PHYSICS AND CHEMISTRY
OF SOLID STATE
V. 24, No. 1 (2023) pp. 134-145

Section: Physics

DOI: 10.15330/pcss.24.1.134-145

Vasyl Stefanyk Precarpathian National University

ФІЗИКА І ХІМІЯ ТВЕРДОГО ТІЛА
Т. 24, № 1 (2023) С. 134-145

Фізико-математичні науки

PACS: 88.40.M

ISSN 1729-4428

T.M. Mazur[1], M.P. Mazur[1], I.V. Vakaliuk[2]

Solar cells based on CdTe thin films (II Part)

[1]Ivano-Frankivsk National Technical University of Oil and Gas, Ivano-Frankivsk, Ukraine, tetiana.mazur@nung.edu.ua;
[2]Vasyl Stefanyk Precarpathian National University, Ivano-Frankivsk, Ukraine

This paper discusses the use of semiconductor solar cells based on thin-film cadmium telluride (CdTe) in modern energy production. The advantages and disadvantages of using CdTe thin-film solar cells are analyzed, and arguments are presented in favor of the implementation of mass production technologies for CdTe solar modules, which can compete with silicon analogs in terms of compromise between efficiency and cost. The physical and chemical properties of the binary Cd-Te system are described, and the relationship between the physical, chemical, electrical, and optical properties of CdTe is analyzed, making it attractive for use in thin-film solar cells. Special attention is given to the investigation of photovoltaic properties, which are important parameters for determining photoconductivity, and the advantages and disadvantages of CdTe film photovoltaic properties are discussed. CdTe thin-film heterostructures (HSs), which are important components of modern solar cells, are considered, and their main advantages and disadvantages are described. It is argued that simple methods of manufacturing and forming HSs, which do not require complex and expensive equipment, are an important advantage of CdTe-based solar cell technology.

Keywords: solar cells, thin films, CdTe, photosensitivity, heterostructures.

Received 14 June 2022; Accepted 9 March 2023.

Content

Introduction

Solar cells (SCs) based on CdTe thin films are a type of photovoltaic solar panels in which the active material for converting solar energy into electricity is a cadmium telluride thin film. CdTe has a high efficiency of converting solar energy and low production cost. It also has good resistance to corrosion and degradation, allowing it to be used in various climate conditions. CdTe is a semiconductor with a bandgap close to the optimum for absorbing sunlight and good electrical conductivity. That is why CdTe is considered one of the most promising semiconductors for thin-film solar energy.

The technology for manufacturing thin-film solar cells based on CdTe has many advantages over traditional silicon wafers, as CdTe is a semiconductor that efficiently absorbs optical radiation with optimal parameters for solar cells. The production of thin-film CdTe does not require complex microelectronic technology, which makes it more productive and less costly. This is explained not only by the micron thickness of the absorbing layer, but also by the low cost of the substrate, onto which the material is typically deposited, which is usually glass, polymer film, or metal foil. In addition, thin film heterostructures based on CdTe are a promising technology for solar cell manufacturing.

In field tests, CdTe-based solar panels demonstrated a 17% efficiency that is comparable to silicon-based panels. According to First Solar, the company is capable of achieving an efficiency of 24% in two years and 19% in real-world conditions in three years [1]. In addition, due to the technology of deposition from the vapor phase, First Solar's thin panels are easier to manufacture - the entire process, from transparent glass to the final product, takes only 3.5 hours, while it takes two days to manufacture a silicon element [1].

I. Requirements for the use of CdTe as thin-film solar cells

SCs based on thin films of CdTe have several advantages compared to traditional crystalline solar panels [2]. In particular, they have a higher energy conversion efficiency: CdTe-based solar cells can achieve efficiencies up to 22%, which is significantly higher than traditional crystalline solar panels [2,3]. They are also more resistant to high temperatures: thin CdTe films can operate at high temperatures without significant efficiency loss. Moreover, better performance under low light conditions is provided by CdTe-based thin-film solar cells, which are capable of generating electric current at low light levels, making them effective in cloudy weather or shaded areas [4].

However, thin-film CdTe-based SCs also have some drawbacks, such as high production costs and less resistance to ultraviolet radiation compared to crystalline solar panels [2, 5].

However, CdTe remains one of the materials used to manufacture thin-film solar cells. To use CdTe as a solar cell material, certain requirements must be met. One of the conditions is material purity, meaning that to obtain high-efficiency solar cells, high-purity CdTe with minimal impurities must be used. Another important condition is the thickness of the CdTe film, which must be optimized to achieve maximum efficiency. Typically, films with a thickness of 1 to 2 micrometers are used. To obtain voltage, a heterojunction between CdTe and another material, such as copper (Cu), must be used, ensuring a high-quality junction. It is important to consider the electrical properties, including the optimal concentration of electrons and holes in CdTe, to achieve maximum solar cell efficiency [6, 7]. Additionally, CdTe must be resistant to moisture, temperature changes, ultraviolet radiation, and mechanical damage [6]. From a production standpoint, the use of CdTe must be economically advantageous.

Adherence to these requirements helps achieve maximum efficiency of CdTe-based solar cells and reduces their production cost.

II. Physical and chemical properties of the Cd-Te binary system

CdTe stands out among II –VI compounds like CdSe, ZnS, and HgTe due to its unique combination of properties, including the highest average atomic number, lowest melting temperature, least negative enthalpy of formation, largest lattice parameter, and highest ionization potential. In its electronic form, cadmium telluride exhibits amphoteric semiconductor properties, allowing for n- and p-type doping [8]. These factors complement its nearly ideal optical bandgap and absorption coefficient for terrestrial photovoltaic devices, making it easily deposited and controlled in the form of a thin film. Table 1.1 presents the main physical and chemical properties of CdTe.

The crystallization of cadmium telluride occurs in the zinc blende structure. Its existence range is asymmetric. Stoichiometric CdTe has a melting point slightly lower than T_m. For temperatures below 1000 K, the majority of the compound's homogeneity range is on the Cd excess side, and for temperatures above 1000 K, it shifts towards the Te excess side [12]. The maximum melting temperature of the compound is $T_m = 1365$ K and corresponds to a non-stoichiometric composition with an excess of tellurium [10, 12].

The synthesis of II–VI compounds is facilitated by large negative enthalpies of formation (ΔH_f) and, consequently, low vapor pressures (p_{sat}) of the compounds compared to their component elements: for CdTe, $\Delta H_f = -22.4$ kcal/mol and p_{sat} (400 °C) = 10^{-5} Torr [13, 14].

The equilibrium reaction for solid CdTe and Cd and Te_2 vapors is given by

$$Cd + 1/2Te_2 \Leftrightarrow CdTe \tag{1}$$

As a result, deposition of CdTe can be achieved by co-evaporation from elemental sources, direct sublimation from a CdTe source, or transport of Cd and Te_2 vapor using a carrier gas from elemental or CdTe sources. Congruent sublimation of CdTe fixes the gas phase composition for deposition from a CdTe source, and the relatively low vapor pressure of CdTe facilitates the deposition of single-phase solid films over a wide range of substrate temperatures [12].

