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Research Article

Development of Back and Front Contacts for CdTe Layer in Tandem Flexible Photoelectric Converters on Basis of $CdTe/CuInSe_2$

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By the method of nonreactive high-frequency magnetron sputtering on Upilex polyimide films, transparent and conductive layers of ITO were obtained. These layers, after high-temperature annealing, at temperatures typical for the solar cell formation, had a resistance of 11 ohm/□ and a transmittance of up to 72%. The use of such an ITO layer with the addition of a 100 nm thick layer of undoped zinc oxide, as the front contact, and Cu/ITO composition, as the back contact, made it possible to obtain a flexible solar cell polyimide/ITO/CdS/CdTe/Cu/ITO with an efficiency of 10.4%. With a thickness of the base layer of cadmium telluride 2.5 μm, the average transmittance of the SC in the 850-1100 nm wavelength range is 46.8%. The developed design of a flexible solar cell based on cadmium telluride due to the use of a transparent back contact with a comb metal electrode is easily interfaced with existing designs of flexible solar cells based on copper and indium diselenide, which allow the formation of flexible tandem photoelectric converters $CdTe/CuInSe_2$.

1. Introduction

At present, economical technologies for the formation of base and interfacing layers of thin-film solar cells are being developed as an alternative to widely used solar cells (SCs) based on crystalline silicon [1-6]. Among the semiconductor compounds, the highest theoretical efficiency in terrestrial conditions, which is 29%, has film layers of cadmium telluride with a band gap of 1.46 eV [7, 8].

Recently, flexible solar cells based on CdS/CdTe and based on copper and indium diselenide $CuInSe_2$ (CIS) have been actively developed (see, for example, [9–11]).

A characteristic feature of this type of solar cells is a significant reduction in their weight by replacing the glass substrate with a thin polyimide film or metal foil on which the instrument structure is formed and also the possibility of mounting on any complex surface.

The modern direction of increasing the efficiency of photoelectric conversion is the creation of tandem instrument structures. In such instrumentation structures, several photoelectrically active base layers with different bandgap width (E_g) are used. In the design of tandem photoelectric converters, it is promising to use film solar cells with a base layer of CdTe and $CuInSe_2$. The combination of the energy structure of these base layers ($E_{gCdTe} = 1.46$ eV and $E_{gCuInSe_2} =$ 1.05eV) makes it possible to efficiently convert solar radiation, both in terrestrial and under atmospheric conditions. One of the stages in the development of efficient flexible solar cells based on CdS/CdTe is the development of a technology for obtaining transparent and electrically conductive front electrodes. In addition, for the use of CdS/CdTe film solar cells in tandem photoelectric converters, these solar cells should have transparent back electrodes. The use of a solar cell with a wider base layer of transparent back electrodes allows photons that are not absorbed to enter the surface of the next SC of a tandem photoelectric converter.

At present, laboratory samples of tandem photoelectric converters based on CdTe/CIS have been tested only when formed on glass substrates [12]. At the same time, the problem of electrical connection of two solar cells to the instrumental tandem structure has not been solved. Therefore, the development of back and front electrodes for wide-band base layers of flexible tandem photovoltaic converters based on CdTe/CIS is an actual problem; the solution of which will allow the creation of film flexible instrument structures with an efficiency higher than the efficiency of solar cells based on crystalline silicon.

2. Technique for Obtaining Samples and Carrying Out Experimental Studies

The ITO layers were deposited by the method of nonreactive high-frequency magnetron sputtering in an industrial installation MRC-6031 on Upilex polyimide films; the thickness of which was 7 μm. At sputtering a target was used, which is a compressed mechanical mixture of powders In_2O_3 (90 wt%) and SnO_2 (10 wt%) of semiconductor purity. The ITO was sprayed in an argon-oxygen mixture at a pressure of $8 \cdot 10^{-1}$ Pa. The concentration of oxygen in the composition of the argon-oxygen mixture was CO = 3 Vol.%, the specific power of the magnetron $P_w = 1.5\,\mathrm{W/cm^2}$. In the preparation of ITO layers, the temperature of the substrate varied from $T_s = 20^\circ C$ to $T_s = 430^\circ C$. The upper limit of the deposition temperature was determined by the temperature stability of the polyimide film.

