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HELIOTECHNICAL MATERIALS SCIENCE

Study of the Physical Properties of CdTe-Based Thin-Film Solar Cells Produced on Metal Substrates by the Method of Chemical Molecular Beam Deposition

T. M. Razykov, K. M. Kuchkarov, B. A. Ergashev, and R. T. Yuldoshov
Physics–Sun Physicotechnical Institute, Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
e-mail: kudrat@uzsci.net
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Abstract—The dark and light voltage–current characteristics (VCC) of Mo/CdTe/CdS and Mo/Ni/CdTe/CdS thin-film structures produced on metal substrates by the method of chemical molecular beam deposition (CMBD) are studied. Based on the obtained results of VCC of the investigated structures, it is shown that the diode characteristics and photoelectric parameters (U_{oc}, J_{sc}, and FF) of the thin-film heterostructures are improved after thermal treatment in air and pure argon atmosphere in the presence of $CdCl_2$.

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INTRODUCTION

Currently, the preparation of thin-film solar cells on flexible metal substrates is one of the important ways of producing rolled photoelectric modular units. This method allows reduction in the cost of rolled modular units and increased market share. However, the cell efficiency is lower than that of solar elements prepared on glass substrates [1, 2]. There are a number of unresolved problems that complicate the improvement of the performance characteristics of thin-film solar cells produced on flexible metal substrates, such as obtaining a high-transparent window, the low resistance of contacts, low density of defects in a junction, etc.

Treatment with the $CdCl_2$ reagent is one of the key steps in the production of CdS–CdTe thin-film solar cells. The efficiency of heterostructures in the CdS–CdTe thin films considerably increases after the treatment with $CdCl_2$ [3]. The mean size of the grains of the CdTe and CdS films obtained by the low-temperature methods of electro- and vacuum deposition [4] usually increases after the thermal treatment with $CdCl_2$, while the morphological and structural properties of the films obtained by the high-temperature method of chemical molecular beam deposition (CMBD) do not change [5]. The electrophysical properties of the CdTe and CdS films also improve; i.e. the mobility of charge carriers and their electric conductivity increase, and the film's lattice parameters decrease [6, 7]. For example, the resistivity of CdTe films of different compositions before treatment ranged from 10^4 to 10^9 Ω cm, and the resistivity after thermal treatment with $CdCl_2$ decreased to values ranging from 10^3 to 10^4 Ω cm [7]. The decrease in the resistivity of CdTe films after chloride thermal treatment is connected with the formation of a new acceptor complex with an activation energy of about 0.05 eV, a value which is less than the energy of the cadmium vacancy, V_{Cd} [7].

A new, lower-cost method of chemical molecular beam deposition at atmospheric pressure of gas for manufacturing of II–VI films from various metal and chalcogenide precursors has been reported earlier. Some characteristics of the CdTe films with different compositions prepared by this method are examined in [8].

In the present work, the electric and photoelectric properties of the CdTe/CdS thin-film heterostructures produced on metal substrates by the CMBD method are studied.

RESULTS AND DISCUSSION

For obtaining good ohmic contacts on CdTe, a thin metal layer of Ni with thickness from 60 to 80 nm was deposited on a cleaned metal substrate made of foil [9]. Then the CdTe films were deposited by the CMBD method at a substrate temperature of 600°C. The thicknesses of the obtained films were in the range of ~3–5 μm, depending on sedimentation time. The preparation of CdTe films by the CMBD method is described in more detail in [10]. In order to improve the electric properties of the CdTe films, they are treated thermally in a closed volume (in pure argon atmosphere) with the use of the $CdCl_2$ solution. The thermal treatment by the $CdCl_2$ solution consists of the following steps: (a) a $CdCl_2$ film with a thickness of 200–300 nm is deposited in high vacuum on the CdTe film surface, and then (b) annealing in argon atmosphere is performed at temperature 350–450°C for

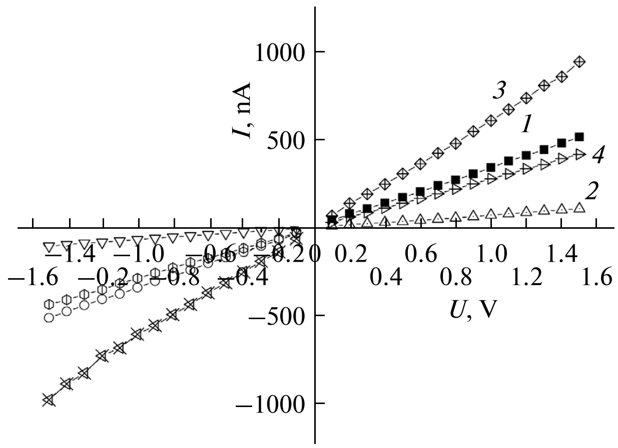

Fig. 1. Dark VCC of the CdTe films of different compositions without thermal treatment, as follows: (*1*) for Cd/Te ~ 0.78, (*2*) for Cd/Te ~ 0.86, (*3*) for Cd/Te ~ 0.92, and (*4*) for Cd/Te ~ 1.02.