The partial pressures of the Cd and Te_2 components are related to each other by the equilibrium constant of the reaction [15]:

$$K_p = P_{Cd}^2 \, P_{Te} \quad \text{or} \quad K_p = P_{Cd} \, P_{Te}^{\frac{1}{2}} \tag{2}$$

The temperature dependence of the equilibrium constants K_p varies slightly according to different authors [2, 15].

According to [16], the phase diagram of the Cd-Te system at atmospheric pressure is shown, reflecting the individual vapor-solid equilibria for individual CdTe, Cd, and Te components in the temperature range from 100 to 600°C, which is commonly used for the manufacture of SCs. The congruent evaporation of CdTe simplifies the methods of deposition from the vapor phase, and the relatively high sublimation pressures of Cd and Te ensure a single-phase composition during vacuum deposition at temperatures above approximately 300°C. Additionally, CdTe is a stable product of cathodic reduction from solutions containing Cd and Te ions, due to the similar reduction potentials for Cd and Te and the low solubility of CdTe [16, 17].

The T–x phase equilibrium of the CdTe system at atmospheric pressure is defined by the end points consisting of Cd (x=0), Te (x=1), and CdTe [16]. The melting temperature of CdTe is much higher than that of Cd (T_m = 321°C) or Te (T_m = 450°C), with a value of T_m = 1092°C [8,9]. The T-x projections surrounding the stoichiometric composition of CdTe show a very narrow and symmetrical region of existence at T<500°C, which is approximately ~10^{-6} atm.%. At higher temperatures, the region of existence expands and becomes asymmetric on the Cd-enriched side up to 700°C, becoming Te-enriched at higher temperatures. The region of existence and the defect structure are related to the conditions of preparing the bulk material and have been the subject of many studies [8, 18]. Recent theoretical studies on defect levels in CdTe have extended this basis [8, 18]. Currently, the transfer of bulk properties to thin films of CdTe remains an important research topic.

The solid-state properties of CdTe are determined by its ionic bonding. According to the Phillips ionicity scale, CdTe has the highest value of 0.717 among II –VI compounds, which is less than the Phillips threshold value of 0.785 for octahedral coordination [8]. Geometric calculations show that tetrahedral coordination prevails in ionic binary compounds that have a cation/anion radius ratio between 0.225 and 0.732, while octahedral coordination is favored for ratios greater than 0.732 [8, 15]. The cation/anion radius ratio in CdTe is $r(Cd^{2+})/r(Te^{2-}) = 0.444$, which favors tetrahedral coordination.

In solid monoatomic substances, tetrahedral coordination of atoms with four nearest neighbors and twelve subsequent neighbor's results in the diamond structure. In double solid substances, this coordination corresponds to the structures of zinc blende and wurzite. Solid CdTe at atmospheric pressure has a face-centered cubic structure of zinc blende, where the size of the elementary cell is 6.481 Å, and the CdTe bond length is 2.806 Å [9].

Cadmium telluride has two possible structures: sphalerite (cubic B3 structure) and wurtzite (hexagonal B4 structure), with the same number of atoms in the first and second coordination spheres [8]. At room temperature and a pressure of 3.3–3.6 GPa, a phase transition occurs in cadmium telluride from a sphalerite or wurtzite structure to a NaCl-type structure, accompanied by a sudden decrease in electrical conductivity [9].

Band gap of CdTe increases with decreasing temperature ($E_g = 1.5976–6.09\cdot10^{-4}T^2/(T+255)$ – [19], $E_g=1.622–3.5\cdot10^{-4}T–1.1\cdot10^{-7}T^2$ – [15], $E_g=1.65–5.35\cdot10^{-4}T$ – [8]). The value of the spin-orbital splitting of the valence band becomes 0.9 eV [10], 0.93 eV [19].

Binary equilibrium between Cd and Te reveals only one composition of CdTe, which is formed in the ratio Cd:Te = 50:50% and has a eutectic solution in liquid Te [4]. When studying the phase state of CdTe at high temperatures, an asymmetric expansion of the single-phase region on the Te side was found at T > 600°C. At 750°C, the absence of Cd in the alloy is 10^{18} sm^{-3}, which corresponds to a deficiency. The distance between nearest

Table 1.1.

Basic physical and chemical properties of CdTe [9, 10]

Parameter name, symbol, dimension	Numeric value
1	2
Lattice type	sphalerite
Space group	$T_d^2 - F\bar{4}3m$
Lattice parameter, a, 10^{-10} m	6.481 6.478
Cd-Te bond length, Å	2.806
Density, ρ, kg/m^3	$5.86\cdot10^3$
Melting temperature, T_m, K	1365
Thermal expansion coefficient (300K)	5.9×10^{-6}/K
Specific heat, $C_{p,298,15}^0$, J/molK	50.2
Heat of formation, $\Delta H_{f,298,15}^0$, 10^3 J/mol	100.5
Melting heat, $\Delta H_{пл}$, 10^3 J/mol	44.4
Heat of sublimation, ΔH, 10^3 J/mol	181.95
Sublimation reaction	$CdTe \rightarrow Cd + 1/2Te_2$
Sublimation pressure p_{sat}	$\log(P_c/bar) = -10650/T(K)$ $2.56 \log(T) + 15.80$
Standard entropy, $S_{298,15}^0$, 10^3 J/molK	98.61
Entropy of formation, ΔS_f^0, J/molK	361.74 (T = 874 K)
Entropy changes during melting, $\Delta S_{пл}$, J/molK	32.53
Upper limit of dissociation energy, E, 10^3 J/mol	129.8
Thermal conductivity, χ, W/cm K	0.075
Coefficient of self-diffusion atoms Cd, $D_{self-dif.}^{Cd}$	$2\cdot10^{-8}$ (T = 1273 K)
Coefficient of self-diffusion atoms Te, $D_{self-dif.}^{Te}$	$8.2\cdot10^{-11}$ (T = 1073 K)
Debye temperature, T_θ, K	200 (T = 80 K)

neighbors in the CdTe structure is at the level of 0.28 nm at 300 K. The Hall mobility of electrons at 300 K is up to $n \leq 1050$ sm^2/Vs, and the Hall mobility of holes at 300 K is up to $p \leq 100$ cm^2/Vs With. The exciton binding energy is 12 meV, the average photon energy is 5.8 meV [8, 20].

III. Electrical and optical characteristics of CdTe

The volumetric optical and electrical properties of CdTe depend on the structure of the electronic bands near the maximum of the valence band (MVB) and the minimum of the conduction band (MCB). For CdTe, the MVB and MCB are located at the same point Γ in the first Brillouin zone, resulting in a direct bandgap width of 1.5 eV at 300 K. The temperature coefficient of the bandgap width for CdTe is approximately −0.4 meV/K, leading to minimal changes in the performance of SCs at typical temperatures. The shape of the bands around the extrema determines the effective mass of electrons in the MCB and holes in the MVB, as well as controls the properties of charge carrier transport and inter-band density of states [21]. Table 1.2 presents the main optical and electrical properties of CdTe.

