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Spectral and Temperature Properties of Solar Cells Based on Cadmium Telluride Thin-Films

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This paper investigates the effect of CdTe layer thickness on the spectral characteristics and parameters of the Au/CdTe/CdS/ITO thin-film heterostructure using both modeling and experimental measurements. The thin-film solar cell was deposited by RF magnetron sputtering in vacuum. Numerical analysis in the SCAPS-1D simulation environment enabled the evaluation of the dependencies: efficiency, short-circuit current density, and open-circuit voltage on the wavelength spectrum and absorber layer thickness. It was shown that increasing the absorber layer thickness to 3-4 µm promotes the growth of both current density and open-circuit voltage, which is consistent with experimental measurements. The obtained temperature dependencies indicate a decrease in efficiency with increasing temperature under both monochromatic spectra and solar illumination, with the temperature dependencies of relative efficiency under monochromatic and direct solar illumination being nearly identical.

Keywords: photovoltaic devices, renewable energy, cadmium telluride, temperature dependencies, optical properties, wavelength spectrum.

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Introduction

The rapid development of photovoltaic technologies is driven by the continuous improvement of solar cell structures and the growing demand for renewable energy sources. Current research is focused on enhancing the efficiency of solar cells and reducing their manufacturing costs. Particular attention has been given to second-generation solar cells based on cadmium telluride (CdTe) [1]. Cadmium telluride is characterized by a direct band gap of approximately 1.5 eV, combined with a high optical absorption coefficient and relatively low manufacturing cost. These features make it one of the most promising materials for commercial applications in solar energy, as well as for the development of thin and lightweight solar cells for biomedical applications [2]. The efficiency of CdTe solar cells strongly depends on the materials used in the device structure. The highest certified efficiency of a CdTe solar cell is 23.1%, achieved with a cell area of 0.45 cm² by First Solar [3]. The most widely studied structure remains TCO/CdS/CdTe, where n-type CdS serves as the window layer forming the p–n junction, while p-type CdTe acts as the absorber that efficiently captures light [4]. Among the key parameters influencing the performance of a solar cell are light intensity and device temperature. Manufacturers typically report efficiency values under standard test conditions; however, determining the temperature and spectral dependences of efficiency requires additional investigations. Therefore, studies aimed at conducting experimental measurements of fabricated thin-film solar cell structures are highly relevant in the context of current challenges.

I. Literature Review and Problem Statement

Study [5] focuses on analyzing the influence of temperature on the performance of CdTe-based solar cells. The authors examine key parameters such as open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), fill factor (FF), and efficiency (η) over a temperature range of 273–

523 K. The results show that V_{oc} decreases due to the exponential increase in the saturation current (J_0), while J_{sc} slightly increases because of the narrowing of the material's bandgap. The values of FF and η decrease as a result of the reduction in V_{oc}, which significantly impacts the overall solar cell efficiency.

In study [6], the authors describe the results of modeling the temperature characteristics of CdTe solar cells, specifically the FTO/SnO_2/CdS/CdTe/Cu_2O structure, using Matlab and Maple software over a temperature range of 200–400 K. The results indicate a sharp decrease in efficiency with increasing temperature, from 32.29% at 200 K to 15.53% at 400 K, highlighting a strong temperature dependence. The open-circuit voltage (V_{oc}) decreased from 2.45 V at 200 K to 0.64 V at 400 K due to an increase in the diode dark current and the carrier recombination rate. The short-circuit current density (J_{sc}) remained nearly constant, measuring 27.9 mA/cm² at 200 K and 27.15 mA/cm² at 400 K, indicating low correlation with temperature. The fill factor (FF) initially increased slightly with temperature, reaching a maximum of 0.9419 at 330 K, and then began to decrease. This behavior is attributed to the changing balance between recombination and carrier mobility.

The spectral dependence of the photovoltaic parameters of CdTe was investigated in study [7]. Monochromatic light with wavelengths of 470, 525, 780, and 850 nm was used for the analysis. The results show that the highest efficiency was achieved at 780 nm, while at 470 and 525 nm the efficiency was lower due to losses in the CdS layer. The short-circuit current density (J_{sc}) was reduced at 470 and 525 nm because part of the light was absorbed by the CdS layer instead of CdTe, with the highest value observed at 780 nm. The open-circuit voltage (V_{oc}) exhibited only minor changes, indicating the stability of the p–n junction's electrical properties. The fill factor (FF) sharply decreased over the 525–780 nm wavelength range due to increased carrier recombination. It should also be noted that the efficiency at 850 nm was very low, likely because the charge carriers were located near the back side of the CdTe layer, far from the internal electric field, reducing the drift transport velocity and increasing the probability of recombination.