On flexible substrates with the ITO layer, CdS films were deposited by thermal evaporation at a substrate temperature of 200°C. Then, vacuum annealing was carried out at a temperature of 430°C for 30 minutes. This was necessary in order, during the subsequent application of cadmium telluride, to avoid the formation of unstable solid solutions of CdS_xTe_{1-x}, which can decay during the final high-temperature "chloride" treatment of the freshly prepared basic CdS/CdTe heterosystem, which leads to a decrease in the efficiency of the SC. After this vacuum annealing without disturbing the vacuum at a substrate temperature of 300°C, CdTe films were deposited. The resulting device heterosystems underwent a "chloride" treatment. For this purpose, $CdCl_2$ films were deposited on the surface of CdTe layers by thermal evaporation without heating the substrate. Then, the resulting multilayer film systems were annealed in air in a closed volume at a temperature of 430°C for 25 minutes. To remove reaction products and form near-surface layers of cadmium telluride enriched with tellurium, the annealed samples were etched in a 5% solution of bromine in methanol. To form the upper electrodes of SC on the etched surface of cadmium telluride, copper nanolayers were deposited by thermal evaporation, and then, ITO films were formed by the magnetron sputtering method.

To reveal the structural features of film layers, their diffraction spectra were measured with θ-2θ scanning with Bragg-Brentano focusing in the radiation of a copper anode in the range of angles $2\theta = 20/120^\circ$. At the diffractogram processing, the position, intensity, and width of the $W_{1/2}$ peaks were analyzed.

The preferential orientation of the films was determined from the value of the texture coefficient C_i calculated by the formula [13]

$$C_i = \frac{NI_i}{I_{i0}\sum_1^N I_i/I_{i0}}, \tag{1}$$

where I_i is the intensity of the detected i-th peak; I_{i0} is the intensity of the i-th peak, according to the JCPDS table data for this phase; and N is the number of diffraction maxima detected in the analysis of diffractograms (reflections corresponding to multiple indices are not taken into account). To compare the samples by the degree of texturization, the parameter G was calculated [13]:

$$G = \sqrt{\sum_1^N (C_i - 1)^2/N}. \tag{2}$$

Precision determination of the lattice period of the base layers of cadmium telluride was carried out using the Nelson-Rile extrapolation function $f(\theta) = (\cos^2\theta/\sin\theta + \cos^2\theta/\theta)/2$.

To investigate the surface electrical resistance of ITO films, a four-probe method was used. The determination of concentration (n) and mobility (μ) of the main charge carriers in ITO films was carried out by the e.m.f. Hall method. To study the optical properties of semiconductor films on the SF-46 two-channel spectrophotometer, the spectral dependencies of their transmittance coefficient in the wavelength range 300-1100 nm were measured.

In the conditions of illumination of AM 1 with the luminous flux of $100\,\mathrm{mW/cm^2}$, the light current-voltage characteristics (CVC) of the manufactured solar cells were measured and the output parameters were determined: the short-circuit current density (J_{sc}), the open-circuit voltage (U_{oc}), the filling factor (FF), and ultimately, efficiency (η). According to the equivalent SC scheme, the quantitative characteristics of photovoltaic processes are the light diode characteristics of the solar cell: the photocurrent density (J_{ph}), the density of the diode saturation current (J_0), the diode ideality coefficient (A), the series resistance (R_s), and the shunting resistance (R_{sh}), calculated per unit area of the solar cell.

The relationship between the efficiency of solar cells with light diode characteristics in an implicit form is described by the theoretical light CVC of the solar cell [14]:

$$J = -J_{ph} + J_0\left\{\exp\left[\frac{e(U - JR_s)}{(Ak_B T)}\right] - 1\right\} + \frac{(U - JR_s)}{R_{sh}}, \tag{3}$$

where J is the current density flowing through the load; e is the electron charge; k_B is the Boltzmann constant; T is the temperature of the solar cell; and U is voltage drop on the load.

By approximating the experimental light current-voltage characteristics with the theoretical dependence (3), the light diode characteristics and efficiency of the solar cell were calculated. In this case, the value of the efficiency, calculated with the help of the theoretical light CVC characteristics and determined experimentally, coincided with an accuracy of 0.05%.

3. Results and Discussion

3.1. Investigation of the Structure, Optical, and Electrical Properties of ITO Layers Formed on Flexible Polyimide Substrates. The analysis of the phase composition of the deposited ITO layers (see Figure 1(a)) shows that in the investigated range of the deposition temperature $T_s = 20$–430°C, they have a cubic modification, which is unambiguously confirmed by the presence of reflections from the crystallographic planes (211), (222), (400), (411), (331), (431), (440), (541), (611), (622), (444), characteristic for this phase.

It was found that the obtained ITO films are oriented in the (100) direction. Quantitative analysis of the preferential orientation degree showed that when the substrate temperature increases, the degree of preferential orientation of the ITO layers increases from $G = 0.07$ at $T_s = 20°C$ to $G = 0.15$ at $T_s = 430°C$.

As the substrate temperature increases, the width of all observed peaks also decreases, which indicates a decrease in the defectiveness of the crystal structure.

