Thin film solar cells on CdS/CdTe/ITO base

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The manufacturing conditions of CdS/CdTe/ITO thin film solar cells for tandem device structure have been optimized. The efficiency of the CdS/CdTe/ITO solar cells amounts up to 7.8 % on glass substrates and 6.1 % on flexible polyimide substrate.

Проведена оптимизация технологии изготовления пленочных солнечных элементов CdS/CdTe/ITO для тандемных приборных структур. На стеклянных подложках эффективность солнечных элементов CdS/CdTe/ITO достигает 7,7 %, при использовании гибких полиимидных подложек — 6,1 %.

The tandem device structures are among perspective ways to increase the solar cell (SC) efficiency [1]. In such device structures, two photoelectrically active base layers with various band gap widths are used [1]. The design of the frontal CS having the base layer with a wider band gap should allow to the long-wave part of solar radiation (being not absorbed therein) to attain the back SC.

Thin film SC on CdTe base are of good promise for large-scale terrestrial application [2]. In tandem device structures with frontal SC on CdTe base, it is of best prospects to use thin film SC on $CuInSe_2$ base as the back SC [1]. In fact, the band gap width of CdTe makes 1.45 eV while that of $CuInSe_2$, 1.04 eV. Such combination of the base layer power structures allows to transform effectively the solar radiation in terrestrial and space conditions. However, the use of frontal SC on the CdTe base in tandem device structures is restrained until recently due to absence of transparent back electrodes to these base layers. This paper presents the manufacturing optimization results for thin film SC on CdTe base where ITO (indium and tin oxide) transparent films are used as back electrodes.

The thin film SC on CdS/CdTe/ITO base (Fig. 1) were prepared on glass substrates with the SnO_x:F layer. The CdS films were deposited by thermal evaporation at the substrate temperature 200°C. Then, without vacuum deterioration, CdTe films were deposited at substrate temperature 300°C. A standard technological operation when manufacturing high-efficiency SC on CdTe base is the "chloride" treatment. That treatment provides a 5–6 times higher efficiency of SC [3]. To realize the treatment, $CdCl_2$ films were deposited onto the CdTe layers by thermal evaporation without substrate heating. The obtained CdS/CdTe/$CdCl_2$ heterosystems were exposed to air in closed volume at 430°C for 25 min. To remove the reaction products and residues of $CdCl_2$ layers, the CdTe surface were etched in the bromine-methanol solution. Then ITO films were formed on the CdTe surface by magnetron sputtering method (see [4]). The SC output parameters: the short-circuit current density (J_{sc}), the open-circuit voltage (U_{oc}), filling factor (FF) of the light current-voltage characteristic (CVC) and efficiency (η) were determined by analytical processing of light CVC of the CS. The light CVC were measured under AM1.5 illumination conditions at light flow power of 100 mW/cm^2 [1].

When developing a frontal CS for tandem device structures, it is necessary to provide its maximum efficiency at the minimal base layer thickness. The reduction of

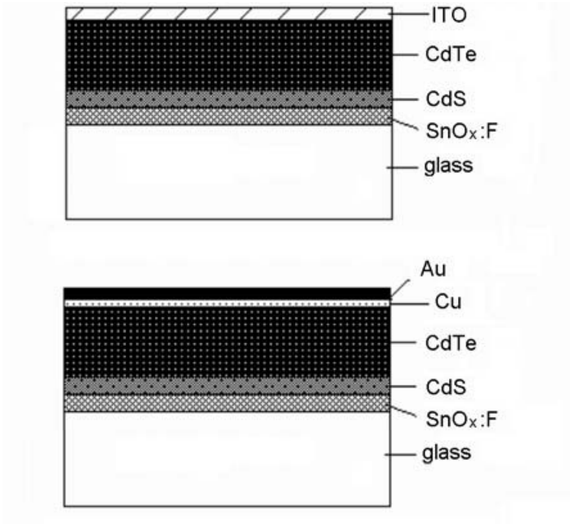

Fig. 1. Designs of solar cells on CdS/CdTe/ITO and CdS/CdTe/Cu/Au base.

