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DEVELOPMENT OF A METHOD FOR OBTAINING A CdS/CdTe/Cu/Au MODULE ON A FLEXIBLE SUBSTRATE DESIGNED FOR BACKUP SUPPLYING SYSTEMS PREVENTION OF EMERGENCY SITUATIONS

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The study of methods for obtaining base layers of cadmium telluride for the creation of efficient solar cells on a flexible substrate, intended for backup power supply of security systems and facility control. Considering that the polyamide film is stable up to a temperature of 450 °C, the formation of the base layers of solar cells based on cadmium telluride on flexible polyamide substrates was carried out by the method of DC magnetron sputtering. Using the chosen method, experimental samples of micromodules on a flexible substrate with series-connected solar cells based on CdS/CdTe/Cu/Au were obtained. To understand the effect of the failure of one or more solar cells on the efficiency of the entire micromodule during operation, an analysis of the initial parameters and light diode characteristics of individual solar cells of micromodules was carried out. The design of the micromodules, in which the solar cells were connected in series, made it possible to separately measure their output parameters. It was found that the creation of a Cu/Au rear tunnel contact made it possible to obtain high values of the output parameters for individual solar cells, but the micromodule contains a limitation by a shunted solar cell. However, the greatest role in reducing the efficiency of the entire micromodule is played by ineffective absorption of radiation when passing through the polyamide film, which led to a decrease in the efficiency of the entire micromodule, in which there is a shunted element, to 3.9 %. The maximum efficiency of the obtained samples of micromodules was 5.3 %

Keywords: film photocell, flexible substrate, micromodule, solar cell, cadmium telluride, current-voltage characteristic

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1. Introduction

The analysis of emergency situations shows that one of the problems of localization and elimination of consequences is a power outage due to damage to power lines. Therefore, it is necessary to provide emergency power supplies or the tools used must operate autonomously.

Modern security and control systems consume only a small part of the total energy consumption of the facility; their uninterrupted operation is ensured by the availability of electricity in the network. As a rule, such security systems have a backup power source in case of an emergency power outage in the network, but, in most cases, its charge lasts no more than 24 hours [1]. In this case, the use of solar cells becomes relevant. In general, the field of application of solar panels is spreading every day. Sometimes the most unexpected industries and the national economy turn to solar cells for help. Solar cells are out of competition in places where there is no conventional power grid, but the sun is sufficient, or in the event of prolonged damage to the grid supply of electricity.

Photovoltaic technology is one of the most important renewable energy sources, for which since the first recognition in 1839 [2]. There have been many studies to improve their effectiveness. But improving efficiency and lowering costs in photovoltaic technology still requires a lot of effort. Crystalline silicon (c-Si) solar cells are known as materials in first generation solar cells [3]. In terms of cost, performance and manufacturability, the use of new advanced materials such as amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) is being achieved in the second and third generations of solar cells. The typical conversion efficiency of first generation technologies currently ranges from 15 % to 24 %, while in second generation technologies currently ranges from 7 % to 16 % [4, 5]. The unique physical characteristics of CdTe make it possible to use this material for a number of microelectronic devices. Films of cadmium chalcogenides are increasingly used as the base layers of various devices [5]. The main goal of many scientific studies of cadmium telluride can be considered to be the development of a technology for obtaining thin films of a compound with certain electrophysical parameters.

Therefore, an urgent topic is the development of approaches to the use of photovoltaic cells based on CdTe for booking a security and control system in the event of a prolonged lack of electricity supply from engineering networks. In such a case, using solar cells as a portable power generator requires a transition from frame panels to flexible solar cells that can be placed on any surface. However, the technology of creating flexible efficient solar cells from the point of view of industrial production requires further research.

2. Literature review and problem statement

Thin-film solar cells, as a rule, can be developed in two structures, known as “superstrate” and “substrate”, depending on the direction of light entry into the volume of the device structure. In film solar cells of the “superstrate” type, light enters the cell from the side of the substrate, on which the base layers are applied and then passes into the volume of the device structure. For “substrate” film solar cells, light comes from the side opposite to the substrate. Thus, for a “superstrate” type FE, the lining must be transparent in order to transmit enough light into the volume of the instrument structure. Therefore, in most cases, the “superstrate” type is used to create efficient CdTe-based solar cells [6]. While metal substrates can be used only for the “substrate” structure, polymer substrates are used in both cases, depending on their transparency [7]. At present, the highest efficiency of CdTe-based film solar cells on a flexible substrate in the implementation of the “substrate” type reaches 13.8 %. For “substrate” film elements, 7.3 % in the case of using a polymer, and 7.8 % in the case of a metal foil, while the predicted theoretical maximum for SC based on CdTe is almost 30 % [8].