Investigations of the optical and electrical properties of ITO films obtained at different substrate temperatures (Table 1) indicate that with increasing T_s from 20°C to 430°C, a monotonic decrease in their surface resistance from $R_\square = 18.1$ ohm/□ to $R_\square = 4.6$ ohm/□ is observed.

Reducing $R_\square$ with increasing deposition temperature due to increased mobility of the majority charge carriers from $\mu = 11.7\,\mathrm{cm^2/(V \cdot s)}$ at $T_s = 20°C$ to $\mu = 38.5\,\mathrm{cm^2}$ at $T_s = 430°C$ on a background substantially unchanged concentration value of the majority charge carriers. The growth of the majority carrier mobility with an increase in the deposition temperature is usually associated with a decrease in scattering of charge carriers with a decrease in defectiveness (see, for example, in [15, 16]), which was fixed experimentally during X-ray structural studies.

As long as the number of photons entering the base layer in the range of its photosensitivity significantly influences the efficiency of solar cells, the average transmission coefficient ($T_{500-900}$) of ITO/polyimide systems was determined in the spectral range from 500 nm to 900 nm, which corresponds to the photosensitivity region of the solar cell based on CdS/CdTe. In the wavelength range from 500 to 900 nm, the average transmittance coefficient of the ITO/polyimide systems obtained in the temperature range of deposition 20–430°C was varied in the range from 68.8% to 70.9% (Table 1).

ITO films should demonstrate a combination of high transmittance coefficient and low surface electrical resistance not only in the initial state but also in the composition of the instrument structure of the solar cell. The use of high-temperature operations in the course of further formation of the ITO/CdS/CdTe SC can lead to a change in the crystal structure and to the degradation of the initial optical and electrical properties.

The most significant effect on the electrical properties of the front electrodes during the formation of the ITO/CdS/CdTe solar cell is provided by the "chloride" treatment, which can be modeled by annealing ITO films in air at 430°C for 25 minutes. Therefore, in order to study the evolution of the crystal structure, the optical and electrical properties of the initial ITO layers during the formation of flexible solar cells based on CdS/CdTe, ITO films obtained at different deposition temperatures on polyimide substrates were annealed in air at 430°C for 25 minutes. Typical X-ray diffractograms and transmission coefficient of the films before and after annealing are shown in Figures 1 and 2, accordingly. The processing of X-ray diffractograms indicates that annealing in air leads to an increase in the degree of preferential orientation of the ITO layers in the direction (100) from $G = 0.08$ to $G = 0.37$ at $T_s = 20°C$ and from $G = 0.15$ to $G = 0.27$ at $T_s = 430°C$ (see Table 2). Thus, a more significant change in the crystal structure after annealing in air is characterized by ITO layers obtained at lower deposition temperatures. Analysis of the data in Table 2 shows that the interplanar distances for planes (222) and (400) after annealing in air vary significantly.

In this case, $d_{(222)}$ and $d_{(400)}$ before annealing are below the corresponding tabulated values (2.921 Å and 2.529 Å [17]) and higher after annealing.

According to the published data [18], in ITO films formed on Kapton polyimide films, there is a significant lack of oxygen compared with the stoichiometric value, which leads to a decrease in the interplanar distances in comparison with their tabulated values. In the ITO layers studied by us which formed on the Upilex polyimide films, a similar mechanism for reducing interplanar distances can also be observed. Annealing in air of ITO layers formed on polyimide films leads to the saturation of the layer with oxygen, which can cause the observed experimentally significant growth of $d_{(222)}$ and $d_{(400)}$.

In freshly produced ITO films, another mechanism for reducing interplanar distances can also be realized in comparison with theoretical values.

As long as the coefficient of thermal expansion for polyimide is $\alpha_{\mathrm{poli}} = 36 \cdot 10^{-6}\,K$ and for ITO $\alpha_{\mathrm{In2O3}} = 10 \cdot 10^{-6}\,K$, then in accordance with the ratio $\Delta d/d = (\alpha_1 - \alpha_2)\Delta T$, the interplanar distances for ITO films, formed on polyimide at a temperature of 430°C after elastic compression of the flexible substrate upon cooling, should increase by $\Delta d = 0.01$ Å. If, however, the polyimide film undergoes plastic deformation when heated to 430°C, then in the ITO layers, due to tensile stresses on the side of the flexible substrate, the interplanar distances should decrease, which was observed experimentally. Since the used deposition temperatures are close to the limit of thermal stability of polyimide films, the plastic deformation of the polyimide film during the deposition of ITO layers is highly probable.