Compared to other semiconductors such as silicon, CdTe has a higher dielectric constant in the infrared and visible light regions, allowing it to transmit more light and provide higher efficiency for photovoltaic panels. CdTe has good absorption in the infrared and visible light regions [2]. Light reflection on the surface of CdTe depends on its structure and the wavelength of the light. Light scattering in CdTe depends on its defects and impurities, and their presence can be significant, reducing the efficiency of CdTe-based SCs [22]. CdTe photoluminescence occurs when the material absorbs photons and emits light of the corresponding wavelength.

The mobility and concentration of charge carriers [23, 24], conductivity of the material, energy of radiative transitions [25] and other electrical and optical properties of CdTe strongly depend on its chemical composition and defect structure of the crystal [26]. This structure can be effectively controlled during post-growth high-temperature processing. It has been established that at room and lower temperatures, the predominant scattering mechanism is scattering on ionized centers, while at higher temperatures it is scattering on optical phonons [27].

The band structure of CdTe can be understood by considering its relatively high ionicity, which is explained by the fact that parts of the Bloch functions with periodicity identical to the lattice are associated with the atomic orbitals of Cd and Te. The conduction band arises from the first unoccupied cationic level, namely the 5s level of Cd. The highest valence band consists of the highest occupied level of the anion, namely the 5p level of Te.

In CdTe, the presence of defects disturbs its periodic structure, leading to the formation of localized electronic states within the bandgap and changes in electrical and optical properties [28, 29]. Such defects can be of various types, including intrinsic defects, chemical impurities, and their complexes, which can arise as either substitutional or interstitial defects. For example, cadmium vacancy (V_{Cd}) leads to shallow acceptor states, while cadmium substitution on the tellurium site (Cd_{Te}) leads to shallow acceptor states. Interstitial cadmium (Cd_i) leads to relatively shallow donor states, while interstitial tellurium (Te_i) leads to deep states. Although shallow states can be easily created by acceptors and donors [18], the overall doping effect depends on the probability of formation and ionization degree, which determine the degree of

Table 1.2.

Optical and electrical characteristics of CdTe [7, 20, 22]

Parameter		Value
Optical range CdTe *Eg* (300K)		1.50eV ± 0.01eV
Optical range. Alloy $CdTe_{0.95}S_{0.05}$		1.47eV ± 0.01eV
Temperature dependence dE_g/dT		−0,4meV/K
Electronic affinity		4.28eV
Absorption coefficient (600 nm)		>5 × 10^5/sm
Refractive index (600 nm)		~3
High frequency dielectric constant ε (∞)		7.1
Low frequency (static) dielectric constant ε_s		9.65 10.9 11.0
Band gap, E_g, eV		1.606 (T = 4,2 K), 1.5 (T = 300 K)
m_e		0.096 m_0
m_h		0.35 m_0
μ_e		500–1000 cm^2 / Vs
μ_h		50–80 cm^2 / Vs
Intrinsic concentration of free charge carriers, n, cm^{-3}		$2.0 \cdot 10^6$-$1.5 \cdot 10^{14}$ (T = 300-700 K)
Hall mobility	electron μ_n, 10^{-3} m^2 V^{-1} sec^{-1}	105
	halls μ_p, 10^{-3} m^2 V^{-1} sec^{-1}	7

compensation of the desired acceptor state.

One of the most important issues in the processing of CdTe solar cells is achieving high concentrations of acceptors that exceed 10^{14} cm^{-3}. During the thermal processing of the semiconductor system, equilibrium is approached, and first-principles-based studies have shown that p-type doping leads to a self-compensation mechanism [29]. When the Fermi level is shifted towards the MVB, the chemical potential for forming donors increases, which compensates for further acceptor formation and significantly limits the maximum acceptor concentration. On the other hand, deep states can act as traps, reducing carrier lifetime and leading to increased carrier recombination. In [29], the reduction of deep electronic states measured in CdTe and CdZnTe is considered. In article [4] shows a group of shallow and deep defects, including intrinsic, dopant, and complex levels in CdTe. To achieve the desired electrical properties, activation treatments that include certain dopants in CdTe and CdS layers are used. After deposition, $CdCl_2$, O_2 and Cu can be applied, which in turn activate or passivate intrinsic defects [4].

However, the electrical characteristics of polycrystalline CdTe used in modern solar cells may differ from those of monocrystalline CdTe for several important reasons. In particular, defects between grain boundaries will have different energies in the bandgap and will have different formation energies. This assumption is based on the fact that different post-deposition methods used to improve the efficiency of solar cells mainly affect the grain boundary states rather than the bulk states of CdTe. For example, in the experiment [31], devices with electro-deposited CdTe films were created, which had fibrous grains with a length of 2 μm and a width of 0.15 μm. Both samples received the same $CdCl_2$ treatment, but one sample underwent a short oxidizing treatment before the $CdCl_2$ treatment. The cells produced similar open-circuit voltages (V_{OC}), but different photocurrents. The CdTe film in the cell with the oxidation step retained the structure of the deposited grain and the thickness of the CdS film. This cell demonstrated improved performance, with an internal quantum efficiency (IQE) > 90%, indicating improved lifetime of photo-generated carriers compared to the sample without the oxidation step, which showed grain coalescence, loss of the CdS film, and IQE < 60% [8].

This result confirms the correlation between the physical, chemical, and electronic properties of the CdTe/CdS thin-film SC. Since the cells are manufactured in a polycrystalline environment, several critical issues arise that affect the development of thin-film photovoltaic devices. The first is the separation of intragrain effects from grain boundary effects. The second is the detection of the influence of grain boundaries on device performance. The third is the control of film properties over a large area with more than 10^{12} grains per square meter in the CdTe module, where grains have a width of 1 micron. However, during the development of CdTe SCs, these problems were successfully addressed using improved methods for determining characteristics, empirical optimization of film deposition, and post-deposition processing. Today, several powerful methods exist for the quantitative evaluation of film properties, including those for CdTe/CdS SCs, which are discussed in references [6,32-34]. Some of these methods can also be used as diagnostic sensors for embedded feedback control during the manufacturing process of CdTe/CdS modules.

IV. Photosensitivity of CdTe films

CdTe films are a well-known photosensitive material capable of converting light energy into electrical current. This allows them to be used in solar panels and other photovoltaic devices, such as X-ray detectors, as well as in scientific research.

The main properties of CdTe film photosensitivity include spectral sensitivity, absorption coefficient, conversion efficiency, response time, and stability. CdTe films have high spectral sensitivity in the infrared and visible ranges. Their spectral range depends on the thickness of the film and impurities present in the material. They have high light absorption coefficients compared to other semiconductor materials such as silicon, meaning they can convert more light energy into electrical current. CdTe films have high conversion efficiency of light energy to electrical current, indicating that they can provide high electrical power at low light levels [21, 22, 33]. Additionally, CdTe films have a fast response time to light, allowing them to be used in devices that require a quick response to light. And importantly, CdTe films have good stability against environmental factors such as temperature and humidity.

The photosensitivity of CdTe films is determined by the energy bandgap and defects in the crystalline structure. Since the bandgap of CdTe is approximately 1.5 eV, corresponding to a spectral range of around 800 nm, CdTe films have the highest photosensitivity in the near-infrared and visible spectral ranges.

