ANALYSIS OF THE DIODE CHARACTERISTICS OF THIN FILM SOLAR CELLS BASED ON CdTe

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A physical approach to the optimization of photoelectric processes in thin film multilayer systems has been developed. By means of a simulation of the influence of light-diode characteristics on the efficiency factor, it is concluded that the optimization of the photoelectric processes in ITO/CdS/CdTe/Cu/Au film solar cells is mainly determined by two competing physical mechanisms: an increase in the efficiency of the process of distribution of nonequilibrium charge carriers and a reduction in the efficiency of their generation, as the CdS layer thickness grows.

It is well known that the thin film solar cells (SC), which are based on CdTe, are very promising for wide-ranging applications [1]. The theoretical value of the efficiency factor for CdTe-based SC equals 29 % [1]. At present, however, the maximum efficiency achieved on the laboratory specimens of the thin film SC with a CdTe base layer is far smaller [2]. Usually, to enhance the SC efficiency, an optimization of the physical properties of separate layers has been performed [2]. However, a more attentive look at the problem reveals that the SC under consideration belong to the novel categories of objects of solid-state physics, namely, to the multilayered polycrystalline systems formed at high temperatures of a deposition. For these systems, the interactions, both the diffusion and interphase ones, between adjacent layers, as well as the developed intergrain area of the base layer can strongly influence the efficiency. As a result, for the film SC, the problem of the efficiency enhancement is not equivalent to that of the optimization of the properties of separate layers. Quite the contrary, it implies the optimization of the photoelectric processes which integrally influence the efficiency value.

That's why the development of a physical approach to studying the photoelectric properties of the film SC is not only of a great importance for the creation of efficient structures for the utilization in devices. This approach can also present a firm physical foundation for the advancement of the materials science of multilayer systems.

According to the equivalent circuit of SC, the photoelectric processes can be quantitatively characterized by a set of light-diode parameters of the SC: the densities of the saturation diode current J_0 and photocurrent $J_{\rm ph}$, diode ideality coefficient A, series resistance $R_{\rm s}$, and shunt resistance $R_{\rm sh}$ [3]. In the implicit form, a relation between the SC efficiency η and diode characteristics is described with the theoretical light current-voltage characteristic (CVC) of the SC [4] as

$$J_{\rm l} = -J_{\rm ph} + J_0 \left\{\exp\left[e(U_{\rm l} - J_{\rm l}R_{\rm s})/(AkT)\right] - 1\right\} + (U_{\rm l} - J_{\rm l}R_{\rm s})/R_{\rm sh}, \qquad (1)$$

where $J_{\rm l}$ — load current density, e — electron charge, k — Boltzmann constant, T — SC temperature, and $U_{\rm l}$ — load voltage.

In this work, a fitting of the values of $J_{\rm l}$ and $U_{\rm l}$, obtained experimentally, with the theoretical dependence (1) was performed with the use of a personal computer. The fitting allowed the determination of the light-diode characteristics, efficiency η, and output SC parameters such as the density of the short-circuit current $J_{\rm s.c}$, open-circuit voltage $U_{\rm o.c}$, and filling factor (FF) of the light CVC. To specify the diode characteristics which define a change in the SC efficiency upon a modification of their construction-technological parameters, a mathematical simulation of the quantitative influence of the light-diode characteristics on the SC efficiency was also performed. In future, this will allow one to essentially simplify the determination of the physical mechanisms responsible for the efficiency of photoelectric processes.

The efficiency of the physical approach, developed here to study the photoelectric processes, was examined in the process of optimization of the thickness of a cadmium sulphide layer, $t_{\rm CdS}$, in the ITO/CdS/-CdTe/Cu/Au film SC. To fabricate the laboratory SC specimens, a CdS layer was first deposited by the thermal evaporation method on a glass substrate with a pre-deposited ITO layer 0.5 μm in thickness. The pressure during the deposition was 10^{-6} Torr; the substrates were held at a temperature of 300 °C. Then, without breaking the vacuum, the CdTe layer was deposited on the obtained composite held at 400 °C.

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Finally, a $CdCl_2$ layer was deposited without heating the composite, under a pressure of 10^{-5} Torr. The heterostructures obtained in such a way were subjected to a heat treatment in air at 430 °C for 25 min, followed by etching in a bromine-methanol solution. After that, Au—Cu bilayers subsequently serving as electric contacts were deposited on the SC surface by the thermal evaporation method and the SC were again annealed in air at 200 °C for 30 min.

