination level [11]. The open-circuit voltage of glass/FTO/CdS/CdTe/Cu/Au and glass/FTO/CdS/CdTe/Au

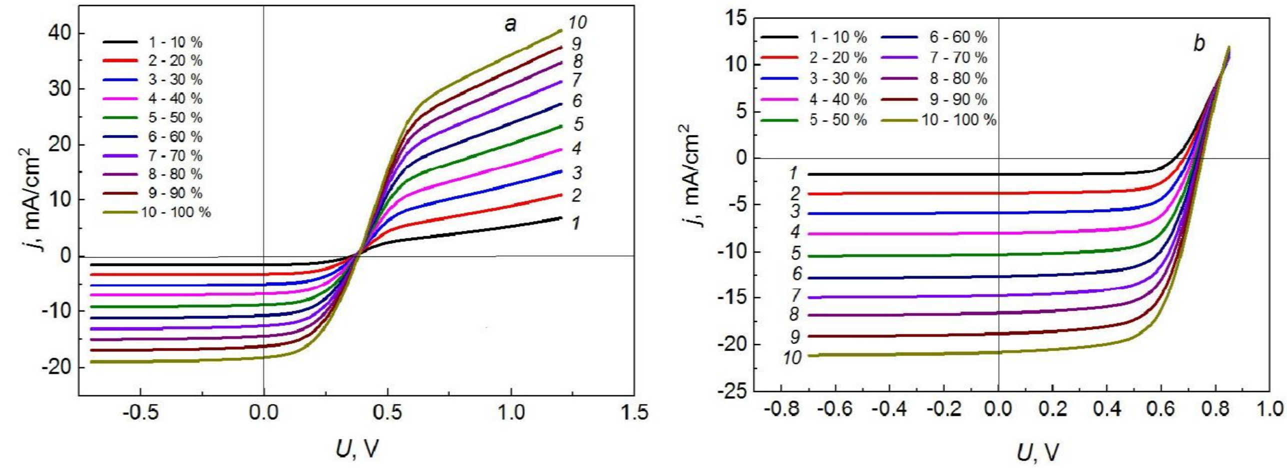

Fig. 1 – Dependences of the light *I-V* characteristics on different illumination levels of SCs for: a) glass/FTO/CdS/CdTe/Au and b) glass/FTO/CdS/CdTe/Cu/Au