In addition, the photosensitivity of CdTe films depends on their thickness. The thickness of the film should be sufficient to absorb a sufficient number of photons, but not too large, as this can reduce the charge collection efficiency. Typically, the optimal thickness of CdTe films ranges from 1 to 2 μm.

An important factor affecting the photosensitivity of CdTe films is the quality of the material itself and the technology used to manufacture it. For example, to ensure high efficiency, CdTe films should have high purity and uniformity. The technology used to manufacture CdTe films also affects their photosensitivity: for example, using the chemical deposition from solutions method can produce films with higher photosensitivity than using the physical deposition from vapors method [30].

To ensure high efficiency of CdTe films, they must also have good conductivity and charge carrier transport properties. Additional layers, such as ultra-fast diffusion layers that reduce charge carrier lifetime, or other materials like ZnO layers that provide efficient charge collection, are often used for this purpose.

CdTe films deposited at a temperature of T_{mel} = 473 K exhibit photosensitivity. The thickness of the films is set at 400 nm, since the light absorption coefficient is practically inversely proportional to the film thickness, providing better absorption of incident light on the films. Measurements of the I–V (current–voltage) characteristics of CdTe films at different ambient temperatures showed that they have ohmic properties both in the dark and under illumination. The dark conductivity of the grown CdTe films measured at room temperature is 10^6 $\text{Ohm}^{-1}\text{m}^{-1}$. It is noted that the dark conductivity and photosensitivity of CdTe films increase with an increase in the deposition temperature T_{mel} in the range of 303 to 573 K [35].

The efficiency of the photoconductivity of the film largely depends on natural and external imperfections, which can act as capture or recombination centers. In polycrystalline films, many defects and broken atomic bonds arise between grains, creating additional energy states. These states effectively capture charge carriers, creating a potential barrier at the grain boundary. Due to the uniform structure of the intergranular boundary with an average barrier height E_{bd}, the dark conductivity of the film is determined by the formula [36]

$$\sigma_D = N_C e\mu_0 e^{-(\Delta E+E_{bl})/kT} = N_C e\mu_0 e^{-\Delta E_{D})/kT} \quad (3)$$

where N_C is the density of states in the conduction band, μ_0 is the carrier mobility in the grain.

During illumination, the conductivity of the film can increase due to an increase in the number of free charge carriers and a decrease in the grain boundary barrier height, which depends on the energy of light. Research [36] has shown that the change in conductivity due to the generation of charge carriers during illumination is insignificant compared to the change in conductivity that arises due to thermal generation of charge carriers. The main factor contributing to the increase in conductivity during illumination is the enhancement of carrier mobility at the grain boundaries, which occurs through barrier modulation. The overall photoconductivity of the films during illumination can be expressed by the formula presented in reference [36]:

$$\sigma_L = N_C e\mu_0 e^{-(\Delta E+E_{bl})/kT} = N_C e\mu_0 e^{-\Delta E_{L})/kT} \quad (4)$$

$$\Delta E_L = (\Delta E + E_{bl}) \quad (5)$$

Here ΔE_L is the photoactivation energy, E_{bl} is the height of the barrier under illumination.

The barrier height reduction (mobility activation energy) can be expressed as:

$$\Delta E_\mu = (\Delta E_D - \Delta E_L) \quad (6)$$

The energy required to activate the mobility of charge carriers ΔE_μ depends on temperature and light intensity, as well as the lifetime of these carriers. The relationship between photoconductivity and the energy of mobility activation can be expressed using the appropriate equations (3) and (4):

$$\frac{\sigma_L}{\sigma_D} = e^{\Delta E_\mu / kT} \quad (7)$$

The photosensitivity S is determined by the formula

$$S = (\sigma_L - \sigma_D)/\sigma_D \quad (8)$$

It should be noted that the efficiency of photosensitivity depends significantly on defects in the structure, which can act as trapping or recombination centers for charge carriers. In CdTe films with a polycrystalline structure, photoconductivity is mainly determined by processes occurring at grain boundaries. Using atomic force microscopy (AFM) (Fig. 1), the average crystal size was determined, and the efficiency of photosensitivity for films of different thicknesses and structure quality is presented in Fig. 2 [20].

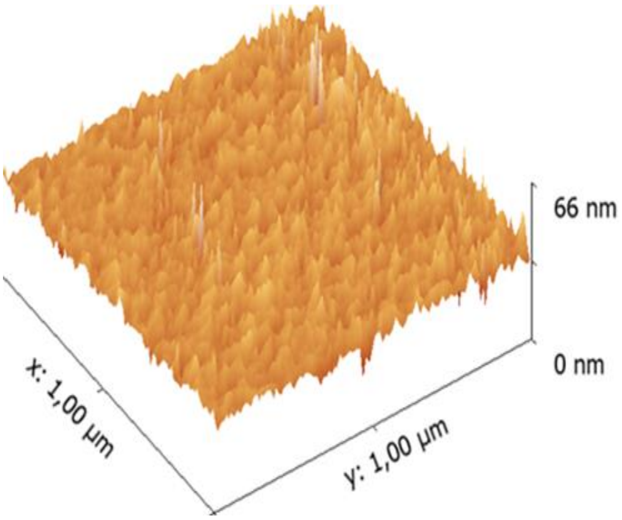

Fig. 1. AFM image of the surface of a 300 nm thick CdTe film on a polished glass substrate.

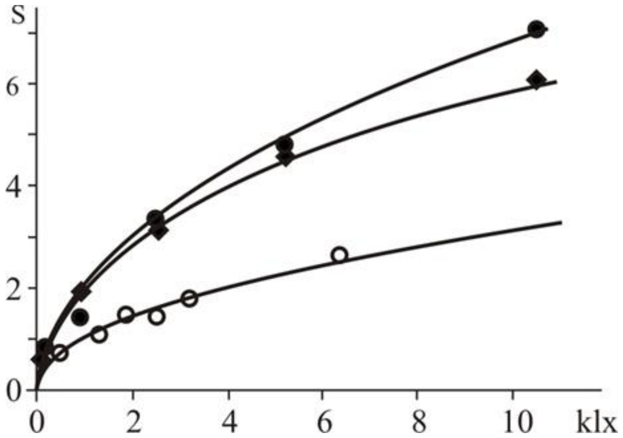

Fig. 2. Dependence of photosensitivity on illumination for thin CdTe films of different thicknesses:
● – thickness 200 nm, lining – polished glass;
♦ – thickness 320 nm, lining – polished glass;
○ – thickness 540 nm, lining – mica;
the average grain size is 25 nm (●), 30 nm (♦),
90 nm (○).

According to the research results, it can be seen that the photosensitivity of films obtained on polished glass substrates is significantly higher than that of films obtained on fresh mica cleavages (111), and it increases with decreasing film thickness. This is explained by the fact that the specific contribution of intergranular regions increases with decreasing crystallite size [20, 22]. Photoactivation energies decrease in darkness as the intensity of white light increases. The decrease in photoactivation energy at a higher level of illumination is primarily explained by a decrease in the intergranular boundary potential barrier height. It is expected that the potential barrier strongly affects the mobility of carriers and thus controls photosensitivity.

Using (7) and (8), the photosensitivity can be expressed as a function of the mobility activation energy:

$$S = e^{\Delta E_\mu / kT} - 1 \tag{9}$$

On Fig.3 dependences of the calculated activation energies of mobility on illumination are given [20].