Most studies have focused on evaluating the effect of temperature under the solar radiation spectrum, while insufficient attention has been paid to:

1. Assessing the influence of monochromatic light on the efficiency of CdTe solar cells and comparing it with modeling results;

2. Investigating the temperature dependences under illumination of thin films with monochromatic light at specific wavelengths.

II. Experimental methods

Thin-film structures were fabricated using thermal vacuum techniques from pre-synthesized materials. To form sensitive solar structures based on cadmium chalcogenides (CdTe and CdS), a radio-frequency (RF) magnetron sputtering method was employed [8]. Commercial glass/ITO substrates (NANOCS IT100-111-25, 100 Ω/sq) were used for the deposition of CdS and subsequent CdTe layers. Prior to CdS film deposition, the substrate surface was cleaned by boiling in high-purity CCl4 for 0.25 hours. The ITO layer provides a transparent ohmic contact with the CdS film. Monocrystalline CdS and CdTe disks, 1 mm thick and 40 mm in diameter, served as targets for RF magnetron sputtering. The distance between the target and the substrate during deposition was 60 mm. The residual gas pressure in the working chamber was $1\cdot10^{-4}$ Pa, achieved using a diffusion pump with the "Polyphenyl Ether 5F4E" fluid, which is characterized by a low vapor pressure ($9\cdot10^{-4}$ Pa). To prevent vapors of the working fluid from entering the vacuum chamber during deposition, a liquid nitrogen trap was employed. Sputtering was carried out in an argon (Ar) atmosphere at a pressure of 1.0–1.3 Pa. The RF magnetron power was maintained at 30 W. The parameters used during the deposition of CdS and CdTe films are summarized in Table 1. The deposition of contacts (Au) onto the fabricated structures was carried out using direct-current magnetron sputtering with a gold target. The DC magnetron discharge current was maintained at 30 mA. A high-temperature tungsten heater with a power of 300 W was used to heat the substrates. The heating and cooling rates, as well as the deposition temperature conditions, were controlled using a PID controller. The start and end of the process were managed with a movable plate. The physico-technological parameters for forming Au contacts on the fabricated structures are presented in Table 1.

Figure 1 shows the configuration and geometric dimensions of the samples with soldered conductors. For the convenience of subsequent measurements, the samples were illuminated through a 10 mm diameter aperture.

Photovoltaic measurements at different radiation frequencies and temperatures were carried out using a custom automated setup for investigating the photoelectric properties of semiconductor structures [9]. The sample was mounted on a textolite sample holder (Figure 2) opposite the light source. Light-emitting diodes (LEDs) with a power of 3 W and corresponding spectral characteristics were used as the light source.

Table1.

Physico-technological parameters for the layer-by-layer deposition of CdS and CdTe films and contacts on the fabricated structures.

Process	**CdS**	**CdTe**	**Au**
Substrate material	glass/ITO	glass/ITO/CdS	glass/ITO/CdS/CdTe
Sputtering target material, purity	CdS, 99.999 %	CdTe, 99.999 %	Au, 99.99 %
Deposition time, s	60	2400	300
Furnace temperature, °C	300	500	300
Substrate temperature, °C	170	292.7	160
Deposition rate, Å/c	~2	~14	~7

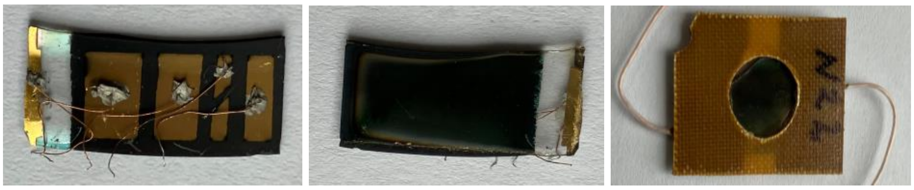

Fig. 1. Fabricated thin-film samples mounted on a textolite plate.