It is believed that with the “superstrate” configuration, solar cells are more efficient. This is due to the “salt” finish, which results in a decrease in the electrical resistivity of CdTe due to the generation of Cl_{Te} -V_{Cd} acceptors. In works [9, 10], the use of “salt” treatment made it possible to obtain experimental samples of solar cells with an efficiency of more than 10 %, but solar cells were manufactured on glass substrates. In the case of “substrate”, the “salt” treatment can be applied only to CdS layers [11, 12]. In this case, the crystallinity of CdTe is not optimized. Several materials are used as substrates to create flexible solar cells, each with its own advantages and disadvantages. Among metals, the most widespread are molybdenum, titanium and stainless steel, and among polymers – polyamide, polyethylene terephthalate and polyethylene naphthalate. The author of [13] used molybdenum as a flexible substrate. However, the efficiency of the obtained samples did not exceed 5 %, which is due to the complexity of the formation of an ohmic contact to such device structures. In [14], molybdenum and stainless steel were used as a flexible substrate. The resulting device structures were investigated by X-ray diffractometry, which made it possible to establish that a limiting factor, in addition to the complexity of the formation of a rear contact, is the presence of defects in the base layer in the form of dislocations. In [15], Upilex polyimide films were used as a substrate, which can withstand high temperatures (450 °C). The obtained results of the study demonstrated low values of efficiency, in the opinion of the authors, associated with ineffective absorption of radiation in the polyamide substrate.

Thus, in the case of creating film solar cells based on CdTe on flexible substrates, the limitation of the efficiency of device structures is due to two groups of factors: firstly, it is the difficulty in creating a high-quality rear contact, and secondly, the significant absorption of the visible part of the spectrum when passing through the substrate.

3. The aim and objectives of research

The aim of research is to develop a technology for creating an efficient solar module based on cadmium telluride on a flexible polyamide substrate.

To achieve this aim, it is necessary to solve the following objectives:

– to carry out research of output parameters and light diode characteristics of micromodules included in the CdS/CdTe/Cu/Au module on a flexible polyamide substrate and separately its constituent elements;

– to study the effect on the efficiency of micromodules on a flexible polyamide substrate of the output parameters of its constituent elements and the conditions for obtaining experimental samples.

4. Materials and research methods for the ITO/CdS/CdTe/Cu/Au module on a polyamide substrate

4. 1. Obtaining samples of the ITO/CdS/CdTe/Cu/Au module on a polyamide substrate

The investigated solar module based on CdS/CdTe consisted of four micromodules connected in parallel. Each micromodule consisted of five solar cells connected in series (Fig. 1). A set of metal masks was used to manufacture the module (Fig. 2). This method is more economical than photolithography. The module was manufactured on polyamide substrates, Kapton brand, manufactured by DuPont, amber color, 50 μm thick, using the method of magnetron sputtering of the target. The target was a compressed mechanical mixture of In_2O_3 (90 wt %) and SnO_2 (10 wt %).

Fig. 1. Appearance of the solar cell module

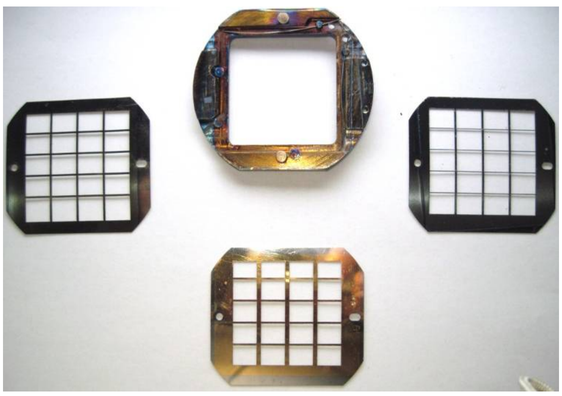

Fig. 2. The system of masks for the module manufacture

ITO films were formed at a deposition temperature of 300 °C. For deposition of ITO films, a mask was used without separation into individual electrodes. The initial partial pressure was 10^{-4} Pa. The specific power of the magnetron was 1.5 W/cm^2, which corresponds to the range of values that are usually used to obtain transparent and electrically conductive ITO films [16]. Sputtering of ITO was carried out in an argon-oxygen mixture at a pressure of 8–10^{-1} Pa. Under such conditions, layers were formed with a surface resistance of 10 Ohm/ð with an average transmittance in the visible spectral range of about 90 %, which is achieved by reducing their thickness to 0.1 μm [16].