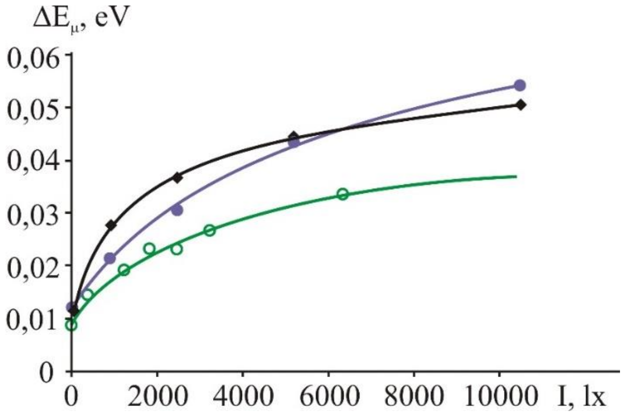

Fig. 3. Dependence of the calculated mobility activation energies on illumination for thin CdTe films of different thicknesses:
● – thickness 200 nm, substrate – mica;
♦ – thickness 320 nm, lining – polished glass;
○ – thickness 540 nm, lining – mica.

The grain boundary effect explains the decrease in the energy of photoactivation in the dark, since the current lost to recombination at the grain boundaries negatively affects the sensitivity of the films to light. Decreasing the temperature leads to a reduction in the photogeneration process and, accordingly, to a decrease in sensitivity to light. It has been found that the lifetime of minority carriers varies inversely with the intensity of light, confirming the defect-controlled photoconductivity of thin CdTe films.

It is worth noting that the obtained activation energies for films obtained on polished glass are close to each other and are in the range of 0.012–0.05 eV. At the same time, for films obtained on fresh mica cleavages, significantly lower values of mobility activation energies were obtained, which are 0.009–0.03 eV [20, 24].

Despite the high photosensitivity of CdTe films, they also have some drawbacks. For example, CdTe is a toxic material, so special safety measures are required for its production and use. In addition, CdTe films can be sensitive to radiation, which can lead to degradation of their efficiency [2, 3]. However, significant advancements in CdTe film manufacturing technology in recent years have allowed these drawbacks to be minimized.

It is also worth noting that CdTe films have high efficiency in collecting light from small collection areas, making them suitable for creating thin photovoltaic cells. This allows for the creation of more compact and efficient solar panels.

In summary, the photosensitivity of CdTe films depends on the spectral range, thickness, and quality of the material, as well as the technology used in their manufacture.

V. Thin-film heterostructures based on CdTe in solar energy

CdTe thin film solar cells are important components of modern solar panels that convert solar energy into electricity. They consist of several layers of different semiconductors that are interconnected. Typically, they are made up of a layer of CdS and CdTe, which allows for an energy conversion efficiency (ECE) - the efficiency of converting solar energy into electrical energy.

Thin film solar cells have several advantages over other solar energy technologies. They have an ECE, are able to withstand high temperatures and high levels of illumination and have a low production cost.

One of the main manufacturers of CdTe thin film solar cells is First Solar. The company uses a thin film production process that allows for the production of cells with low cost and HCE. According to the company's data, its SCs have a HCE of over 18%, making them some of the most efficient cells produced [2].

The main advantages of using CdTe thin-film HSs in solar energy are their high efficiency, low cost, ease of production, high stability, and flexibility. CdTe thin-film HSs have a high efficiency of converting solar energy into electrical current, allowing for more power output for the same battery size compared to other materials. In addition, CdTe is a cheap semiconductor, which reduces the production cost of solar panels, particularly CdTe-based thin-film HSs. CdTe thin films can be produced using thin film deposition processes such as chemical bath deposition and physical vapor deposition, which allow for high-quality films to be obtained at low temperatures [29,37]. CdTe thin-film HSs have good stability against environmental and thermal stresses, which ensures the longevity of solar panels [38]. CdTe can be used in flexible solar panels, allowing for the creation of highly efficient solar energy systems that can be applied in various fields such as transportation, aerospace, medicine, and others.

Despite many advantages, thin-film CdTe HSs have certain drawbacks. For example, the low or unsatisfactory stability of the HSs to moisture and acids, which can cause a decrease in their efficiency. Another important aspect of using thin-film CdTe HSs is the issue of cadmium toxicity, which is one of the components of the heterostructure. Additionally, the use of cadmium can cause environmental problems during the disposal of solar panel waste [3]. Despite this, the issues of cadmium toxicity and stability HSs under external factors require further research and the development of effective measures to minimize negative impacts.

Furthermore, there are alternative materials for creating solar cells, such as perovskite materials [39]. These materials have high efficiency in converting solar energy into electricity and are less toxic than cadmium. However, perovskites have their own drawbacks, such as insufficient stability to moisture, acids, and other factors.

One of the main challenges of CdTe thin-film HSs is their relatively low stability to ultraviolet radiation and high temperatures. This can lead to a decrease in the ECE and a reduction in the service life of the SCs. To mitigate this effect, various protection methods can be used, such as applying protective coatings or using stabilizers [37, 38]. Additionally, there is a limitation on the thickness of CdTe films, which can restrict the effective thickness of the device and thus its ECE. To address this issue, various film strengthening technologies can be employed, or thin heterostructures with other semiconductors, such as $CuInGaSe_2$ (CIGS), can be utilized [40].

CdTe-based semiconductors have an advantage over Si in that they absorb optical radiation more efficiently, allowing the production of cheaper thin-film CEs. In particular, the average efficiency of the n-CdS/p-CdTe HS is about 16% under AM1.5 illumination conditions and a temperature of 300 K, which is almost half the theoretical value [2].

It is believed that one of the reasons for the low efficiency of CdTe-based SCs is the short lifetime τ_s of non-majority carriers, which leads to a high recombination velocity υ_s at the interfaces of the HSs junction and grains in the polycrystalline CdTe film. Reducing the recombination velocity υ_s should lead to improvements in the main parameters of solar cells, such as short-circuit current J_{sc} and open-circuit voltage V_{oc}. This is confirmed by experiments that have shown an increase in the open-circuit voltage V_{oc} from 0.84 to 0.93 V when replacing the polycrystalline CdTe film with a single-crystal substrate in n-CdS/p-CdTe heterostructure solar cells [41]. The low values of the short-circuit current and efficiency η of these samples are associated with the high resistance of the p-CdTe base substrates, the concentration of free holes in which does not exceed $7\ 10^{15}$ cm^{-3} at 300 K. Improving the structural perfection of the photoactive layer of p-CdTe in thin-film n-CdS/p-CdTe SCs allowed the efficiency η to be increased to ~21%, while V_{oc} increased by only 0.03 V [42, 43].

In this case, the increase in efficiency is associated with an increase in short-circuit current (J_{sc}), which is caused by a significant reduction in the series resistance of the HS through the thin p-CdTe layer. The dependence of the short-circuit current on the level of illumination (L) is linear and changes by more than four orders of magnitude. The open-circuit voltage (V_{oc}) depends on $lg\,L$ at low levels of illumination and saturates at high levels, as shown in Fig. 4.