30–40 min. After annealing, the film is washed with deionized water and dried in a nitrogen flow.

The CdS films with thickness 0.2–0.3 μm are deposited on the surface of the Mo/Ni/CdTe structures by thermal vaporization at a pressure of 5–10 mm Hg and a substrate temperature of 200°C. The obtained Mo/Ni/CdTe/CdS heterostructures with thickness 100–150 nm were annealed in the presence of $CdCl_2$ in both argon and air atmosphere at a temperature of 200°C for 20 min. The heterostructure surfaces were also washed with deionized water and dried in a nitrogen flow.

In order to measure the electric properties, ohmic contacts were deposited on freshly prepared films and heterostructures by the vacuum deposition method. Nickel and silver paste was used as an ohmic contact to the CdTe films with the *p*-type conductivity, and grid indium contacts were used on the Mo/CdTe/CdS heterostructures. The conductivity type of the samples was determined by the sign of the thermal electromotive force (EMF). The use of a B7-30 electrometer with an input resistivity of more than 10^{14} Ω for the indication of the thermal EMF sign made it possible to determine the conductivity type of the high-resistance samples with a resistivity of more than 10^8 Ω cm. The thickness of the CdTe films (3–6 μm) was determined on a MII-4 microinterferometer and also by the method of precision microweighing on an FA 120 4C balance (with an accuracy up to 0.1 mg).

The dark voltage–current characteristics (VCC) were measured after making ohmic contacts on the *p*-CdTe films (Fig. 1). Analysis of the dark VCC of the CdTe films showed that all the samples exhibit ohmicity; i.e., current rectification in the range of measured voltages ($V = 0.01$–2) is not observed. The resistivity of the contact between the CdTe and the metal substrate was also calculated. The contact resistivity value was within the range 10^3–10^4 Ω, depending on the presence of an enriched Te layer in the Cd telluride film surface.

The dark voltage–current characteristics of the obtained Mo/(Ni)/CdTe/CdS/In heterostructures before the thermal treatment with $CdCl_2$ were measured. As seen from Fig. 2, the dark VCC after the treatment show a strongly expressed diode character with a rectification factor of about 10^3 at the 1-V shift. The straight VCC branches correspond to a positive potential on *p*-CdTe and negative on *n*-CdS. At the direct shifts, $kT \leq U \leq U_D$, the VCC is described by the expression $J = J_0\exp(eV/AkT)$. The cutoff current voltage, which is determined by extrapolation of the ohmic section to the voltage axis, was equal to U_0 in the range from 0.6 to 0.65 V. The series resistance value of the heterostructures determined from the ohmic section by the expression $R_s = dU/dJ$ was 10^2 Ω for the given VCC. The reverse branches of the dark VCC followed the dependence $I_{rev} = U^n$, where $n = 2.4$ in the voltage range $kT/e \leq U \leq 0.8$–1 V, turning further to a soft breakdown at higher reverse shift values.

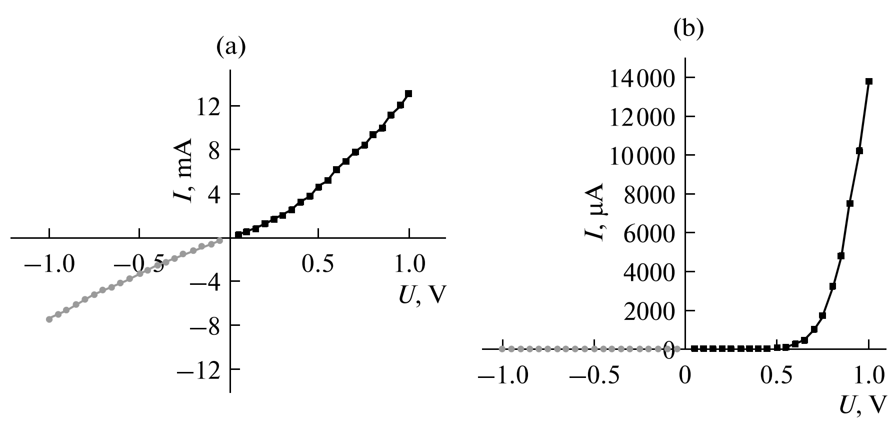

Fig. 2. Dark VCC of the Mo/Te/CdTe/CdS/In heterostructures (a) before and (b) after treatment.