The measurements of the light CVC were carried out on ITO/CdS/CdTe/Cu/Au solar cells with various values of t_{CdS}, in the AM1.5 illumination mode. The thickness of a CdS layer varied up to 0.6 μm, whereas that of the other layers was constant and equaled 4 and 0.35 μm for the cadmium telluride and cadmium chloride ones, respectively. Both the output parameters and light-diode characteristics of the experimental SC specimens were determined by means of the analytical processing of the light CVC. As follows from the analysis of the thickness dependences of both these sets of quantities, there can be distinguished several regions with a specific behavior. The output parameters and diode characteristics for the specimens which correspond to these regions are presented in the Table. It is evident from these data that, as the thickness of CdS layer grows from zero to 0.4 μm, the SC efficiency η increases from 2.5 to 10.3%. The numerical simulation of the effect of a change of the light-diode characteristics on the SC efficiency has revealed the following trends. For the values of t_{CdS} less than or equal to 0.1 μm, the growth of η is equally determined by both an increase in the shunt resistance and a decrease in the density of the saturation diode current. In fact, Fig. 1,*a*,*b* clearly demonstrates that, within this thickness region, such a character of the SC efficiency growth, as is observed experimentally, cannot be achieved by a variation of only a single parameter. On the contrary, within the region $0.1 < t_{\mathrm{CdS}} < 0.4$ μm, a decisive contribution to η belongs to the second factor, namely, to a decrease in the density of the saturation diode current (Fig. 1,*c*). Thus, an increase in t_{CdS} leads to a rise in the efficiency of the process of distribution of the nonequilibrium charge carriers induced by the light action.

According to the literature data [2], thin layers of the cadmium sulphide often contain through pores which can shunt the n-CdS/p-CdTe transition with the n-ITO/p-CdTe one. As follows from our studies, the n-ITO/p-CdTe heterojunction displays worse diode characteristics than the n-CdS/p-CdTe one (see Table, sample 1). This is caused by a different degree of the lattice mismatch between the corresponding layers, for