The same mask was used to apply a layer of cadmium sulfide and telluride. The deposition of these layers was carried out in a single technological cycle by the method of thermal vacuum deposition from graphite evaporators at an initial vacuum of 10^{-4} Pa without violating it.

The resulting device heterosystems were subjected to the standard "chloride" treatment for this type of PE. In this case, smaller mask sizes were used. This is due to the fact that cadmium telluride layers were used as dielectric layers that separated the elements from each other, on which the cadmium chloride layer did not influences and which, therefore, were not subjected to "salt" treatment, in which the series resistance decreases. To carry out the "salt" treatment, $CdCl_2$ films were deposited on the surface of CdTe layers by thermal evaporation without heating the substrate. It is well known that "salt" treatment [17] causes an increase in efficiency by several times. As a result of such treatment, a decrease in the electrical resistivity of CdTe occurs due to the generation of acceptors Cl_{Te}-V_{Cd} with a concentration of about 10^{14} cm^{-3}, decreases R_p. Small grain size transforms into a structure of free orientation with large grain sizes. As a result, the probability of partial shunting of the separating barrier by the grain boundary surface decreases, causing an increase in R_{sh}. Then, the obtained ITO/CdS/CdTe/$CdCl_2$ multilayer film systems were annealed in air in a closed volume at a temperature of 430 °C for 25 min. To remove the reaction products, the annealed samples were etched in a 5 % bromine solution in methanol.

To form the PE back electrodes, two-layer Cu/Au electrical contacts were deposited on the etched surface of cadmium telluride in a vacuum installation by thermal evaporation. Since it is impossible to obtain efficient device structures without a copper interlayer, a nanosized copper layer 2 nm thick was deposited on the surface of cadmium telluride. Minimizing the thickness of the copper layer was aimed at increasing the degradation stability of the device structure.

4. 2. Technique of measurement and analytical processing of light current-voltage characteristics of a module on a flexible polyamide substrate

Measurements of the light current-voltage characteristics (hereinafter – CVC) were carried out according to the method described in [18]. Simulation of solar radiation close to the standard AM1.5 mode was carried out using a system of LEDs.

The light CVC of the micromodule and separately of each of the solar cells included in its composition were measured by the compensation method in a stationary irradiation mode, close to the standard AM1.5. The determination of the initial parameters and light diode characteristics was carried out according to the experimental light volt-ampere characteristics. Analytical processing of the light CVC of the module under study and separately of the solar cells included in its composition was carried out using a personal computer.

The relationship between the PVC efficiency and the light diode characteristics is implicitly described by the theoretical light PVC CVC:

$$J_l=-J_p+J_0\{\exp[e(V_l-J_lR_s)/(AkT)]-1\}+(V_l-J_lR_s)/R_{sh}, \quad (7)$$

where J_l – current density flowing through the load, e – electron charge; k – Boltzmann constant, T – solar cell temperature; V_l – voltage drop across the load.

According to the numerical simulation program [18], analytical expression (7) for light CVC turns into an expression that has the form:

$$I_l=A_0-A_1 V_l-A_2\exp(A_3V_l+A_4I_l), \quad (8)$$

$$A_0=(I_{ph}+I_0)R_{sh}/(R_s+R_{sh}), \quad (9)$$

$$A_1=1/(R_s+R_{sh}), \quad (10)$$

$$A_2=I_0R_{sh}/(R_s+R_{sh}), \quad (11)$$

$$A_3=e/(AkT), \quad (12)$$

$$A_4=eR_s/(AkT). \quad (13)$$

Using expression (2) and the experimentally obtained values of I_l and V_l, by varying the values of the above coefficients A_0, A_1, A_2, A_3, A_4, they achieve the best approximation of the experimental data $I_l=I_l(V_l)$ of the curve described by the transformed theoretical expression (2). Usually, during analytical processing, the average deviation does not exceed 10^{-8}, which corresponds to a relative error in determining the initial parameters and light diode characteristics at a level of no more than 1 %. After finding the specified coefficients that provide the best approximation, the initial parameters of the PVC are determined: I_{sc}, V_{oc}, FF, P_{nm}, efficiency. Light diode characteristics R_s, R_{sh}, A and I_0 are calculated according to the found coefficients A_0, A_1, A_2, A_3, A_4, with the help of relations (3)–(7) [19]. The error in determining the initial parameters and light diode characteristics is determined not only by the value of the root-mean-square deviation, but also by the error in measuring the light CVC.