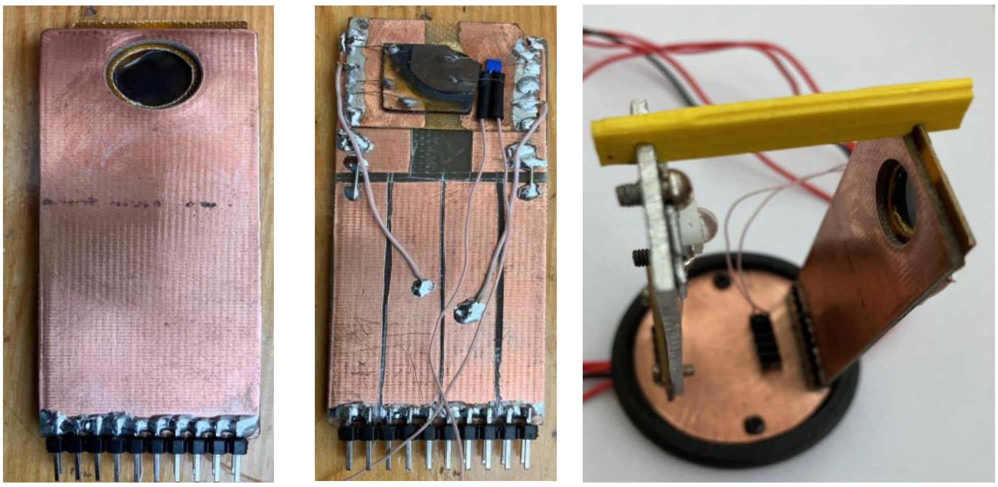

Fig. 2. Setup for experimental measurements of thin-film solar cells.

The wavelength was changed manually by replacing the LED. The sample holder and the light source holder were mounted inside a black plastic cylinder via a detachable connection, providing protection from ambient light. A precision PT1000 temperature sensor and a digital illuminance meter VELM7700 (Vishay Intertechnology, USA) were installed inside the cylinder. To measure the temperature dependence of photovoltaic parameters, an electric heater was placed in the cylinder, allowing measurements up to 100 °C. The load characteristics were measured using a four-wire scheme by connecting appropriate resistors to the output of the photovoltaic converter. The measurement accuracy was ±0.5 K for temperature, ±3% for illuminance, and ±1% for electrical parameters.

The radiation energy incident on a unit area of the photovoltaic converter was calculated based on the datasheet characteristics of the light sources at the corresponding distance from the sample and was monitored using the illuminance sensor readings. For sunlight, the energy was determined from the measured illuminance according to the methodology described in [10].

Experimental measurements of the angle dependence of the fabricated CdTe-based films were carried out on a sunny day under direct solar radiation using a custom automatic positioning setup for photovoltaic converters [11]. The measurements were performed in manual mode for tilt and azimuth angles, with values recorded every 10° as the tilt angle was varied within a range of ±90°.

The photovoltaic properties were simulated using the SCAPS-1D environment, developed at the Department of Electronics and Information Systems, University of Gent, Belgium [12].

For the SCAPS simulations, the electrical properties of the Au/CdTe/CdS/ITO heterostructure (Fig. 3) including optical bandgap, absorption coefficient, carrier concentration, and other input parameters were determined based on literature data [13–15] (Table 2). The photovoltaic device, whose structure is depicted schematically, is a thin-film system designed for efficient conversion of solar radiation into electrical energy. The entire structure begins with a glass substrate, which provides mechanical support and serves as an optical interface for incident light. High transparency in the visible and near-infrared ranges is critical to minimizing photon losses before they reach the active layers [16]. The next layer deposited on the glass is indium tin oxide (ITO), which performs a dual function: it is electrically conductive, enabling the collection of photogenerated charge carriers, while remaining optically transparent, allowing light to penetrate deeper into the device. This layer acts as the front electrical contact, establishing the interface between the semiconductor layers and the external circuit. The efficiency of light absorption at this stage is a key factor determining the overall device performance [17].

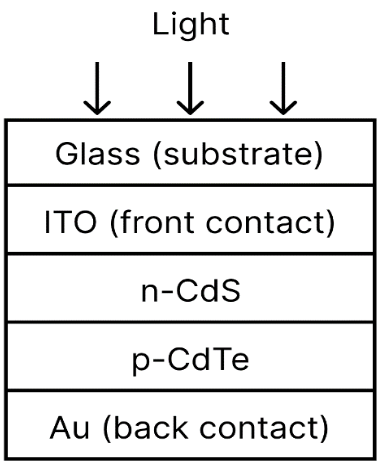

Fig. 3. – Structure of the investigated photovoltaic converters.