Photoelectric parameters of the CdTe-based thin-film solar cells

	U_{oc}, V	J_{sc}, mA/cm^2	FF (%)	η (%)
Before treatment	0.55	6	39	1.6
After treatment in air atmosphere (in the presence of $CdCl_2$)	0.55	15	39	3.6
After treatment in pure argon atmosphere (in the presence of $CdCl_2$)	0.67	20	55	7.8

The light VCC of the flexible solar cells prepared on the basis of the Mo/Ni/CdTe/CdS/In heterostructures were also measured at an incident light flux of 100 mW/cm^2 (Fig. 3). Based on the experimental light VCC, the efficiency and output parameters of the produced laboratory samples of solar cells were determined. The photoelectric parameter values are given in table. The filling factor was calculated by the following formula:

$$f = \frac{I_0 - U_0}{I_{sc} - U_{oc}}, \quad (1)$$

where I_0 and U_0 are the values of the current and voltage in the point with the maximum produced power of the light VCC (Fig. 3). The efficiency factor was determined by the formula

$$\eta = \frac{I_{sc} - U_{oc}f}{W} \times 100\%, \quad (2)$$

where W is the incident light energy, which was 100 mW/cm^2 in our case.

As seen from the table, the efficiency of the Mo/Ni/CdTe/CdS/In thin-film heterostructures is enhanced after the thermal treatment.

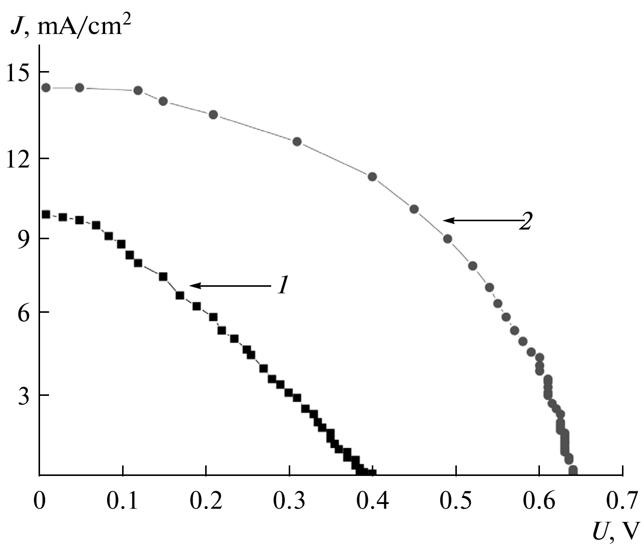

Fig. 3. Light VCC of the Mo/Te/CdTe/CdS/In heterostructures (*1*) before and (*2*) after treatment.

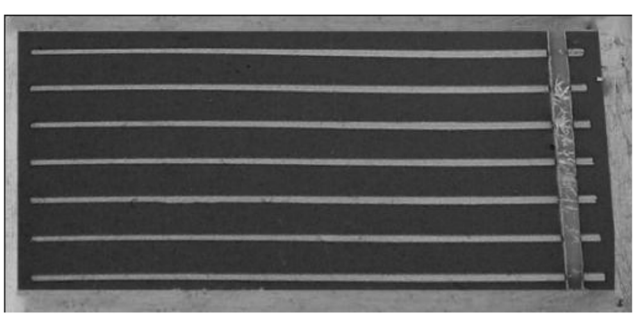

Fig. 4. Solar cell on the basis of the Mo/Ni/CdTe/CdS/In heterostructures.

CONCLUSIONS

CdS–CdTe thin-film solar cells on metal substrates have been prepared for the first time by the method of chemical molecular beam deposition in a carrier gas current from elementary sources, which have the following characteristics: U_{oc} = 0.670 V, I_{sc} = 20 mA, FF = 0.55, and efficiency factor of about 7.8% (Fig. 4). Methods for increasing the efficiency up to 12% have been outlined.

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