In the ITO layers, after annealing in air, the angular width of all diffraction peak decreases. The width of the peak (211),

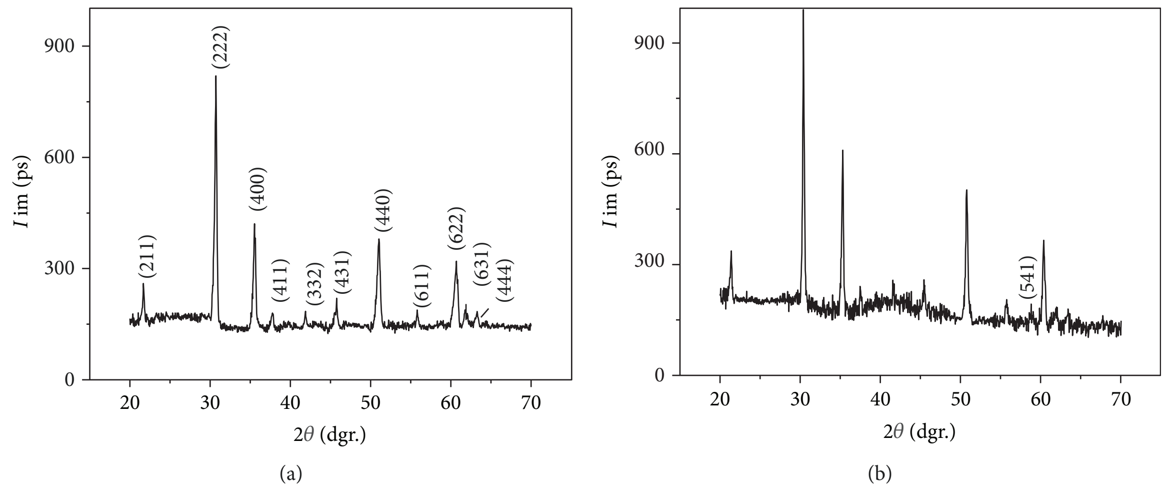

Figure 1: The crystal structure of ITO films on the polyimide film ($P_w = 1.5\,\mathrm{Wt/cm^2}$, CO = 3 Vol.%): (a) $T_s = 430°\mathrm{C}$; (b) $T_s = 430°\mathrm{C}$, after annealing.

Table 1: The effect of deposition temperature on the optical and electrical properties of ITO layers formed on flexible substrates.

T_s (°C)	t (μm)	$T_{(500-900)}$ (%)	$R_\square$ (ohm/□)	$\rho \cdot 10^4$ (ohm·cm)	$n \cdot 10^{20}$ (cm^{-3})	μ (cm^2/(V·s))
20	0.51	69.5	18.1	9.2	5.8	11.7
200	0.50	70.6	12.6	6.3	5.9	16.8
250	0.54	70.3	10.4	5.6	6.0	18.6
300	0.49	70.9	8.8	4.3	5.7	25.5
350	0.52	69.1	6.2	3.2	6.1	32.0
400	0.53	69.5	6.0	3.2	5.9	33.1
430	0.54	68.8	4.6	2.5	6.5	38.5

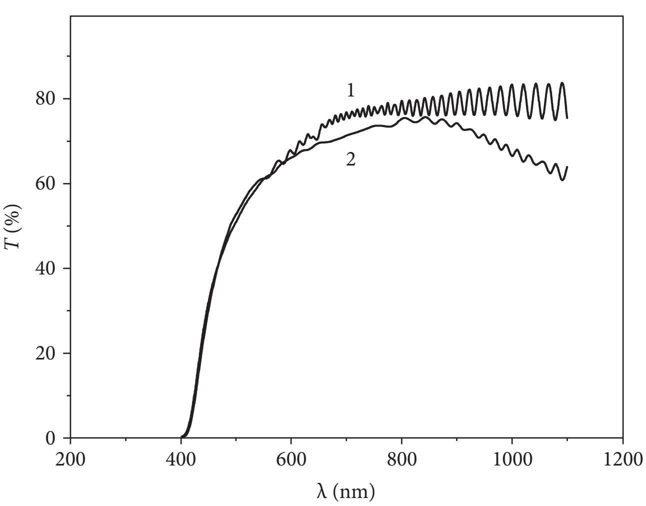

Figure 2: Optical properties of ITO/polyimide systems before (1) and after (2) annealing.

located at small angles, decreases by a factor of two, which indicates that the dimensions of the coherent scattering regions increase. A significant decrease in the width of the peak (622), located at large angles, indicates a simultaneous microdeformation decrease in the annealed ITO layers. Experimentally, we have shown that heat treatment in air causes a slight increase in the transmittance coefficient of ITO/polyimide systems against the background of a more significant increase in the surface electric resistivity of ITO formed on a polyimide substrate (Table 3).