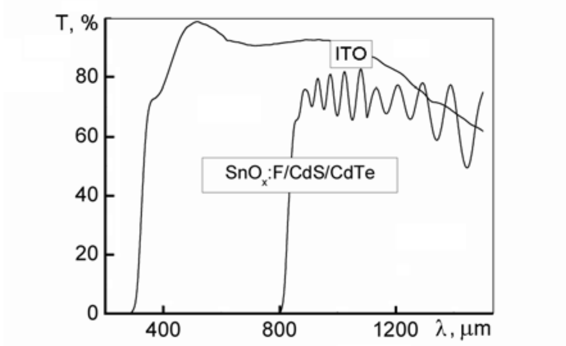

Fig. 2. Transmission spectra of SnO_x:F/CdS/CdTe heterosystems and ITO layer.

the base layer thickness will make possible to minimize the absorption of photons with energy lower than the band gap width of cadmium telluride. We have optimized the thin film CS deposition technology on the CdS/CdTe base where traditional Cu/Au back contacts of 110/500 Å thickness were used (Fig. 1). It has been shown that the maximum efficiency of 10.4 % (Table 1) is observed at CdS layer thickness of 0.4 μm, CdTe one of 4 μm, and $CdCl_2$ one of 0.6 μm. The studies have shown that at constant $CdCl_2$ layer thickness, the reduction of CdTe layer thickness results in decreased SC efficiency due to reduction of the open-circuit voltage and filling factor of the light CVC. So as the CdTe layer thickness reduces from 4 μm to 3 μm, the efficiency decreases from 10.4 % to 7.8 %, that is connected with U_{oc} reduction from 786 mV to 726 mV and FF from 0.66 to 0.55 (Table 1). According to [5], at a constant CdTe base layer thickness, the increase of $CdCl_2$ layer thickness results first in an increased CdS/CdTe SC efficiency followed by its reduction.

According to literature data [3], the "chloride" treatment causes re-crystallization of the base layer and generation of electrically active intrinsic point defects due to interphase interaction of $CdCl_2$ layers with CdTe ones. This causes an increased lifetime of non-equilibrium charge carriers and, as a result, increased SC efficiency. The excess cadmium chloride causes occurrence of micro-strains on the CdS/CdTe surface due to increased re-crystallization rate. As a result, micro-cracks are formed in the junction region. This results in decreasing SC efficiency. Thus, as the CdTe layer thickness diminishes, the optimum thickness of $CdCl_2$ layer should be reduced correspondingly. Our studies have shown that an SC on CdS/CdTe base with efficiency higher than 10 % (Table 1) is possible to obtain at the CdTe layer thickness not less than 3 μm. In this case, the optimum thickness of $CdCl_2$ layer amounts 0.3 μm. The studies of spectral dependences of transmission coefficient for SnO_x/CdS/CdTe heterosystems with CdTe layers thickness of 3 μm testify that in the wavelengths range 0.82 to 1.20 μm, the average transmission coefficient exceeds

Table 1. Influence of the CdTe layer thickness (d_{CdTe}) and $CdCl_2$ layer thickness (d_{CdCl_2}) on the output parameters of SnO_x:F/CdS/CdTe/Cu/ITO SC

d_{CdTe}, μm		4	3	3
d_{CdCl_2}, μm		0.60	0.60	0.30
Output parameters	V_{oc}, mV	786	726	770
	J_{sc}, mA/cm^2	20.0	19.6	20.2
	FF	0.66	0.55	0.65
	η, %	10.4	7.8	10.1

Table 2. Influence of the Cu film thickness (d_{CdTe}) on the output parameters of SnO_x:F/CdS/CdTe/Cu/ITO SC

d_{Cu}, Å		90	60	30	0
Output parameters	V_{oc}, mV	306	514	714	714
	J_{sc}, mA/cm^2	18.8	16.9	15.2	17.1
	FF	0.50	0.44	0.47	0.58
	η, %	2.9	3.8	5.1	7.1

Table 3. Influence of the ITO film deposition temperature (T_{ITO}) on the output parameters of SnO_x:F/CdS/CdTe/ITO SC

T_{ITO}, °C		100	200	250	300
Output parameters	V_{oc}, mV	514	714	692	612
	J_{sc}, mA/cm^2	14.8	17.1	18.5	16.3
	FF	0.51	0.58	0.60	0.62
	η, %	3.9	7.1	7.7	6.2

70 %. This range corresponds to a spectral interval located between the long wavelength photosensitivity edges of CdTe and $CuInSe_2$ (Fig. 2). This makes it possible to use in the tandem device structure the generated heterosystems as frontal SC. However, these heterosystems should include a transparent back electrode. As back electrodes in generated SC, transparent and conducting ITO films were approved. The magnetron sputtering conditions to deposit these layers were developed in [4]. It was established that the average transmission coefficient of such ITO films in wavelength range 0.82 to 1.20 μm exceeds 85 % (Fig. 2).