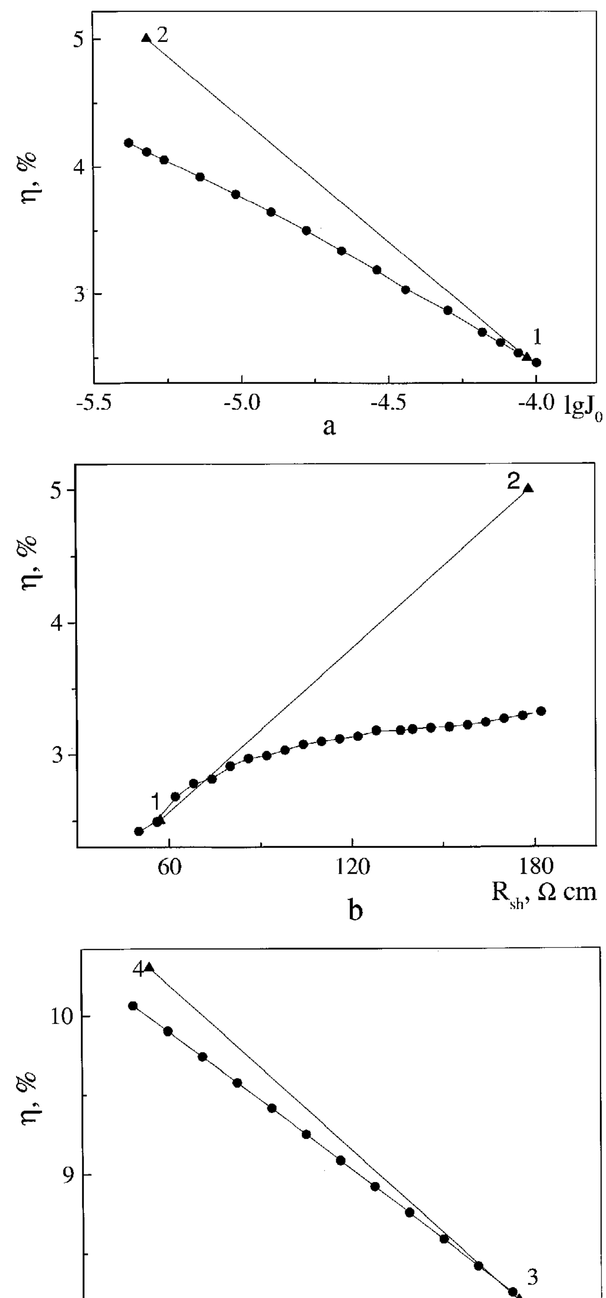

Fig. 1. Simulation of the influence of a change in diode parameters on the efficiency of the ITO/CdS/CdTe/Cu/Au solar cells, as the thickness of the cadmium sulphide layer grows from 0 to 0.4 μm (specimens No. 1, 2, 3, and 4 in the Table): solid circles — theoretical efficiency; solid triangles — experimental efficiency

the former and latter cases, respectively. So, the difference in the lattice spacings of ITO and CdTe

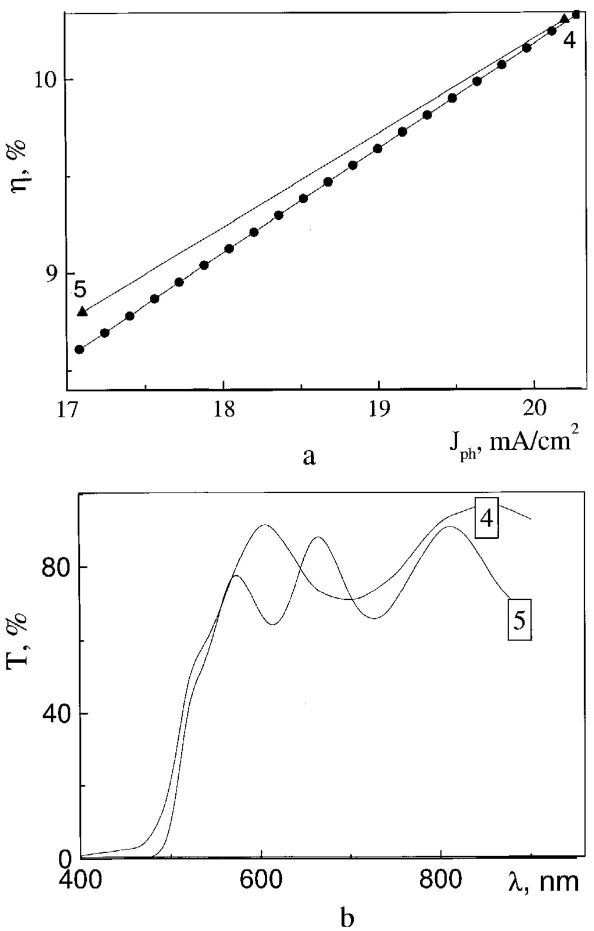

Fig. 2. Influence of the growth in the CdS layer thickness from 0.4 to 0.6 μm (samples No 4 and 5 in the Table) on the efficiency of the photoelectric processes in the ITO/CdS/-CdTe/Cu/Au: *a* — simulation of the effect of the $J_{\rm ph}$ change on the efficiency η (solid circles — theoretical efficiency; solid triangles — experimental efficiency); *b* — transmission spectra for the CdS/glass heterosystem ($t_{\rm CdS}$ = 0.4 μm (curve *4*); 0.6 μm (curve *5*))

equals 20 %, while that for CdS and CdTe is 9.7 % [4,5]. Thus, it is likely that an increse of the shunting resistance occurring upon a growth in $t_{\rm CdS}$ results from a decrease in the concentration of the through pores in this layer. Earlier, we showed that the CdS–CdTe interface of the ITO/CdS/CdTe/Cu/Au film SC contains the interlayers of CdS_xTe_{1-x} solid solutions formed as a result of the interphase interaction [6]. According to [7], these interlayers display the *n*-type of electric conduction. The formation of the interlayers not only reduces the effect resulting from the lattice mismatch between cadmium telluride and cadmium sulphide, but also shifts a depletion region, caused by the CdS/CdTe phase boundary, deep into the base layer of cadmium telluride. In our opinion, it is this effect that gives rise to the lowering of the density of the saturation diode current, observed in experiment, as the thickness of the cadmium sulphide layer grows. Thus, it becomes evident that an enhancement of the efficiency of the process of distribution of nonequilibrium charge carriers in ITO/CdS/CdTe/Cu/Au solar cells, which is observed upon a growth in $t_{\rm CdS}$ to 0.1 μm, occurs due to both a decrease in the concentration of the through pores in CdS layer and an increase in the thickness of the n-CdS_xTe_{1-x} solid solution interlayer. As $t_{\rm CdS}$ grows further, the latter contribution becomes decisive.

