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Numerical Simulation of CdS/CIGS Tandem Multi-Junction Solar Cells with AMPS-1D

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Abstract: Numerical modeling of polycrystalline thin-film solar cell serves as an imperative procedure to test the suitability of proposed physical clarification and to anticipate the effect of physical changes on cell performance. All in all, this must be conducted with only partial knowledge of input parameters. In this paper, we evaluated the numerical simulation of CdS/CIGS tandem multi junction solar cells by applying the AMPS-1D software aiming at finding the optimum design of the new multi-junction tandem solar cell preparing the ground for its most efficient operation. We studied the effect of CIGS p-layer thickness on the output parameters of the CdS/CIGS tandem multi junction solar cells, such as the density of short-circuit current, open circuit voltage, fill factor and efficiency. By applying the results of the numerical simulation, it was concluded that the maximum efficiency of this solar cell was equal to 48.3%, which could be obtained with the CIGS p-layer thickness of 600 nm at a standard illumination of AM 1.5.

Key words: Tandem multi junction solar cells, efficiency, thickness, AMPS-1D.

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INTRODUCTION

$Cu(In_xGa_{1-x})(Se_xS_{1-x})$ or CIGS is a four-component alloy of I-III-IV groups, being formed by replacing the indium atoms with those of gallium in the sub lattice of CuInSe2(CIS), which is crystallized into the stable structure of chalcopyrite [1]. Changing the CIS band gap (1.02eV), to maintain the photoelectric conversion optimal range is the aim of replacing the anion or caution. The chemistry of their internal defects could be used to explain the electronic conductivity of these materials. CIGS photovoltaic device could be obtained by forming the p-n- hetero-junctions on the CdS thin film, shown in Fig.1. Similar to the CdTe devices, the role of CdS semiconductor of n-type, with a band gap of 2.4 eV, serve two functions of making a p-n-junction with the absorber and forming a window layer transmitting incident light with relatively low losses at the time of absorption and reflection. Back contact deposition is usually instigated by Mo, followed by a p-type absorber, a thin CdS window layer (50-100 nm), and ZnO doped with a transparent front contact Al. for maximizing the absorption, we can add the conductive oxide ITO layer to this contact and, in turn, the current density is obtained from these solar cells structures. The flexible substrates (such as soda-lime glass, aluminum foil, or high temperature polyamide) on which these layers are deposited can be considered as an advantage of CIGS solar cells [2].

CIGS holds a direct optical band, and is usually developed on a substrate of soda lime glass or flexible substrates. The ability to create devices with thin absorbent layers on various substrates sits as one of the advantages of using a CIGS as a solar cell material leading to a significant reduction of production costs which reduces production time.

2. Tandem multi-junction CdS/CIGS solar cells

Multi-junction solar cells involve several p-n-junctions of different semiconductor materials with different band gap shaving the ability to absorb a large part of the solar energy spectrum. Compared with single-junction solar cells, which provide, in the same conditions, nearly twice the efficiency based on elements of III-V groups, multi-junction solar cells represent the new technology [3].They are used only in special cases, for example, in space technologies, because of the production costs of these elements.

The utilization of such cells, each using a specific solar radiation spectrum part for the electric current production, serve as another way to increase the efficiency of solar cells. If the current in both cases are similar, Tandem solar cells can be applied in either single or serial connection. The series connection solar cells have a very simple structure, but owing to the limitations caused by wide band gaps and because of efficiency, single compound solar cells are more

optimal.

The most common method for creating tandem solar cells is their growing even when the layers are built up sequentially on the substrate and provide a tunneling contact of layers in individual cells. Because of the band gaps number rise, the efficiency of the cell also increases. The band gap is at its widest on the upper part of a cell; it absorbs photons enjoying higher energy of incident light spectrum, while the lower part of the cell has a small band gap width, and hence, it provides the absorption of the low energy photons [4].Conversely, since the existence of multi layers and the energy-intensive nature of their processing, tandem structures are typically high-efficient and high-cost cells which can be considered as a promising technology, but before becoming competitive with the incumbent devices, it is required to reduce cost further.

In the initial approximation, the multi-junction tandem solar cells act as mononuclear cells in series connection, therefore, their open circuit voltage would be the stem (basic) cells voltage totality and their short-circuit current is equal to lowest stem (basic) current. For this reason, the performance of each multi-junction tandem cells can be obtained independently from each stem cell function. The current density of J can be attained by diode and photo- generated current superposition.