Measurements of the Hall e.m.f indicate that the growth of $R_\square$ is due to a decrease in the concentration of the majority charge carriers against a background of less significant growth of their mobility. For example, for ITO layers obtained without heating the substrate, annealing in air leads to a decrease in the concentration of the majority charge carriers six times from $n = 5.8 \cdot 10^{20}\,\mathrm{cm^{-3}}$ to $n = 1.0 \cdot 10^{20}\,\mathrm{cm^{-3}}$ while the mobility of the majority charge carriers increases three times from $\mu = 11.7\,\mathrm{cm^2/(V \cdot s)}$ to $\mu = 29.6\,\mathrm{cm^2/(V \cdot s)}$.

We believe that the decrease in the concentration of the majority charge carriers is due to the oxidation of the alloying impurity. The increase in the mobility of the majority charge carriers is associated with an increase in the sizes of coherent scattering regions and a decrease in microdeformations in the annealed ITO layers.

It was found that only ITO films deposited at a substrate temperature of 430°C, after annealing in air, have electrical parameters (the surface resistance is 11 ohm/□), which makes it possible to use them in the construction of effective flexible solar cells based on cadmium sulfide and cadmium telluride. The average transmission coefficient of the ITO/polyimide system in the wavelength range corresponding to the photosensitivity of solar cells based on cadmium sulfide and cadmium telluride reaches 72%.

TABLE 2: Effect of annealing in air on the structure characteristics of ITO films formed on polyimide substrates at a temperature of 430°C.

Condition of ITO layer	G (urb. un.)	$d_{(222)}$ (Å)	$d_{(400)}$ (Å)	$\Delta d_{(222)}$ (Å)	$\Delta d_{(400)}$ (Å)	$\Delta W_{1/2(211)}$ (dgr.)	$\Delta W_{1/2(622)}$ (dgr.)
Before annealing	0.15	2.910	2.526	+0.011	+0.003	0.24	0.52
After annealing	0.27	2.937	2.542	-0.016	-0.013	0.12	0.33

TABLE 3: Effect of annealing in air on the optical and electrical properties of ITO layers obtained at different substrate temperatures.

T_s (°C)	t (μm)	$T_{(500-900)}$ (%)	$R_\square$ (ohm/□)	$\rho \cdot 10^4$ (ohm·cm)	$n \cdot 10^{20}$ (cm^{-3})	μ (cm^2/(V·s))
20	0.51	71.5	41.4	21.1	1.0	29.6
200	0.50	72.2	38.3	19.1	1.1	29.7
250	0.54	71.8	31.1	16.8	1.2	31.0
300	0.49	72.3	23.7	11.6	1.7	31.7
350	0.52	71.1	18.5	9.6	1.9	34.3
400	0.53	70.9	15.5	8.2	2.2	34.6
430	0.54	72.0	11.1	6.0	2.8	37.2

For annealed ITO films formed on polyimide substrates at deposition temperatures of 430°C and annealed in air at the same temperature for 25 minutes, repeated similar annealing in air was carried out. Investigations of the crystalline structure of the reannealed layers indicate the absence of appreciable changes in the parameters of their crystal structure. The value of the surface resistance of the layer increased by only a few percent; the average transmittance coefficient in the 500–900 nm range did not change. Thus, the annealed ITO films have stable properties.

3.2. Development of Flexible Solar Cells Based on CdS/CdTe with a Transparent Back Electrode. To use a CdS/CdTe solar cell as a part of tandem photoelectric converters, a transparent back electrode must be formed on the surface of the CdTe base layer. It is known [19] that the back electrodes Cu/Au form low-resistance tunnel junctions with a cadmium telluride layer. According to [20], when a CdTe surface is etched in a solution of bromine in methanol and diffused into the base layer of copper near the surface, an interlayer of $p+$ type of electrical conductivity is formed, which provides a low contact resistance. It was shown in [21] that the copper diffusion at a copper layer thickness of 10 nm leads to the degradation of the output characteristics of the solar cell. On the other hand, in the development of bifacial sensitive solar cells on a glass substrate [22], it was shown that without the use of copper these solar cells have a low efficiency. Therefore, in the development of transparent back electrodes, as back contacts to CdTe layers, Cu/ITO film compositions with a copper film thickness of less than 1 nm were used [23].