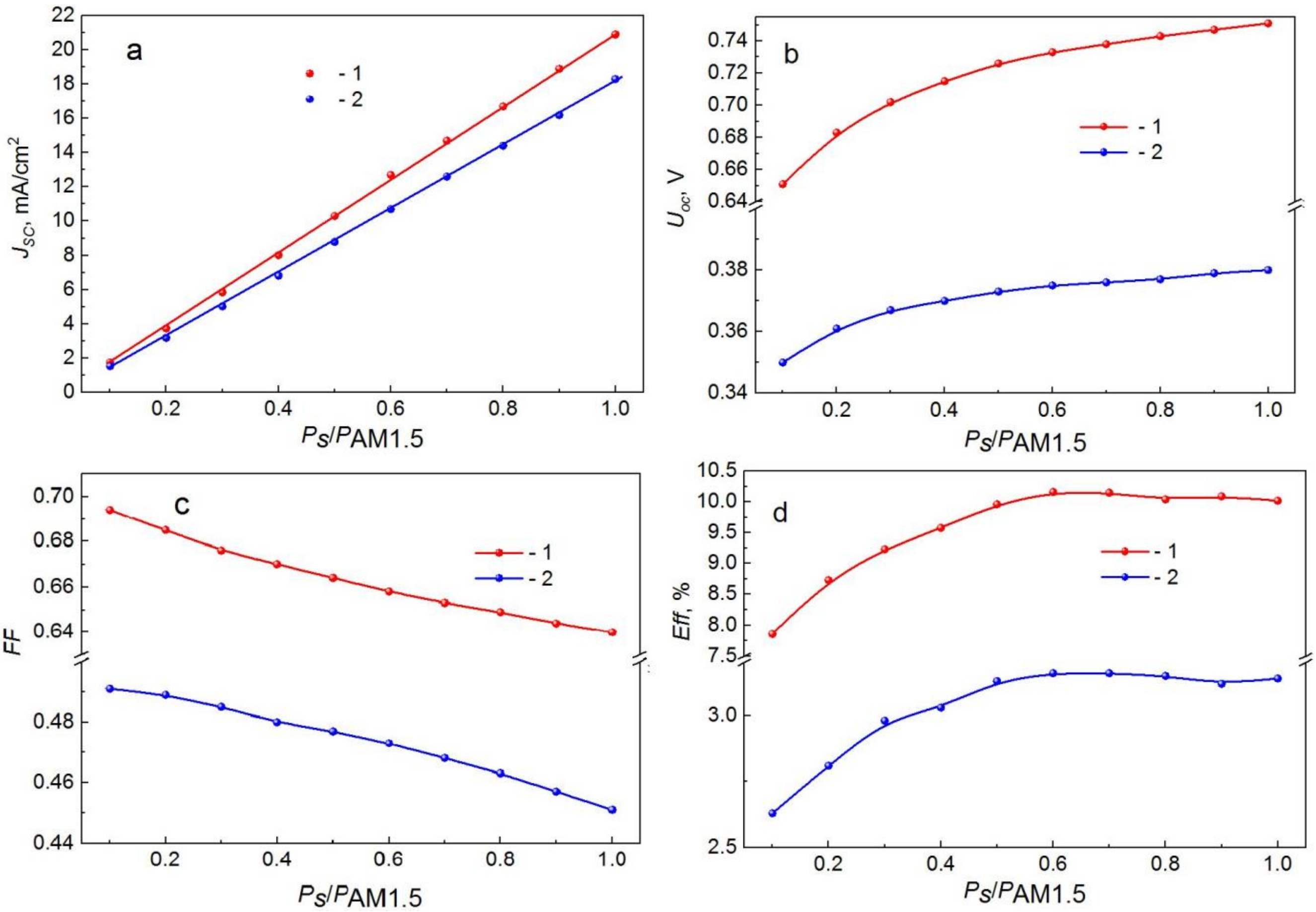

Fig. 2 – Dependences of the output characteristics on different illumination levels of the investigated samples for: 1 – SC with nanoscale Cu layer in glass/FTO/CdS/CdTe/Cu/Au back contact; 2 – SC without nanoscale Cu layer in glass/FTO/CdS/CdTe/Au back contact

SCs (Fig. 2b) also obeys the logarithmic dependence [11], which follows from formula (1) for large values of R_{sh}:

$$U_{oc}(x) = (Ak_BT/e)\ln(1 + J_{ph}(x)/J_0), \qquad (3)$$

where $J_{ph}(x) = bx$, $x = I/I_{AM1.5}$ is the illumination level in relation to AM1.5; I is the absolute value of illumination; b is the coefficient in a linear dependence, approximating the experimental data of the dependence of the photocurrent on the illumination level. By adding a zero point to the graph, the best approximation of the experimental dependence $U_{oc}(x)$ could be obtained, if we take its average value for the diode saturation current in (3), while the ideality factor in (3) will also be close to the average. This suggests that the observed dependence of J_0 and A on illumination (Fig. 3) has no significant effect on the $U_{oc}(x)$ dependence.

The fill factor of the light *I-V* characteristic decreases linearly with increasing intensity for glass/FTO/CdS/CdTe/Cu/Au and glass/FTO/CdS/CdTe/Au SCs (Fig. 2c). Thus, the presence of an extremum in the graph of efficiency versus illumination level for both types of SC is due to the fact that with an increase in illumination from 10 to 60 %, an increase in the short-circuit current density and open-circuit voltage outstrips the decrease in the fill factor of the light *I-V* characteristic. With a further increase in intensity, a decrease in the fill factor becomes a determining factor for the decrease in efficiency.

An analysis of the light diode parameters shows that at STC, the shunt resistance of glass/FTO/CdS/CdTe/Au SC is approximately two times greater than for glass/FTO/CdS/CdTe/Cu/Au SC. Nevertheless, the experimental dependences of the shunt resistances on illumination level of both types of SCs (Fig. 3a) can be represented as $R_{sh} \sim I^q$, where $q \approx -1.1$ for a SC with a nanoscale copper interlayer in the back contact ($R_{sh} = 455.91x^{-1.075}$) and without a nanoscale copper interlayer in the back contact ($R_{sh} = 998.62x^{-1.129}$). The observed dependence of the shunt resistance on illumination level for a SC with a nanoscale copper interlayer in the back contact can be explained by assuming the semiconductor nature of the shunt area, in which the concentration of generated nonequilibrium charge carriers by the action of light increases due to increasing illumination:

$$R_{sh} = a/(\sigma_0 + \Delta\sigma) = a/(\sigma_0 + e(\mu_n + \mu_p)\Delta n), \qquad (4)$$

where a is the thickness of the base layer, σ_0 is the electrical dark conductivity, e is the electron charge, μ_n and μ_p are the electron and hole mobility, respectively, $\Delta n = \beta I \exp(-\gamma a)$ is the concentration of charge carriers generated by illumination (β is the quantum yield, γ is the absorption coefficient).