Table 2.

SCAPS Model Parameters [13-15]

Parameters	**p-CdTe**	**n-CdS**	**ITO**
thickness, μm	3.5	0.01	0.01
bandgap (eV)	1.5	2.4	3.7
electron affinity (eV)	3.9	4.5	4.5
dielectric permittivity (relative)	9.4	10	9.4
CB effective density of states (1/cm^3)	$8\cdot10^{17}$	$1.5\cdot10^{18}$	$4\cdot10^{19}$
VB effective density of states (1/cm^3)	$1.8\cdot10^{19}$	$1.8\cdot10^{18}$	$1\cdot10^{18}$
electron thermal velocity (cm/s)	$1.0\cdot10^{7}$	$1.0\cdot10^{7}$	$1.0\cdot10^{7}$
hole thermal velocity (cm/s)	$1.0\cdot10^{7}$	$1.0\cdot10^{7}$	$1.0\cdot10^{7}$
electron mobility (cm²/Vs)	300	50	30
hole mobility (cm²/Vs)	40	20	5
shallow uniform donor density ND (1/cm^3)	0	$1\cdot10^{22}$	$1\cdot10^{21}$
shallow uniform acceptor density NA (1/cm^3)	$2\cdot10^{15}$	0	0

The subsequent layer is cadmium sulfide (n-CdS) layer is deposited onto the ITO layer, serving as both a "window" and a buffer layer [18]. Due to its wider bandgap compared to the subsequent layer, CdS absorbs only a small fraction of the incident light, allowing most photons to reach the absorber material. Its primary function is to form a heterojunction with the following cadmium telluride (p-CdTe) layer. It is at this n-p junction that the internal electric field is established, which acts as the driving force for separating the electron–hole pairs generated by light absorption.

The most critical component of the structure is p-CdTe, which serves as the absorber layer. Cadmium telluride possesses an almost ideal bandgap for solar energy conversion (approximately 1.5 eV), allowing it to efficiently absorb a broad spectrum of solar radiation and generate a large number of electron–hole pairs. Upon photon absorption, its energy is transferred to an electron, exciting it from the valence band to the conduction band and leaving behind a "hole" in the valence band. Under the influence of the internal electric field at the n–p junction, electrons drift toward the n-CdS and ITO contact, while holes drift toward the back contact [19]. The structure is completed by a gold (Au) layer, which serves as the back electrical contact. Gold is chosen due to its high electrical conductivity and its ability to form an ohmic contact with p-CdTe, effectively collecting holes and transferring them into the external circuit, thereby closing the electrical loop and generating photocurrent.

III. Results and Discussion

Figure 4 presents the results of SCAPS simulations as a function of the optical radiation frequency. Both plots (a) and (b) illustrate the dependence of the conversion efficiency and short-circuit current density on the wavelength of the incident light (ranging from 350 nm to 850 nm). The different curves in the graphs correspond to various thicknesses of the primary absorber layer, p-CdTe, ranging from 1 μm to 4 μm, enabling an assessment of the influence of this parameter on the device performance.

Based on the data shown in Figure 4(a), it can be seen that in the short-wavelength range, approximately up to 400 nm (ultraviolet and blue light), the efficiency is relatively low for all samples. This can be explained by the fact that high-energy photons corresponding to these wavelengths may be absorbed in the upper layers, such as the transparent ITO contact or the n-CdS "window" layer, where their energy is dissipated, or the charge carriers generated near the surface have an increased probability of recombination before being collected. As the wavelength increases (from 400 nm to approximately 700–750 nm), the efficiency of all samples rises sharply. This corresponds to the range of optimal light absorption directly within the main active p-CdTe layer, where the photon energy is sufficient for effective generation of electron–hole pairs [20]. The maximum efficiency, exceeding 40%, is observed for the thickest CdTe layers in the 700–750 nm range. However, after reaching this peak, a sharp decline in efficiency occurs in the long-wavelength range, starting at approximately 800 nm and practically dropping to zero beyond 830–840 nm. This steep drop corresponds to the optical bandgap of CdTe. Photons with wavelengths exceeding this limit (low-energy infrared photons) do not possess sufficient energy to excite electrons across the CdTe bandgap and therefore pass through the material without being absorbed [21].