In the formation of flexible solar cells, the deposition temperature of ITO was 430°C; the thickness of the cadmium sulfide layer was $d_{Cds} = 0.5\,\mu$m. Polyimide/ITO/CdS/CdTe/Cu/ITO SCs with different thicknesses of the CdTe base layer were investigated. As shown in [12], the maximum efficiency of the SC is observed when the cadmium telluride layer is $d_{CdTe} = 2.5\,\mu$m. In [24, 25], it was also found that at a given thickness of the cadmium telluride layer, optimization of the photoelectric conversion is observed at a well-defined thickness of the cadmium chloride layer and the time of the "chloride" treatment. In our case, using a flexible substrate, an efficiency of 9.2% was obtained with the thickness of cadmium chloride $d_{CdCl_2} = 0.08\mu$m.

The current-voltage characteristics of a solar cell under illumination from the front side are shown in Figure 3; curve 1 and their output parameters and diode characteristics are given in Table 4.

In [26], it was shown that the use of an additional undoped layer with the thickness of 50–120 nm at the front contact between ITO and CdS layers leads to an increase in the efficiency of the solar cell. As such a layer, we used undoped ZnO layers with 100 nm thickness and this allowed to increase the efficiency of flexible solar cells from $\eta = 9.2\%$ to $\eta = 10.4\%$ (Figure 3 curve 2 and Table 4).

Figure 4 shows the transmittance spectra of the polyimide/ITO/ZnO/CdS/CdTe/Cu/ITO solar cell with different thicknesses of the CdTe layer. With a base layer thickness of 2.5 μm, the average transmittance of solar cells in the wavelength range 850-1100 nm is 46.8%, and for a base layer thickness of 1.0 μm, it is 55.2%. Despite the fact that the transmission of polyimide/ITO/ZnO/CdS/CdTe/Cu/ITO solar cell with the CdTe layer thickness decreasing to 1 μm increases, their efficiency decreases to 7%. Therefore, in order to create a flexible tandem CdTe/$CuInSe_2$ solar cell, the thickness of the CdTe 2.5 μm layer will be optimal.

CIS flexible SCs are developed on metallic and polymer foil substrates (see [27–29]). The following construction of effective thin-film solar cells based on CIS, Mo/$CuInSe_2$/$CuIn_3Se_5$/CdS/ZnO/ZnO:Al, was considered in paper [30]. In this construction, n^+-n-p structure is formed, in which the high-conductivity phase of the ZnO:Al plays the role of the n^+ layer, and the thin high-resistivity layers of ZnO and CdS play the role of the n-type interlayer. In such solar cell, the space charge region is concentrated in the base layer of $CuInSe_2$ [31] due to the presence of an interlayer of

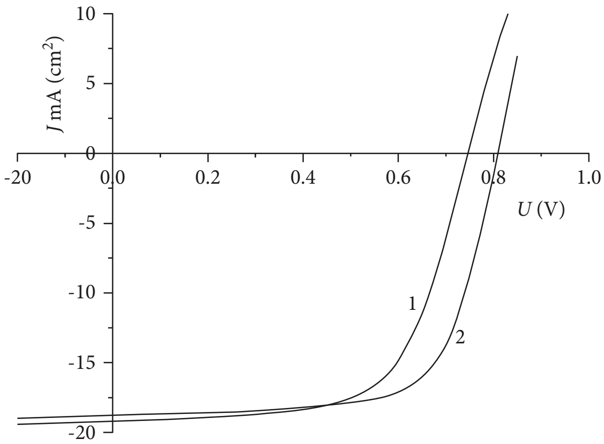

Figure 3: Light current-voltage characteristics of flexible polyimide/ITO/CdS/CdTe/Cu/ITO solar cell (1) and flexible polyimide/ITO/ZnO/CdS/CdTe/Cu/ITO solar cell (2).

Table 4: Output parameters and light diode characteristics of flexible polyimide/ITO/ZnO/CdS/CdTe/Cu/ITO solar cells under illumination from the front side.

Output parameters and light diode characteristics	SC without ZnO layer	SC with ZnO layer d_{ZnO} = 100 nm
J_{sc} (mA/cm^2)	19.2	18.7
U_{oc} (mV)	750	808
FF (rel. units)	0.64	0.69
η (%)	9.2	10.4
J_{ph} (mA/cm^2)	19.4	19.0
R_s (ohm·cm^2)	3.3	2.3
R_{sh} (ohm·cm^2)	600	510
A (rel. units)	2.2	2.0
J_0 (A/cm^2)	$3.7 \cdot 10^{-8}$	$4.9 \cdot 10^{-9}$

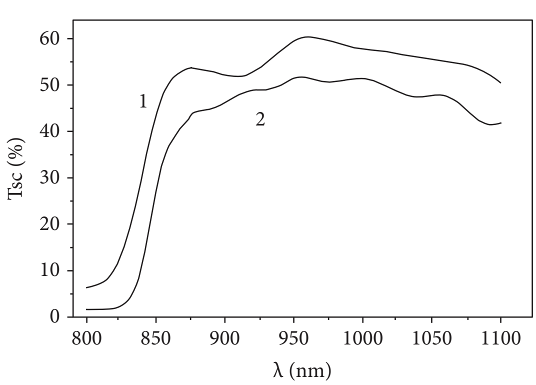

Figure 4: Transmittance spectra of polyimide/ITO/ZnO/CdS/CdTe/Cu/ITO solar cell.

n-$CuIn_3Se_5$, which is synthesized as a "pseudohomo compound" inside the $CuInSe_2$ layer [32].