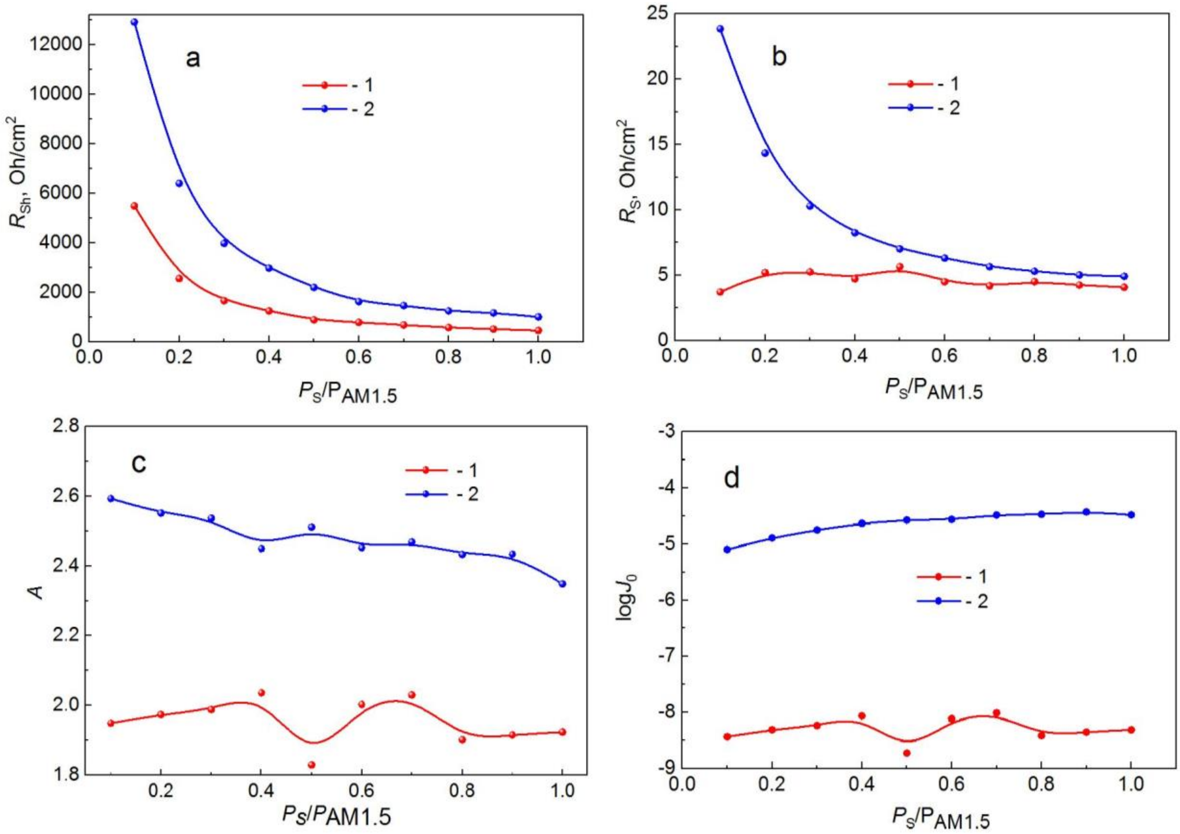

Fig. 3 – Dependences of the diode parameters on the illumination level of the studied samples: 1 – SC with a nanoscale Cu layer in glass/FTO/CdS/CdTe/Cu/Au back contact, 2 – SC without a nanoscale Cu layer in glass/FTO/CdS/CdTe/Au back contact

It is the rapid decrease in the shunt resistance with increasing illumination level that leads to the observed decrease in the fill factor of the light *I-V* characteristic with an increase in illumination above 60 %.

It was experimentally established that the value of the series resistance of glass/FTO/CdS/CdTe/Au SC is higher than for glass/FTO/CdS/CdTe/Cu/Au SC. But the difference between the series resistance of these SCs decreases with increasing illumination level. This is due to the different nature of the dependence of the series resistance for the investigated SCs. For glass/FTO/CdS/CdTe/Cu/Au SC, with an increase in illumination, the series resistance first increases slightly and then decreases very slowly, in general, very weakly responding to the illumination level. For glass/FTO/CdS/CdTe/Au SC, a monotonic decrease in the series resistance is observed in accordance with the expression $R_s = 4.5255x^{-0.704}$.