Figure 4(b) presents the dependence of the short-circuit current density (J_{sc}) on the wavelength (λ). J_{sc} is another key parameter, representing the maximum current that the device can generate under zero voltage. The spectral dependence of J_{sc} mirrors the efficiency trends, which is entirely expected, as the current is directly proportional to the number of effectively collected charge carriers. A similar pattern can be observed here: low J_{sc} values in the short-wavelength range, a sharp rise to peak values (approximately 0.35 mA/cm² for the thickest layers) in the 600–750 nm range, followed by a steep decline to zero beyond 830–840 nm. This confirms that the greatest contribution to current generation comes from photons with energies close to the CdTe bandgap. The absorber layer thickness also affects the increase in short-circuit current density, particularly in the long-wavelength region. This emphasizes that the optimal thickness of the CdTe active layer represents a trade-off between maximum light absorption and efficient carrier collection, as an excessively thick layer may increase the probability of carrier recombination during their drift to the contacts [22].

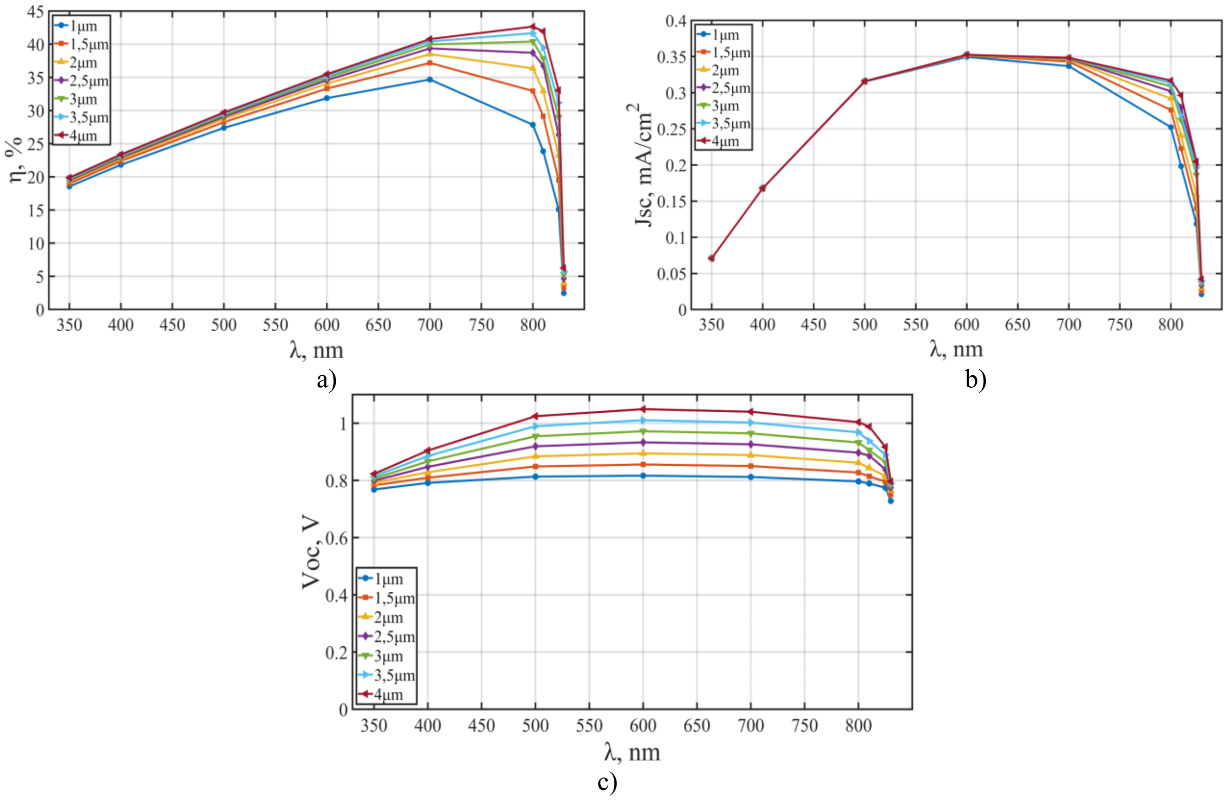

Fig. 4. SCAPS simulation of the structure efficiency under monochromatic spectra at different CdTe layer thicknesses: a) efficiency; b) short-circuit current density; c) open-circuit voltage.