The main problem in creating a tandem photoelectric converter based on CdTe/$CuInSe_2$ is the inability to generate an SC based on cadmium telluride on the surface of solar cells based on CIS. To prevent the diffusion of aluminum from the zinc oxide layer into high-resistivity interlayers, the deposition of ZnO:Al in high-efficiency SCs is carried out without heating the substrate. According to the results in Section 3.1, the formation of an ITO layer with optimal electrical and optical properties for use in the construction of effective CdTe-based solar cells should occur at a temperature of 430°C. If this process is carried out directly on the surface of the SC based on the CIS, this will lead to the degradation of the output parameters of this (such) solar cell. Therefore, when creating a tandem photoelectric converter, it is expedient to make both flexible SCs separately and then to connect them together, by soldering.

For this purpose, on the surface of the Cu/ITO SC back electrode based on cadmium telluride, a comb of Ni (Figure 5(a)), whose configuration completely coincides with the configuration of the front electrode of the SC based on copper and indium diselenide, should be additionally created. Then, the commutation of the two finished solar cells can be carried out by soldering the nickel electrodes, after which a completely sealed flexible photoelectric module is obtained (Figure 5(b)).

4. Conclusions

By the method of nonreactive high-frequency magnetron sputtering on Upilex polyimide films, transparent and conductive layers of ITO were obtained. The ITO films deposited at a specific magnetron power 1.5 Wt/cm^2, the oxygen partial pressure in the composition of the argon-oxygen mixture is 3 vol. % and a deposition temperature of 430°C, have a surface resistivity of 4.6 ohm/□. The transmission coefficient of the ITO/polyimide system in the 500-900 nm wavelength range, which corresponds to the spectral range of photosensitivity of the CdS/CdTe--based solar cell, is 68.8%. After annealing in air at 430°C for 25 minutes, the surface resistivity of the ITO layers formed on the polyimide film increases to 11 ohm/□; the transmittance coefficient increases to 72%. Such optical and electrical parameters of the ITO layer make it possible to use it as transparent electrodes in the design of efficient flexible CdS/CdTe solar cells in the back configuration.

It has been experimentally shown that the polyimide/ITO/CdS/CdTe/Cu/ITO solar cell is promising for use in the design of tandem photoelectric converters, since it has a sufficiently high transmittance coefficient in the near-infrared region.

With a base layer thickness of 2.5 μm, the average transmittance coefficient of solar cells in the 850-1100 nm wavelength range is 46.8%, and at a base layer thickness of 1 μm reaches a record value of 55.2%.

It has been established that the use of undoped layers of zinc oxide of 100 nm in thickness allows increasing the efficiency of flexible polyimide/ITO/CdS/CdTe/Cu/ITO solar cell from 9.2% to 10.4%, wherein it was proved that the experimentally observed increase in efficiency is due to a decrease in the density of the diode saturation current.

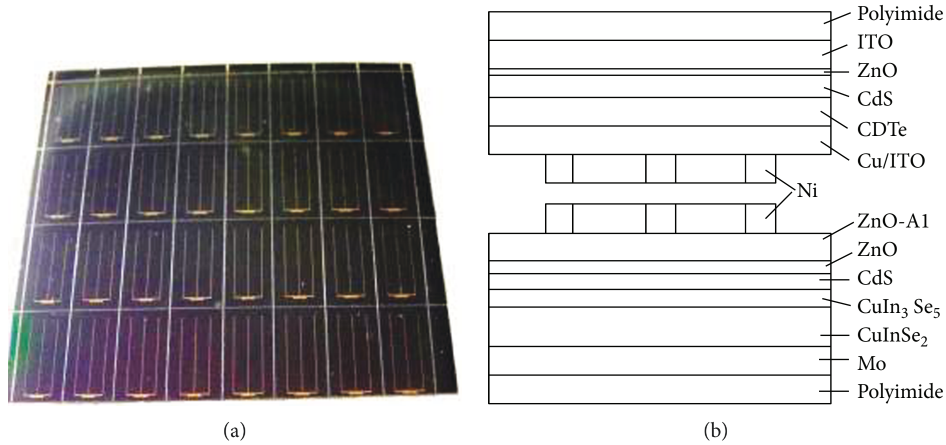

Figure 5: (a) Photo of a laboratory sample of the polyimide/ITO/CdS/CdTe/Cu/ITO SC. (b) The scheme of a tandem photoelectric converter CdTe/$CuInSe_2$.