A slight increase in the open-circuit voltage (V_{oc}) indicates that the main factor affecting the minority carrier lifetime (τ_s) is the recombination velocity at the junction interface of the semiconductor components. Various surface passivation methods can be applied to reduce this recombination velocity (υ_s) by 1-2 orders of magnitude. These methods can be used for both single crystal and large-grain semiconductor films [38, 44].

The internal quantum efficiency of the CdS/CdTe heterostructure significantly increases with the increase in the charge carrier lifetime and the specific resistance of the CdTe layer. However, it remains at the level of 17–18.5% for lifetimes within the range of 10^{-9}–10^{-10} s. To increase the efficiency to the theoretical limit (28–30%), it is necessary to increase the charge carrier lifetime in the CdTe layer to about 10^{-6} s and increase its thickness to several tens of micrometers. However, this is not economically justified [45].

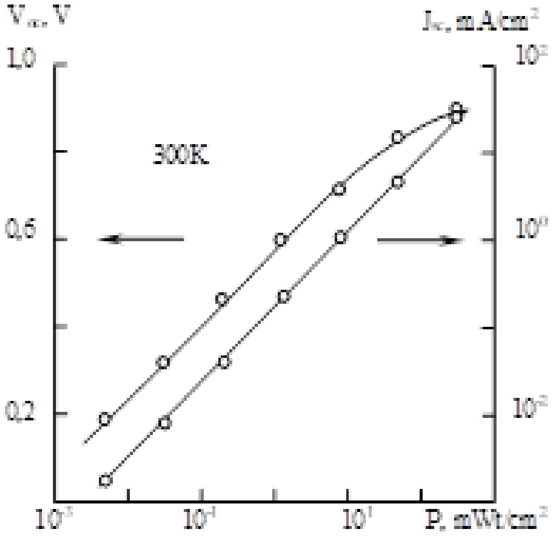

Fig. 4. Dependences of J_{sc} and V_{oc} for surface-barrier diodes on a CdTe:O substrate on the solar energy flux density.

An analysis of optical losses in thin-film CdS/CdTe solar cells with a transparent conducting layer of ITO or SnO_2 showed that even with 100% efficiency of photovoltaic conversion in CdTe and minimal thickness of CdS and ITO layers, the short-circuit current density (J_{sc}) cannot exceed more than 60% of the maximum possible value [46]. If the thickness of CdS and ITO layers is reduced below 30–50 nm, it is impossible to reduce optical losses, and a greater effect can be achieved by improving the transparency of the front electrode using other materials such as Cd_2SnO_4, Zn_2SnO_4 or ZnO. Even in the absence of absorption in CdTe, optical losses at a thickness of 50 nm of CdS reduce the short-circuit current by approximately 35%. The main reason for this reduction is the fundamental absorption in CdS (at $\lambda < 500$ nm), which cannot be eliminated without replacing CdS with a semiconductor material with a wider bandgap [3, 47].

It can be confidently asserted that research on CdTe HSs and other thin-film PV materials for creating SCs is an important direction for science and technology, as it can help reduce dependence on fossil fuels and decrease carbon emissions into the atmosphere. Moreover, the development of solar energy can create new job opportunities and contribute to economic growth. To achieve high ECE and efficiency of CdTe-based SCs, various optimization methods can be used, such as optimization of the thickness and composition of the heterostructure layers, optimization of the element's geometry, using different quality control methods, and developing new production methods. Additionally, it is important to ensure effective recycling of CdTe-based SCs, which will help reduce their environmental impact and contribute to creating a sustainable and environmentally friendly solar energy sector.

Conclusions

CdTe material possesses the necessary properties for creating thin-film SCs, including high energy conversion efficiency, durability, cost-effectiveness, and ease of manufacturing. This makes it an attractive material for PV production. The conductivity coefficient, electron mobility, energy conversion efficiency, transparency, light absorption, scattering coefficient, electrical conductivity, high absorptivity in the near-infrared and visible regions of the spectrum, good chemical and mechanical stability, and other properties of CdTe play an important role in the production of thin-film SCs based on this material.

The photosensitivity of CdTe films depends on several factors, including the film growth method, material purity, and its structure. These films have high sensitivity to light and high-energy radiation, which allows them to be used in various devices, particularly in solar cells. However, the photosensitivity of CdTe films also depends on the presence of defects and impurity levels in the material, so it can be improved through appropriate processing and optimization methods.

Despite the fact that the efficiency of CdTe thin-film solar modules in large-scale production is only around 10–11%, which is significantly lower than the efficiency of silicon-based modules (13–17%), there is still potential for significant improvement of CdTe SCs efficiency through certain combinations of parameters. The thickness of the absorbing layer, carrier lifetime, specific resistance, and concentration of uncompensated acceptors in CdTe are key factors that can greatly influence efficiency improvement [48].

However, in order to achieve the highest efficiency and ensure resistance to harmful factors, it is necessary to continue developing manufacturing technologies for thin-film PV based on CdTe. This includes the development of new methods for protection against ultraviolet radiation and high temperatures, improvement of the mechanical stability of films, reducing the use of cadmium, and ensuring resistance to the harmful effects of long-term operation.

Research and development conducted over the past decade have enabled the mass production of CdTe-based solar modules that can compete with silicon modules in terms of compromise between efficiency and cost. This contributes to the construction of powerful solar power plants, and rapid development of this industry is expected in the future.

Mazur T.M. – Doctor of Philosophy, Assistant Professor of General and Applied Physics;
Mazur M.P. Associate Professor, Ph.D (Physics and Mathematics), Director of the Institute of architecture, Construction and Power Engineering;
Vakaliuk I.V. – Ph.D. student.

[1] M.A. Green, E.D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, & A.W. Ho-Baillie, *Solar cell efficiency tables (Version 55)*,Progress in Photovoltaics: Research and Applications, 28(1), 3 (2020); https://doi.org/10.1002/pip.3228.

[2] T.M. Mazur, V.V. Prokopiv, M.P. Mazur, U.M. Pysklynets, *Solar cells based on CdTe thin films*, Physics and chemistry of solid state, 22(4), 817 (2021); https://doi.org/10.15330/pcss.22.4.817-827.

[3] L.A. Kosyachenko, & E.V. Grushko, *Prospects for the Use of Thin-Film Cadmium Telluride in Solar Energetics*, Ukr. Phys. Journ., Rev., 7(1), 3 (2012); http://archive.ujp.bitp.kiev.ua/files/reviews/7/1/r070101pu.pdf.

[4] B.E. McCandless, *CdTe solar cells: Processing limits and defect chemistry effects on open circuit voltage*, MRS Online Proceedings Library, 1538(1), 249 (2013); https://doi.org/10.1557/opl.2013.1017.

[5] M.A. Green, E.D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, & A. W. Ho-Baillie, *Solar cell efficiency tables (Version 55)*, Progress in Photovoltaics: Research and Applications, 28(1), 3 (2020); https://doi.org/10.1002/pip.3228.

[6] M.A. Green, E.D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, &, H. Xiaojing, *Solar cell efficiency tables (Version 59)*, Progress in Photovoltaics: Research and Applications, 30(1), 1062 (2021); https://doi.org/10.1002/pip.3506.