Based on Figure 4(c), it can be seen that the layer thickness also affects the open-circuit voltage (V_{oc}). Increasing the thickness of the active layer (from 1 µm to 4 µm) leads to a rise in V_{oc} across all wavelengths. For instance, at 4 µm, the V_{oc} values are significantly higher than those for 1 µm, exceeding 1.05 V and approaching saturation. This can be explained by the fact that a thicker CdTe layer absorbs a larger number of photons, resulting in the generation of more charge carriers and, consequently, an increase in the quasi-Fermi levels within the semiconductor [23–24]. This elevates the potential difference across the junction and, correspondingly, the V_{oc}. Therefore, optimizing the thickness of the active layer is critical not only for maximizing the current but also for enhancing the open-circuit voltage, which ultimately determines the overall efficiency of the photovoltaic device.

A comparison of the simulation results with the experimental data for the frequency dependence of the relative efficiency of cadmium telluride–based thin-film photovoltaic converters is shown in Figure 5. Although the experimental samples demonstrated significantly lower absolute efficiency values, the relative variation of efficiency with light radiation frequency closely agrees with the simulation results, particularly for sample S1 with a CdTe layer thickness of 3.5 µm and a CdS thickness of 100 nm. Achieving the slight improvement in theoretical efficiency predicted for further increases in film thickness is rather difficult experimentally, since thicker films tend to develop microcracks, which substantially increase their internal resistance. Overall, the layer thicknesses are well defined by the deposition time, which is a key parameter in the technological process of film fabrication.

The obtained results indicate higher solar cell efficiency under light in the 600–800 nm range, with the short-circuit current density beginning to decrease from 700 nm onward, while the open-circuit voltage changes only slightly, exhibiting a curved profile with a maximum at approximately 600 nm.

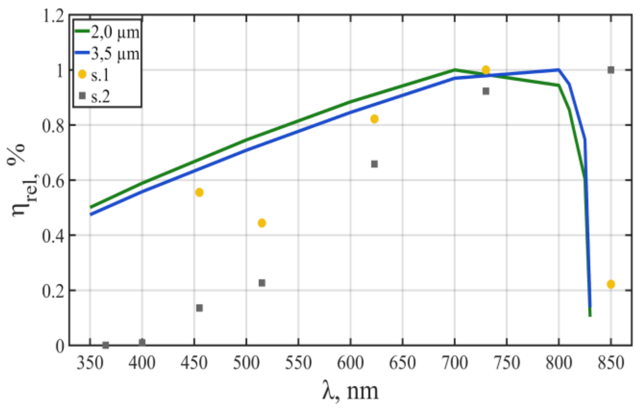

Fig. 5. Relative efficiency dependences of the solar cell under monochromatic spectra: solid lines – SCAPS model; dots – experimental values for samples s.1 and s.2.

The results of the temperature-dependent simulations in SCAPS under monochromatic light at 800 nm are presented in Figure 6. From Figure 6(a), it can be seen that the device's quantum efficiency exhibits an inverse dependence on temperature: as the temperature increases from 283 K to 373 K, the efficiency decreases linearly from approximately 44% to 32%. This reduction is caused by several factors, such as an increased carrier recombination rate at higher temperatures, resulting in fewer collected electrons and holes. Additionally, the device's internal resistance may increase, and the optical

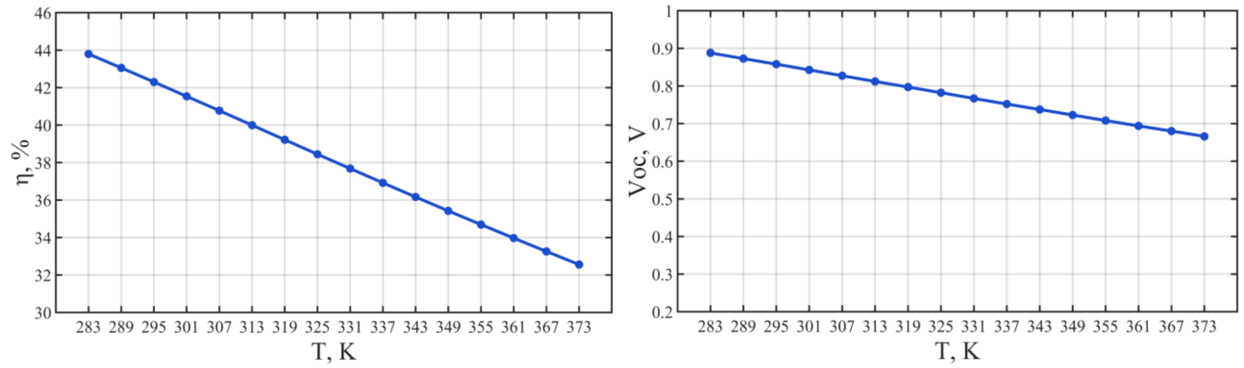

Fig. 6. SCAPS simulation results of temperature dependences under monochromatic light at 800 nm.