As follows from further analysis of the simulation results, the reason for the reduction of the SC efficiency, observed upon the increase in $t_{\rm CdS}$ from 0.4 to 0.6 μm, is a lowering of the photocurrent density (Fig. 2,*a*). The results of investigations of the absorption spectra for the CdS/glass heterosystem (Fig. 2,*b*) show that, as $t_{\rm CdS}$ grows from 0.4 to 0.6 μm, the transmission coefficient within the range of photosensitivity of the CdS/CdTe-based SC (0.5 – 0.9 μm) diminishes from 77.9 to 69.7 %. Thus, the reduction of the photocurrent density upon the $t_{\rm CdS}$ growth is caused by a decrease in the transmission coefficient, which means a diminution of the photon flux density that reaches the base SC layer. As a result, the growth in $t_{\rm CdS}$ gives rise to a decrease in the efficiency of the generation of nonequilibrium charge carriers in the base layer.

Influence of the thickness of the cadmium sulphide layer on the output parameters and diode characteristics of the ITO/CdS/CdTe/Cu/Au solar cells

Specimen No	CdS layer thickness, μm	Output parameters				Diode characteristics				
		$U_{\rm o.c}$, mV	$J_{\rm s.c}$, mA/cm^2	FF, a. u.	η, %	$R_{\rm s}$, $\Omega\cdot$cm^2	$R_{\rm sh}$, $\Omega\cdot$cm^2	J_0, A/cm^2	A, a. u.	$J_{\rm ph}$, mA/cm^2
1	0	295	19.74	0.428	2.5	1.8	57	$9.3\cdot10^{-5}$	2.2	20.5
2	0.1	435	20.3	0.566	5.0	1.0	178	$4.7\cdot10^{-6}$	1.8	20.4
3	0.2	749	19.7	0.558	8.2	3.9	211	$4.1\cdot10^{-7}$	2.6	20.0
4	0.4	774	20.1	0.660	10.3	2.8	954	$5.7\cdot10^{-8}$	2.3	20.2
5	0.6	783	17.0	0.661	8.8	2.3	453	$1.2\cdot10^{-8}$	2.1	17.1

Thus, we have developed and tested experimentally a physical approach to the study of photoelectric processes in film SC. Its first step consists in the identification, by means of the mathematic simulation, of the diode characteristics, whose influence on the experimentally observed variation in the SC efficiency upon a change in the fabrication parameters is most essential. The second and final step lies in the specification of the physical mechanisms, which determine the values of these diode parameters. Such an approach allows fulfilling the physically well-grounded optimization of the parameters of the construction-technological process of the SC formation.

The application of the newly developed physical approach to the ITO/CdS/CdTe/Cu/Au film SC allows us to establish that the optimization of the photoelectric processes in this multilayer polycrystalline system is mainly determined by two competing factors: a rise in the efficiency of the process of distribution of nonequilibrium charge carriers and a decrease in the efficiency of the their generation, as the growth in the thickness of the cadmium sulphide layer occurs.

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АНАЛІЗ ДІОДНИХ ХАРАКТЕРИСТИК ПЛІВКОВИХ СОНЯЧНИХ ЕЛЕМЕНТІВ НА ОСНОВІ CdTe

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Р е з ю м е

Розроблено фізичний підхід до оптимізації фотоелектричних процесів у плівкових багатошарових системах. Шляхом моделювання впливу світлових діодних характеристик на коефіцієнт корисної дії визначено, що оптимізація фотоелектричних процесів у плівкових сонячних елементах ITO/CdS/CdTe/Cu/Au значною мірою визначається двома конкуруючими фізичними механізмами: підвищенням ефективності процесу розподілу нерівноважних носіїв заряду та зниженням ефективності процесу їх генерації при збільшенні товщини шару сульфіду кадмію.