It is known [2] that the Cu/Au back electrodes form tunnel contacts with CdTe layers. In [5], it was shown that, as a result of CdTe surface etching in bromine-methanol solution and copper diffusion near to base layer surface, a p^+-type conductivity CdTe sublayer is formed. It is just the formation of this layer that provides a low contact resistance. Therefore, at the first development stage of transparent back electrodes, a bilayer Cu/ITO film contact was used. The CVC of SnO_x/CdS/CdTe/Cu/ITO SC with various Cu layer thickness (d_{Cu}) were examined. The ITO layer deposition temperature was constant and amounted 200°C. The SC output parameters are presented in Table 2. Consideration of these data shows that as the Cu layer thickness reduces down from 90 Å, the SC efficiency increases monotonously. This is caused due to increase of the open-circuit voltage and filling factor of the light CVC. The SC peak efficiency of 7.1 % is attained at the absence of Cu layer.

The influence of ITO layer deposition temperature on the efficiency of photo-electric processes in SnO_x/CdS/CdTe/ITO was investigated. Consideration of the SC output parameters (Table 3) shows that the peak efficiency of 7.7 % (see Fig. 3, Sample 1) is observed at deposition temperature 250°C. The deposition temperature lowering results in the efficiency reduction due to reduction of U_{oc} and FF. The deposition temperature elevation causes efficiency reduction resulting from U_{oc} reduction. The developed technology of back ITO electrodes manufacturing was tested in a design of flexible CdS/CdTe/ITO SC. In such SC, to increase the generated electrical power size per unit mass of device structure, the glass substrate was replaced by polyimide film of 10 μm thickness. As a result, flexible SnO_x/CdS/CdTe/ITO SC with efficiency 6.1 % (Fig. 3, Sample 2) have been obtained for the first time. The open-circuit voltage was 636 mV, the short-circuit current density, 17.8 mA/cm^2, the filling factor, 0.53. A lowered efficiency of flexible SnO_x/CdS/CdTe/ITO SC as compared to that of SC on glass substrates is caused by lower U_{oc} and FF values.

Thus, the CdTe layer thickness and manufacturing technology of ITO back electrodes for frontal solar cells on the CdS/CdTe/ITO basis for tandem device structures have been optimized. It has been shown that at CdTe layers thickness 3 μm,

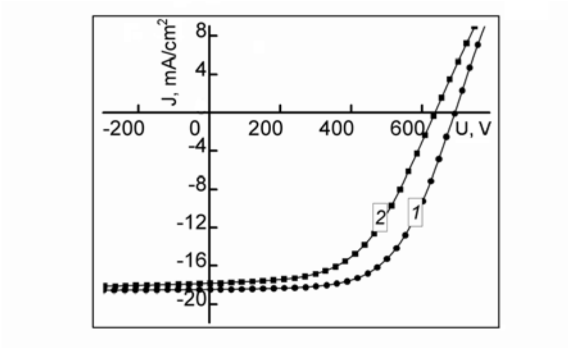

Fig. 3. Light CVC of SC on CdS/CdTe/ITO base on a glass substrate (*1*) and on a flexible substrate (*2*).

the ITO film deposition temperature of 250°C and absence of Cu film on CdTe layer surface provide the efficiency of solar cells on CdS/CdTe/ITO basis up to 7.7 % under the AM1.5 illumination conditions at light flow power of 100 mW/cm^2. For the first time, flexible CdS/CdTe/ITO solar cells have been obtained by replacement of the glass substrate by the polyimide film. In the same conditions of light exposure, the efficiency of flexible CdS/CdTe/ITO solar cells amounted 6.1 %.

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Плівкові сонячні елементи CdS/CdTe/ITO

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Проведено оптимізацію технології виготовлення плівкових сонячних елементів CdS/CdTe/ITO для тандемних приладових структур. На скляних підкладках ефективність сонячних елементів CdS/CdTe/ITO досягає 7.7 %, при використанні гнучких підкладок — 6,1 %.