The series resistance of the SC consists of the resistance of FTO, CdS and CdTe layers and the space charge region of the back contact. The last two components listed above are the main ones. The observed difference in the behavior of the series resistance suggests that in this case for both SCs, the resistance of the back contact area is the main one among all the components of this resistance. However, the properties of this contact are significantly different. According to existing concepts, the use of a nanoscale copper interlayer is necessary to create a tunnel contact up to the formation of an interlayer of a degenerate conductor p^+-$Cu_{2-x}Te$ during the interaction of a nanoscale copper interlayer and a nanoscale tellurium interlayer, which is formed on the surface of CdTe layer after its etching [12]. If there is no nanoscale copper interlayer at the CdTe/Au contact, a sufficiently high-quality metal-semiconductor transition with a sufficiently high barrier and an extended space charge region is formed, as evidenced by the shape of the light *I*-*V* characteristic (Fig. 1a). In the absence of a nanoscale copper interlayer, the following reaction of the space charge region of the back contact to illumination level can be expected. As the illumination grows due to the generation of an increasing number of nonequilibrium charge carriers, the resistance should decrease according to the law determined by expression (4). However, the corresponding dependence turns out to be weaker. This is due to the fact that the barrier at the back contact during the operation mode of the SC is under the reverse bias voltage of the front barrier. As the voltage generated by the front barrier increases with increasing illumination, this should lead to an increase in its space charge region width, and, therefore, to an increase in its resistance. An increase in the concentration of nonequilibrium carriers generated by light with an increase in the illumination level turns out to be stronger than a slow increase in the voltage generated by the front barrier. Therefore, the dependence $R_s \sim 1/I$ is replaced by a weaker dependence $R_s \sim 1/I^{0.7}$ as a result of the competition between these two factors.

As it can be seen from the graphs in Fig. 3b, for a SC with a nanoscale copper interlayer in the back contact, the series resistance first increases and then decreases very slowly and, generaly speaking, responds very weakly to the illumination intensity. This result can be explained if we assume that the formed interlayer of the $Cu_{2-x}Te$ compound did not lead to the complete disappearance of the barrier at the back contact but led to its partial shunting. As a result, the series resistance is determined by the resistance of the $Cu_{2-x}Te$/Au transition region, which is independent of the illumination level.

Studies have shown that at STC, the diode saturation current for glass/FTO/CdS/CdTe/Cu/Au SC is approximately four orders of magnitude lower than for glass/FTO/CdS/CdTe/Au SC. The analysis of the dependence of the light diode saturation current for the investigated SC also differs significantly. For glass/FTO/CdS/CdTe/Cu/Au SC, the diode current has a nonmonotonic character of the dependence in the considered range of illumination values. For glass/FTO/CdS/CdTe/Au SC, with increasing illumination level, a monotonic increase in the diode saturation current is observed. We consider that the observed nonmonotonic dependence is associated with two competing physical mechanisms. One mechanism assumes the traditional increase in the diode saturation current due to an increase in the concentration of nonequilibrium charge carriers in accordance with the dependence $J_0 \sim qD_{n(p)}n(p)/\tau_{n(p)}$. The other one determines a decrease in the diode saturation current due to the filling of traps in the space charge region and, in accordance with the formula, an increase in the charge carrier lifetime. Since the diode saturation value for glass/FTO/CdS/CdTe/Au SC is four orders of magnitude higher than for glass/FTO/CdS/CdTe/Cu/Au SC, the second physical mechanism does not significantly affect the dependence of the diode saturation current on the illumination level.

4. CONCLUSIONS

The presence of a maximum in the dependence of the efficiency on the illumination level was experimentally established for both glass/FTO/CdS/CdTe/Cu/Au and glass/FTO/CdS/CdTe/Au SCs at illumination of 60 % AM1.5. The presence of this maximum is due to the fact that with an increase in illumination, the fill factor of the light *I*-*V* characteristic decreases, which compensates for an increase in the short-circuit current density and open-circuit voltage values at illumination above 60 %. It was found that the main factor that leads to a decrease in the fill factor of the light *I*-*V* characteristic is a decrease in the shunt resistance. At the same time, with an increase in the illumination level, all other diode parameters either practically do not change, or show a tendency to improve. This allows us to assume that in the case of solving the problem with a decrease in the shunt resistance, it can be expected that the tendency to an increase in the efficiency with increasing illumination level can be continued in the region of concentrated radiation.

The revealed differences in the character of the dependence on the illumination level of the series electrical resistance of glass/FTO/CdS/CdTe/Cu/Au and glass/FTO/CdS/CdTe/Au SCs prove that the resistance of the transition region of the back contact has a decisive influence on the value of this resistance. The properties of this transition region are determined by the nature of the interphase interaction of the back contact with the base layer and the accuracy of technological operations when creating the back contact.