[7] V.P. Makhniy, M.M. Berezovskiy, O.V. Kinzerska, M.P. Mazur, T.M. Mazur, V.V. Prokopiv, *Prospects of using surface and barrier CdTe-diodes in solar energy*, Sensor Electronics and Microsystem Technologies, 16(2), 42 (2019); https://doi.org/10.18524/1815-7459.2019.2.171227.

[8] B. E McCandless, & J. R. Sites, *Cadmium telluride solar cells*, Handbook of photovoltaic science and engineering, 600 (2011); https://kashanu.ac.ir/Files/Content/Handbook.pdf.

[9] D.V Korbutyak, S.V. Melnichuk, E.V Korbut, & M.M. Borisyuk, (2000). Cadmium telluride: impurity-defect states and detector properties.(Ivan Fedorov: Kyiv, 198 (2000)).

[10] D.V. Korbutiak, O.V. Kovalenko, S.I. Budzuliak, S.M. Kalytchuk, I.M. Kupchak, *Light-rectifying properties of quantum dots of semiconductor compounds A2B6*, Ukrainian Physical Journal, 7(1), 95 (2012); http://archive.ujp.bitp.kiev.ua/files/reviews/7/1/r070103pu.pdf.

[11] R. Grill, & A. Zappettini, *Point defects and diffusion in cadmium telluride*. Progress in crystal growth and characterization of materials, 48, 209 (2004); https://doi.org/10.1016/j.pcrysgrow.2005.06.001

[12] V.V. Prokopiv, I.V. Horichok, V.V. Prokopiv, & L.V. Turovska. Point defects of Cadmium, Tin and Lead Tellurides. Ivano-Frankivsk, 248 p. (2016); http://hdl.handle.net/123456789/2541.

[13] J. H. Greenberg, *P–T–X phase equilibrium and vapor pressure scanning of non-stoichiometry in the Cd–Zn–Te system*, Progress in crystal growth and characterization of materials, 47(2-3), 196 (2003); https://doi.org/10.1016/j.pcrysgrow.2005.02.001.

[14] R. Fang, & R.F. Brebrick, *CdTe I: Solidus curve and composition-temperature-tellurium partial pressure data for Te-rich CdTe (s) from optical density measurements*, Journal of Physics and Chemistry of Solids, 57(4), 443 (1996); https://doi.org/10.1016/0022-3697(95)00251-0.

[15] D.Y. Goswami, S. Vijayaraghavan, S. Lu, & G. Tamm, *New and emerging developments in solar energy*, Solar energy, 76(1-3), 33 (2004); https://doi.org/10.1016/S0038-092X(03)00103-8.

[16] H. Okamoto, & H. Okamoto, *Phase diagrams for binary alloys*, 314, Materials Park, OH: ASM international, (2000); https://www.asminternational.org/documents/10192/1849770/57751G_Frontmatter.pdf.

[17] O. Knacke, & K. Hesselmann, *Thermochemical properties of inorganic substances*, Springer, (1991); https://worldcat.org/en/title/644053530.

[18] T. Mazur, V. Prokopiv, L. Turovska, *Quasi-chemistry of intrinsic point defects in cadmium telluride thin films*, Molecular Crystals and Liquid Crystals, 671(1), 85 (2018); https://doi.org/10.1080/15421406.2018.1542088.

[19] L. Tsakalakos, J. Balch, J. Fronheiser, B.A. Korevaar, O. Sulima, & J. Rand, *Silicon nanowire solar cells*, Applied physics letters, 91(23), 233117 (2007); https://doi.org/10.1063/1.2821113.

[20] V.V. Prokopiv, O.B. Kostyuk, B.S. Dzundza T.M. Mazur, L.V. Turovska, O.M. Matkivskyi, M.V. Deychakivskyi, *Electrical properties of CdTe<Ca> thin layers*, Physics and chemistry of solid state, 20(4), 372 (2019); https://doi.org/10.15330/pcss.20.4.372-375.

[21] O. Madelung, (Ed.), *Semiconductors: group IV elements and III-V compounds*, Springer Science & Business Media, (2012); https://doi.org/10.1007/978-3-642-45681-7.

[22] V. Prokopiv, I. Horichok, T. Mazur, O. Matkivsky, L. Turovska, *Thermoelectric materials based on samples of microdispersed PbTe and CdTe*, Proceedings of the 2018 IEEE 8th International Conference "Nanomaterials: Applications and Properties", NAP 2018, (2018); https://doi.org/10.1109/NAP.2018.8915357.

[23] B. Naidych, T. Parashchuk, I. Yaremiy, M. Moyseyenko, O. Kostyuk, O. Voznyak, ... & L. Nykyruy, *Structural and thermodynamic properties of Pb-Cd-Te thin films: Experimental study and DFT analysis*, Journal of Electronic Materials, 50, 580-591 (2021); https://doi.org/10.1007/s11664-020-08561-5.

[24] T. Mazur, M. Mazur, *Thickness Dependence of the Kinetic Parameters in CdTe and PbTe Thin Films*, Proceedings of the 2022 IEEE 12th International Conference "Nanomaterials: Applications and Properties", NAP 2022, (2022); https://doi.org/10.1109/NAP55339.2022.9934352.

[25] T. Mazur, M. Slyotov, M. Mazur, O. Slyotov, *Heterolayers of Hexagonal α-CdTe*, Journal of Nano- and Electronic Physics, 14(5), 05029 (2022); https://doi.org/10.21272/jnep.14(5).05029.

[26] R. Grill, J. Franc, P. Hoschl, I. Turkevych, E. Belas, P. Moravec, ... & K.W. Benz, *High-temperature defect structure of Cd-and Te-rich CdTe*, IEEE Transactions on Nuclear Science, 49(3), 1270 (2002); https://doi.org/10.1109/TNS.2002.1039650.

[27] D.M. Freik, V.M. Chobanyuk, O.S. Krynytskyi, & I.V. Horichok, *Photovoltaic trasformers of solar irradiation based on cadmium telluride. Part II. Achievements and State of Art. (Review)*. Physics and Chemistry of Solid State, 13(3), 744 (2012); http://page.if.ua/uploads/pcss/vol13/!1303-29.pdf.

[28] T.M. Mazur, V.P. Makhniy, V.V. Prokopiv, M.M. Slyotov, *Thermal annealing effect on optical properties of the cadmium telluride films*, Journal of Nano- and Electronic Physics. 9(5), 05047 (2017); http://doi.org/10.21272/jnep.9(5).05047.

[29] S. H.Wei, S. B.Zhang, & A.Zunger, *First-principles calculation of band offsets, optical bowings, and defects in CdS, CdSe, CdTe, and their alloys*, Journal of applied Physics, 87(3), 1304 (2000); https://doi.org/10.1063/1.372014.

[30] B. Dzundza, O. Kostyuk, & T. Mazur, *Software and Hardware Complex for Study of Photoelectric Properties of Semiconductor Structures*, IEEE 39th International Conference on Electronics and Nanotechnology (ELNANO), Kyiv, 635 (2019); https://doi.org/10.1109/ELNANO.2019.8783544.