5. Research results for the ITO/CdS/CdTe/Cu/Au module on a polyamide substrate

5. 1. Results of studying the light CVC of CdS/CdTe/Cu/Au micromodules on a flexible polyamide substrate

The initial parameters of the micromodules included in the ITO/CdS/CdTe/Cu/Au module with series connection of elements were obtained by analytical processing of the light CVC (Table 1).

Table 1

Output parameters of ITO/CdS/CdTe/Cu/Au micromodules with series connection of solar cells

Micromodule	V_{oc}, mV	J_{sc}, mA/cm^2	FF	Efficiency, %
M5_1	2,449	2.8	0.59	4.0
M5_2	3,489	2.7	0.39	3.7
M5_3	3,572	2.8	0.54	5.3
M5_4	3,052	2.1	0.56	3.5

The light CVC of micromodules, measured at a luminous flux power of 100 mW/cm^2 and with a series connection of solar cells, are shown in Fig. 3, 4.

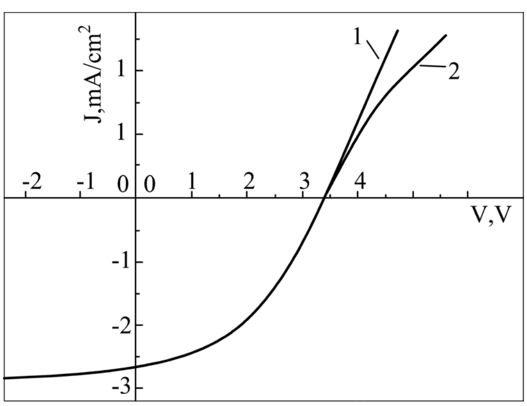

Fig. 3. Light CVC of micromodule M5_1 with a series connection of four (1) and five (2) SCs

As it is possible to see from the Table 1, with a series connection of elements in the composition of micromodules, the efficiency of micromodules reaches the maximum efficiency value at the level of 5.3 %.

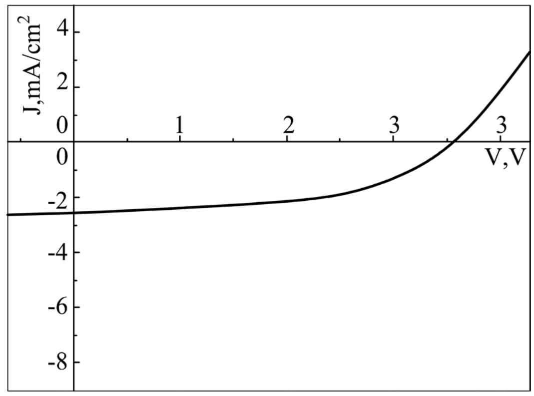

Fig. 4. Light CVC of micromodule M5_3 with a series connection of five SCs

5. 2. Results of the study of the effect of the output parameters of constituent elements and conditions for obtaining experimental samples on the efficiency of micromodules on a flexible polyamide substrate

By analytical processing of the light CVC, the initial parameters and light diode characteristics of the investigated solar cells were obtained separately and when they were connected in series as part of micromodules.

The results obtained are presented in Tables 2, 3, where S is a single SC, $S2$–$S5$ is a micro-module M5_1 with a serial connection of four SCs, $C1$–$C5$ is a micro-module with a serial connection of five SC.

Table 2

Output parameters and light diode characteristics of SE micromodule M5_1

Sample	$S1$	$S2$	$S3$	$S4$	$S5$	$S2$–$S5$	$S1$–$S5$
V_{oc}, mV	97	748	755.5	133	752	2389	2486
J_{sc}, mA/cm^2	10.6	16.6	18.2	12.6	16.2	3.4	2.7
FF, rel.unit	0.27	0.61	0.61	0.26	0.59	0.59	0.58
Efficiency %	0.3	7.5	8.4	0.4	7.1	4.9	3.9
R_s, Ohm×cm^2	4.1	8.77	8.47	3.03	8.77	186	239
R_{sh}, Ohm×cm^2	9.4	498	673	808	623	7×10^3	1×10^5
J_0, A/cm^2	9×10^{-4}	5×10^{-11}	4×10^{-11}	9×10^{-6}	6×10^{-9}	2×10^{-14}	2×10^{-14}
A, rel.unit	1.8	1.5	1.5	1.1	2.0	3.7	3.8
J_{ph}, mA/cm^2	18.4	16.7	18.4	17.3	16.5	3.5	2.8