properties of the materials (e.g., the bandgap) can change slightly with temperature, affecting light absorption.

From Figure 6(b), it can be observed that as the temperature increases from 283 K to 373 K, the open-circuit voltage (V_{oc}) gradually decreases, starting from approximately 0.9 V and dropping to around 0.68 V. The reduction of V_{oc} with temperature is a typical characteristic of semiconductor p–n junctions and is explained by the increase in the concentration of intrinsic charge carriers and the corresponding rise in the diode saturation current. Both graphs emphasize the impact of operating temperature on the performance of photovoltaic devices: an increase in temperature leads to a significant decrease in both conversion efficiency and output voltage, which is an important factor to consider in the design and operation of solar cells.

Figure 7 presents the experimental dependence of the voltage of sample s.1 on temperature under varying load conditions. The graph shows three curves: the green curve corresponds to the open-circuit voltage (V_{oc}), while the blue and yellow curves represent the voltage measured across external resistive loads of 10 kΩ and 1 kΩ, respectively. For all three curves, a clear trend of decreasing output voltage with increasing temperature from 283 K to 373 K is observed. This behavior is characteristic of semiconductor devices, as a rise in temperature enhances internal carrier recombination mechanisms and increases the diode saturation current, resulting in a reduction of the potential the device can generate. The decrease in V_{oc} is particularly pronounced, dropping from approximately 140 mV to 110 mV over the indicated temperature range.

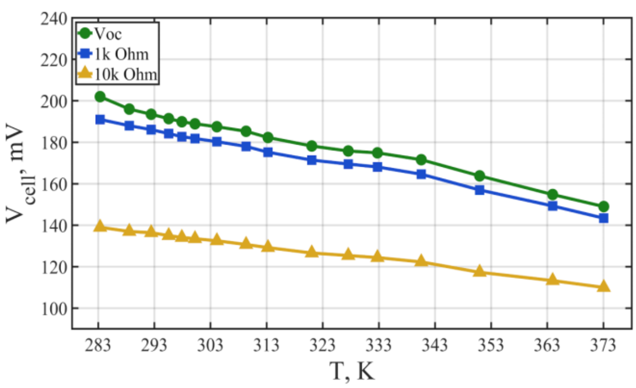

Fig. 7. Experimental voltage–temperature dependences of sample S1 under variable load.

However, the overall trend of voltage reduction with increasing temperature is also preserved under loaded conditions. For the 1 kΩ load (yellow curve), the voltage remains the highest, decreasing from approximately 203 mV to 150 mV, whereas for the 10 kΩ load (blue curve), the voltage is slightly lower, dropping from 190 mV to 143 mV.

Both theoretical and experimental curves exhibit a linear temperature dependence. To assess the impact of temperature under white and monochromatic illumination, and to compare the obtained results, Figure 8 presents the temperature dependence of the relative efficiency of the photovoltaic cell under different lighting conditions.

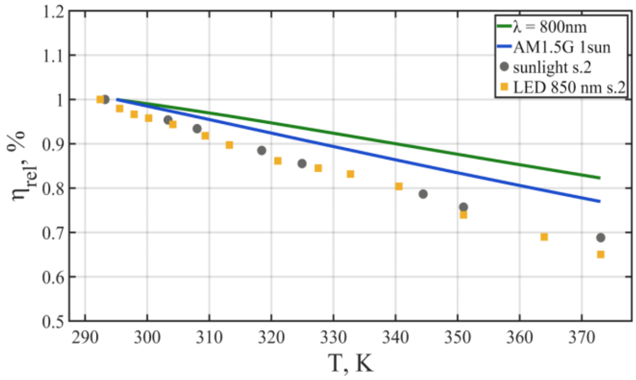

Fig. 8. Relative efficiency of the solar cell under different temperature conditions: solid lines – SCAPS simulation; dots – experimental data for sample s.1.