[31] H.S. Patel, J.R. Rathod, K.D. Patel, V.M. Pathak, *Structural and surface studies of vacuum evaporated Cadmium Telluride thin films*, American J Mater Sci & Tech, 1, 11 (2012); https://doi.org/10.7726/ajmst.2012.1002.

[32] M.A. Green, K. Emery, D.L. King, S. Igari, & W. Warta, Solar cell efficiency tables (version 20), Progress in photovoltaics, 10(5), 355 (2002); https://doi.org/10.1002/pip.453.

[33] L. Nykyrui, Y. Saliy, R. Yavorskyi, Y. Yavorskyi, V. Schenderovsky, G. Wisz, & S. Górny, *CdTe vapor phase condensates on (100) Si and glass for solar cells*. In 2017 IEEE 7th International Conference Nanomaterials: Application & Properties (NAP), 01PCSI26-1, IEEE (2017); https://doi.org/10.1109/NAP.2017.8190161.

[34] T. Mazur, M. Slyotov, M. Mazur, V. Prokopiv, O. Kinzerska, O. Slyotov, *Features of the cadmium chalcogenide substrates with surface nanostructure*, Materials Today: Proceedings, (2021); https://doi.org/10.1016/j.matpr.2019.12.112.

[35] S. Chander and M.S. Dhaka, *Effect of thickness on physical properties of electron beam vacuum evaporated CdZnTe thin films for tandem solar cells*, Physica E, 84, 112 (2016); https://doi.org/10.1016/j.physe.2016.05.045.

[36] P.K. Kalita, *Temperature dependence of dc photoconductivity in CdTe thin films*, Pramana, 60(6), 1247 (2003); https://www.ias.ac.in/public/Volumes/pram/060/06/1247-1257.pdf.

[37] P.M. Gorley, V.P. Makhniy, P.P. Horley, Yu.V. Vorobiev and J. González-Hernández, *Surface-Barrier Solar Cells Based On Monocrystalline Cadmium Telluride with the Modified Boundary*, Solar Energy [Internet], (2010, Feb 1); http://dx.doi.org/10.5772/8061.

[38] Mykhailo Slyotov, Tetiana Mazur, Volodymyr Prokopiv, Oleksii Slyotov, Myroslav Mazur, *Sources of optical radiation based on ZnTe/ZnSe/ZnS heterostructures*, Materials Today: Proceedings (2022); https://doi.org/10.1016/j.matpr.2022.03.476.

[39] M.I. Elsmani, N. Fatima, M.P.A. Jallorina, S. Sepeai, M.S. Su'ait, N. Ahmad Ludin, M.A. Mat Teridi, K. Sopian, M.A. Ibrahim, *Recent Issues and Configuration Factors in Perovskite-Silicon Tandem Solar Cells towards Large Scaling Production*, Nanomaterials, 11, 3186 (2021); https://doi.org/10.3390/nano11123186.

[40] V.K. Kamble, & V.B. Pujari, *Electrical and micro-structural properties of cadmium chalcogenides: A comparative study*, Int. J. Emerg. Technol. Appl. Eng, 5, 172 (2015); https://api.semanticscholar.org/CorpusID:16313665.

[41] J.N. Duenow, J.M.Burst, D.S. Albin, D. Kuciauskas, S.W. Johnston, R.C. Reedy, & W.K. Metzger, *Single-crystal CdTe solar cells with Voc greater than 900 mV*, Applied Physics Letters, 105(5), 053903 (2014); https://doi.org/10.1063/1.4892401.

[42] M.O. Reese, C.L. Perkins, J.M. Burst, S. Farrell, T.M. Barnes, S.W. Johnston, & W. K. Metzger, *Intrinsic surface passivation of CdTe*, Journal of Applied Physics, 118(15), 155305 (2015); https://doi.org/10.1063/1.4933186.

[43] T.M. Mazur, M.M. Slyotov, V.V. Prokopiv, O.M. Slyotov, M.P. Mazur, *Light emitters based on II-VI chalcogenides with nanostructured surface*, Molecular Crystals and Liquid Crystals, 752, 95 (2022); https://doi.org/10.1080/15421406.2022.2091276.

[44] V.P. Makhniy, *Influence of thermal annealing on physical properties of surface layers of monocrystalline cadmium telluride*, Surface, X-rays, synchrotron and neutron investigation, 2, 108 (2007); https://naukarus.com/vliyanie-termicheskogo-otzhiga-na-fizicheskie-svoystva-poverhnostnyh-sloev-monokristallicheskogo-tellurida-kadmiya.

[45] X. Mathew, L.A. Kosyachenko, V.V. Motushchuk, O.F. Sklyarchuk, *Requirements imposed on the electrical properties of the absorbed layer in CdTe-based solar cells*, J. Materials Science: Materials in Electronics, 18, 1099 (2007); https://doi.org/10.1007/s10854-007-9317-2.

[46] Nowshad Amin, et al., *Encyclopedia of sustainable technologies*, 11, (2017); https://doi.org/10.1016/B978-0-12-409548-9.10092-2.

[47] L. Kosyachenko, *Solar Energy*, edited by R.D. Rugescu, Intech, Croatia, 105 (2010); https://cdn.intechopen.com/pdfs/8547/InTech-Chapter_download.pdf.

[48] M. A.Green, E. D.Dunlop, J.Hohl-Ebinger, M.Yoshita, N.Kopidakis, & A. W.Ho-Baillie, *Solar cell efficiency tables (Version 55)*, Progress in Photovoltaics: Research and Applications, 28(1), 3 (2021); https://doi.org/10.1002/pip.3228.

Т.М. Мазур[1], М.П. Мазур[1], І.В. Малярська[2]

Сонячні елементи на основі тонких плівок CdTe (II частина)

[1]Івано-Франківський національний технічний університет нафти і газу, Івано-Франківськ, Україна,
tetiana.mazur@nung.edu.ua;
[2]Прикарпатський національний університет імені Василя Стефаника, Івано-Франківськ, Україна

У роботі проведено дослідження щодо використання напівпровідникових сонячних елементів (СЕ) на основі тонкоплівкового телуриду кадмію (CdTe) в сучасній енергетиці. Проаналізовано переваги та недоліки використання СЕ на основі тонких плівок CdTe, а також приведено аргументи на користь впровадження технологій масового виробництва CdTe сонячних модулів, які можуть конкурувати з кремнієвими аналогами за компромісних значень ефективності та вартості. Описано фізико-хімічні властивості бінарної системи Cd-Te та вказано зв'язок між фізичними, хімічними, електричними та оптичними властивостями CdTe, що робить його привабливим для використання у тонкоплівкових СЕ. Особлива увага приділяється дослідженню фоточутливості, яка є важливим параметром у визначенні фотопровідності, та обговорюються переваги і недоліки фоточутливості плівок CdTe. Розглянуто тонкоплівкові гетероструктури (ГС) CdTe, які є важливими компонентами сучасних сонячних батарей, та описуються їх основні переваги та недоліки. Аргументується, що прості способи виготовлення та формування ГС, які не потребують складного та дорогого обладнання, є важливою перевагою технології СЕ на основі CdTe.

Ключові слова: сонячні елементи, тонкі плівки, CdTe, фоточутливість, гетероструктури.