The developed design of a flexible solar cell based on cadmium telluride due to the use of a transparent back contact with a comb metal electrode is easily interfaced with existing designs of flexible solar cells based on copper and indium diselenide, which allows the formation of flexible tandem photoelectric converters CdTe/$CuInSe_2$.

Data Availability

The data sets obtained during the research and the analysis are already available in the article. However, if there are any information/data that are needed, these may be obtained from the corresponding author on a reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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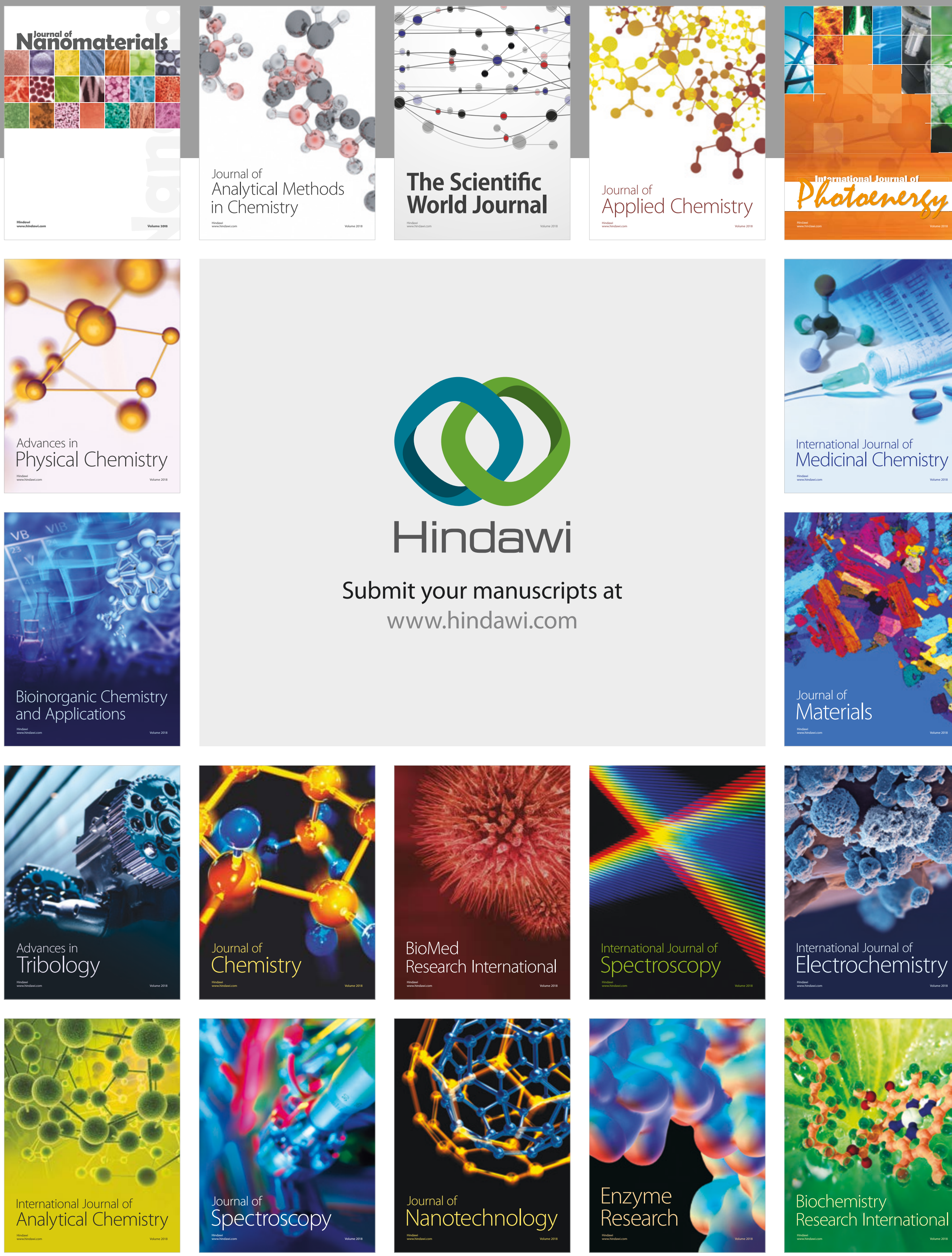
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