The simulation results confirm the experimental dependences. As expected, an increase in temperature leads to a decrease in the relative efficiency of the solar cells due to a sharp reduction in V_{oc}, observed for both the AM1.5G solar spectrum simulation and the simulation of a monochromatic spectrum near the red edge of the photoeffect for CdTe converters ($\lambda \sim 800$ nm). In this case, the monochromatic light exhibits a gentler slope compared to AM1.5G, and the experimental values under monochromatic illumination and direct sunlight are practically identical. The steeper temperature dependence observed in the experimental samples compared to theoretical predictions may be caused by structural imperfections inherent to real samples. The film structure strongly depends on the technological fabrication factors and requires further investigation.

Figure 9 presents the experimental dependence of the incident angle of sunlight on a thin-film cadmium telluride–based photovoltaic converter, showing a sharp decrease in the relative open-circuit voltage when deviating more than 30° from perpendicular incidence. Small deviations within 20–25° have practically no effect on the solar cell voltage, which can be explained by the presence of pyramid-shaped micro-roughness on the film surface, capable of effectively capturing radiation at small angles.

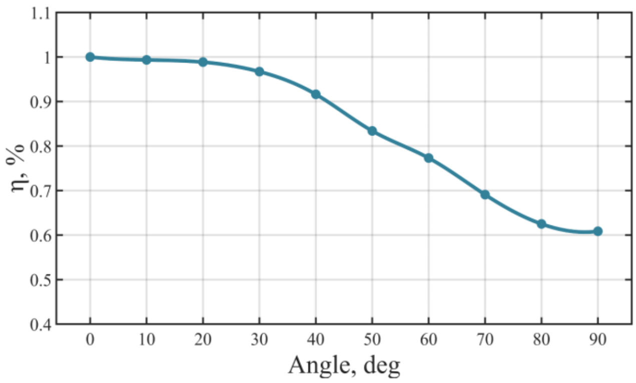

Fig. 9. Relative change of the open-circuit voltage of sample S1 under sunlight with varying angle.

Conclusions

Theoretical modeling and experimental investigations of the spectral and temperature dependences of the electrical properties of thin-film photovoltaic converters based on Au/CdTe/CdS/ITO heterojunction were carried out. It was shown that the maximum solar cell efficiency is observed under light with a wavelength of 600–800 nm, with the short-circuit current density starting to decrease from 700 nm, while the open-circuit voltage exhibits a curved profile with a maximum at approximately 600 nm. As expected, an increase in temperature leads to a decrease in the relative efficiency of the solar cells due to a sharp reduction in V_{oc}. Experimentally, it was demonstrated that the temperature dependences of the relative efficiency under monochromatic illumination and direct sunlight are practically identical.

Experimental measurements of spectral efficiency and short-circuit current demonstrated that increasing the CdTe thickness from 1 µm to 4 µm leads to an increase in both the current density and the open-circuit voltage. In this case, V_{oc} exceeds 1.05 V, which is consistent with the simulation results. Using SCAPS modeling, the layer thicknesses providing high photovoltaic performance suitable for practical application as solar energy conversion elements were determined and experimentally confirmed. Specifically, the optimal thicknesses are 150–200 nm for the contact layer, 50–100 nm for the CdS layer, and 3–4 µm for the CdTe layer.

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Спектральні та температурні властивості тонкоплівкових фотоелектричних перетворювачів на основі телуриду кадмію

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У роботі представлено результати експериментальних досліджень та моделювання у програмі SCAPS спектральних та температурних властивостей тонкоплівкових напівпровідникових фотоелектричних структур Au/CdTe/CdS/ITO. Показано, що довжина хвилі світлового випромінювання має прямий вплив на ефективність тонких плівок CdTe, монохроматичне світло з енергією близькою до ширини забороненої зони CdTe демонструє максимальні значення ефективності. Отримані температурні залежності свідчать про зниження ефективності при збільшенні температури, як при монохроматичних спектрах так і при сонячному світлі, при чому температурні залежності відносної ефективності при освітленні монохроматичним світлом та прямим сонячним світлом практично співпадають.

Ключові слова: фотоелектричні перетворювачі, відновлювальна енергія, телурид кадмію, температурні залежності, оптичні властивості, спектр, довжина хвилі.