The observed nonmonotonic dependence of the diode saturation current density on the illumination level is associated with two competing physical mechanisms. One mechanism assumes the traditional increase in the diode saturation current due to an increase in the concentration of nonequilibrium charge carriers generated by light, and the other one determines a decrease in the diode saturation current due to the filling of traps, which leads to an increase in the charge carrier lifetime.

REFERENCES

1. N.P. Klochko, K.S. Klepikova, I.I. Tyukhov, Y.O. Myagchenko, E.E. Melnychuk, V.R. Kopach, G.S. Khrypunov, V.M. Lyubov, A.V. Kopach, *Sol. Energy* **120**, 330 (2015).
2. N.E.I. Boukortt, S. Patanè, Y.M. Abdulraheem, *Sol. Energy* **204**, 440 (2020).
3. N.K. Elangovan, A. Sivaprakasam, *Mol. Cryst. Liq. Cryst.* **710** No 1, 66 (2021).
4. B.T. Boiko, G.S. Khripunov, V.B. Yurchenko, H.E. Ruda, *Sol. Energy Mater. Sol. C.* **45** No 4, 303 (1997).
5. Z. Guanggen, L. Xiaolan, Z. Yubo, S. Yuanmao, L. Bing, Z. Jingquan, F. Lianghuan, W. Qionghua, *Int. J. Photoenergy* **2019**, 3579587 (2019).
6. M. Barbato, E. Artegiani, M. Bertoncello, M. Meneghini, N. Trivellin, E. Mantoan, A. Romeo, G. Mura, L. Ortolani, E. Zanoni, G. Meneghesso, *J. Phys. D: Appl. Phys.* **54** No 33, 333002 (2021).
7. H.S. Raushenbach, *Solar Cells Array Design* (New York: Litton Uducation Publishing: 1980).
8. G.S. Khrypunov, *Semiconductors* **39**, 1224 (2005).
9. W. Li, R. Yang, D. Wang, *Sol. Energy Mater. Sol. C.* **123**, 249 (2014).
10. K. Shen, Q. Li, D. Wang, R. Yang, Y. Deng, M. Jer-Jeng, D. Wang, *Sol. Energy Mater. Sol. C.* **144**, 472 (2016).
11. A.L. Fahrenbruch, R.H. Bube, *Fundamentals of Solar Cells: Photovoltaic Solar Energy Conversion* (New York: Academic Press, 1983).
12. B.E. McCandless, J.E. Philips, J. Titus, *Proceeding of 2nd World Conference on Photovoltaic Solar Energy Conversion*, 448 (Vienna: 1998).

Особливості фотоелектричних процесів в плівкових гетеросистемах сульфіду та телуриду кадмію з нанорозмірними шарами у тильних контактах

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Проведено порівняльне дослідження впливу рівня інтенсивності сонячного випромінювання на вихідні параметри та світлові діодні характеристики сонячних елементів на основі гетеросистеми CdS/CdTe з різними типами тильного контакту. Показано, що досліджувані сонячні елементи, отримані методом вакуумного термічного випаровування, мають максимальне значення ККД в умовах освітленості 60 % АМ1,5. Наявність максимуму обумовлена зменшенням значення коефіцієнта заповнення світлової вольт-амперної характеристики за рахунок зменшення значення шунтуючого опору, на фоні зростання струму короткого замикання і напруги холостого ходу при збільшенні освітленості. У разі розв'язання задачі зі зменшенням опору шунта можна очікувати, що тенденція до зростання ККД із збільшенням рівня освітленості може бути продовжена в області концентрованого випромінювання. Показано, що не тільки матеріал зворотного контакту, а й характер міжфазової взаємодії тильного контакту з базовим шаром CdTe має визначальний вплив на залежність значення послідовного опору цих сонячних елементів, отриманих методом вакуумного термічного випаровування, від рівня освітленості. Спостережувана немонотонна залежність густини діодного струму насичення від рівня освітленості пов'язана з двома конкуруючими фізичними механізмами. Один механізм передбачає традиційне збільшення значення діодного струму насичення за рахунок збільшення концентрації нерівноважних носіїв заряду, що генеруються під дією сонячного випромінювання, а другий визначає зменшення діодного струму насичення за рахунок заповнення пасток, що призводить до збільшення часу життя носіїв заряду.

Ключові слова: Сульфід кадмію, Телурид кадмію, Вихідні параметри, Сонячний елемент, Світлові діодні характеристики.