Table 3

Output parameters and light diode characteristics of SC micromodule M5_3

Sample	$C1$	$C2$	$C3$	$C4$	$C5$	C1–C5
V_{oc}, mV	752	762	552	758	741	3582
J_{sc}, mA/cm^2	15.2	16.7	16.9	17.8	16.9	2,7
FF, rel.unit	0.54	0.61	0.28	0.60	0.55	0.55
Efficiency %	6.2	7.7	2.6	8.1	6.8	5.3
R_s, Ohm×cm^2	5.6	5.7	12.8	6.3	10.1	243
R_{sh}, Ohm×cm^2	238	476	24	520	400	15630
J_0, A/cm^2	3×10^{-7}	5×10^{-8}	6×10^{-8}	2×10^{-8}	7×10^{-9}	5×10^{-8}
A, rel.unit	2.8	2.3	2.0	2.2	2.0	2.8
J_{ph}, mA/cm^2	15.6	16.9	25.9	18.0	17.3	2.8

As it is possible see from the Tables 2, 3, the solar cell in the composition of micromodules M5_1 has the highest efficiency at the level of 8.4 %. However, the maximum efficiency of the entire micromodule is limited to 4.9 %.

6. Discussion of the research results for the ITO/CdS/CdTe/Cu/Au module on a polyamide substrate

The study of the initial parameters of micromodules in the composition of the module on a polyamide substrate showed that the maximum efficiency (Table 1) is observed for micromodule M5_3 at the level of 5.3 %. Serial connection of solar cells in micromodules M5_1, made it possible to obtain an efficiency of 3.9 %. Such a low value of efficiency for the micromodule M5_1 in comparison with the micromodule is associated with the low value of V_{oc} for M5_3. It is likely that the low V_{oc} value for the M5_1 micromodule is due to the shunting of solar cells into the micromodules. This assumption was confirmed by analyzing the initial parameters and light diode characteristics of single solar cells in modules M5_1 and M5_3. Analysis of the initial parameters and light diode characteristics of single solar cells of modules M5_1 and M5_3 showed that the first of the micromodules (M5_1) had two practically shunted solar cells. The second micro-module (M5_3) had one solar cell with a significantly lower efficiency.

Analysis of the Table 2 shows that for individual solar cells of the first micromodule the light diode characteristics and output parameters varied in the following intervals: R_s=(3–9) Ohm×cm^2, R_{sh}=(9–620) Ohm×cm^2, J_0=($4{\cdot}10^{-11}$–$9{\cdot}10^{-4}$) mA/cm^2, V_{oc}=(97–755) mV, J_{sc}=(10.6–18.2) mA/cm^2, FF=(0.26–0.61), efficiency=(0.3–8.4) %, for the second micromodule – R_s=(5.5–10) Ohm×cm^2, R_{sh}=(24–520) Ohm×cm^2, J_0=($7{\cdot}10^{-9}$–$3.0{\cdot}10^{-7}$) A/cm^2, V_{oc}=(550–760) mV, J_{sc}=(15–17,8) mA/cm^2, FF=(0.28–0.6), efficiency=(2.6–8.1) %.

Thus, it can be argued that the low values of the efficiency of micromodules in comparison with the efficiency of single solar cells as part of a micromodule is due to a decrease in all output parameters. The creation of a Cu/Au rear tunnel contact made it possible to obtain high V_{oc} values for individual solar cells, but as part of a micromodule it is limited to a shunted solar cell. The greatest role in reducing the efficiency of the entire micromodule has J_{sc}, both for the first and for the second micromodules. This circumstance may be associated with ineffective absorption of radiation when passing through a dark yellow polyamide film. Therefore, for further research, it is necessary to focus on reducing the thickness of the polyamide film.

7. Conclusions

1. Experimental samples of a module based on cadmium telluride on a flexible polyamide substrate, which consists of four micromodules with solar cells connected in series, have been obtained by the method of DC magnetron sputtering. The study of the output parameters and light diode characteristics of the micromodules included in the module is carried out. It is found that the maximum efficiency of a micromodule in a module reached 5.3 %.

2. It has been established that low values of the efficiency of micromodules are due to partial shunting of solar cells in the composition of micromodules and ineffective absorption of the visible part of radiation when passing through a polyamide substrate.

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