Short circuits current is given by:

$$J_{Sc} = qN_C N_V \left(\frac{1}{N_A} \sqrt{\frac{D_n}{\tau_n}} + \frac{1}{N_D} \sqrt{\frac{D_P}{\tau_P}} \right) e^{-\frac{E_g}{KT}} \tag{1}$$

In which N_C and N_V are the states density in the conduction and valence bands, respectively [5]. N_A and N_D are the acceptor and donor doping concentration. The open circuit voltage, the voltage appearing on the solar cell when no load is connected, is:

$$V_{OC} = \frac{KT}{q} \ln\left(\frac{I_{SC}}{I_S} + 1 \right) \approx \frac{KT}{q} \ln\left(\frac{I_{SC}}{I_S} \right) \tag{2}$$

When dp/dV=0, then:

$$V_m = \frac{KT}{q} \ln\left(\frac{1 + (I_{SC} / I_S)}{1 + (qV_m / KT)} \right) \approx V_{OC} - \frac{KT}{q} \ln\left(1 + \frac{qV_m}{KT} \right) \tag{3}$$

And

$$I_m = I_S \left(\frac{qV_m}{KT} \right) e^{\frac{qV_m}{KT}} \approx I_L \left(1 - \frac{1}{qV_m / KT} \right) \tag{4}$$

Where V_m and I_m represent maximum operation voltage and current for the solar cells [5].

The combination of V_m and I_m is the maximum power delivered to the load:

$$P_m = V_m \cdot I_m = \left[V_{OC} - \frac{KT}{q} \ln\left(1 + \frac{qV_m}{KT} - \frac{KT}{q} \right) \right] \cdot I_{SC} \tag{5}$$

The solar cell efficiency, η, is defined as:

$$\eta = \frac{V_m \cdot I_m}{P_{in}} = \frac{FF \cdot V_{OC} \cdot I_{SC}}{P_{in}} = \frac{\left[V_{OC} - \frac{KT}{q} \ln\left(1 + \frac{qV_m}{KT} - \frac{KT}{q} \right) \right] \cdot I_{SC}}{P_{in}} \tag{6}$$

P_{in} is the incident power and FF is the fill factor defining how c loses the solar cell and gets to the theoretical maximum power value. Therefore, the fill factor is:

$$FF = \frac{P_m}{V_{OC} \cdot I_{SC}} = \frac{V_m \cdot I_m}{V_{OC} \cdot I_{SC}} = 1 - \frac{KT}{qV_{OC}} \ln\left(1 + \frac{qV_m}{KT} \right) - \frac{KT}{qV_{OC}} \tag{7}$$

3. CIGS tandem solar cell Simulation

As one of the best approaches for solar cell researchers, numerical simulation helps find out an optimized structure with good fitted parameters. Accordingly, we can have significant decrease in the fabrication complexity, costs, and time. Testing the validity of proposed physical structures, geometry on cell performance, and fitting of modeling output to experimental results are the major objectives of numerical modeling and simulation in solar cell research. For designing a high-efficiency solar cell, the numerical modeling has turned out to be an indispensable tool. To gain insight into the thin-film solar cells physical operation details, researchers increasingly applied numerical modeling. The AMPS-1D (Analysis of microelectronic and photonic structure-one dimension) as one of the complex semiconductor device simulation used to analyze transport in a wide range of device structures containing crystalline, polycrystalline, or amorphous layers combinations which was developed by S.Fonash colleagues at Pennsylvania State University. AMPS-1D is a professional computer program for simulating one-dimensional transport physics in solid state devices. This program uses the -principles continuity and

Poisson's equations approach to analyze the semiconductor electronic and optoelectronic device structures transport behavior [6].

4. Experimental details

This section presents the research aiming at increasing the efficiency of solar cells and the design of the solar cell structure which has the most optimal efficiency and used the results of investigations of single-junction solar cells whose efficiency is studied in previous papers. By applying AMPS-1D software, we conduct a study of new multijunction tandem CdS/CIGS solar cell structures in order to determine the most optimal one with the highest efficiency.

In order to enhance the efficiency and to determine the most optimal solar cells, we use two single solar cells connected back to back. In Fig. 1, the proposed solar cell layers and the order of their arrangement are depicted. This multilayer solar cell is made of two CdS layers of p-type and n-type and two layers of CIGS of p-type and n-type. On the top of the solar cell, the layer of indium tin oxide (ITO) with 200 nm thickness is located to provide greater absorption of light flux by the solar cell and the lower layer is a molybdenum one with 500 nm thickness for reflecting the light flux.

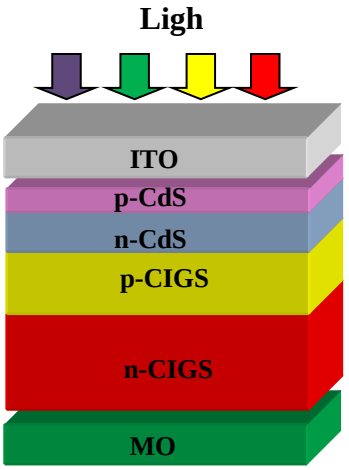


Fig. 1. Schematic representation of the CdS/CIGS multijunction tandem solar cell

The parameters of each solar cell layer used as input data in the numerical simulation by AMPS-1D are shown in the Table 1. In this simulation, the thickness of the p-CdS layer is chosen to be equal to 50 nm and the n-CdS is

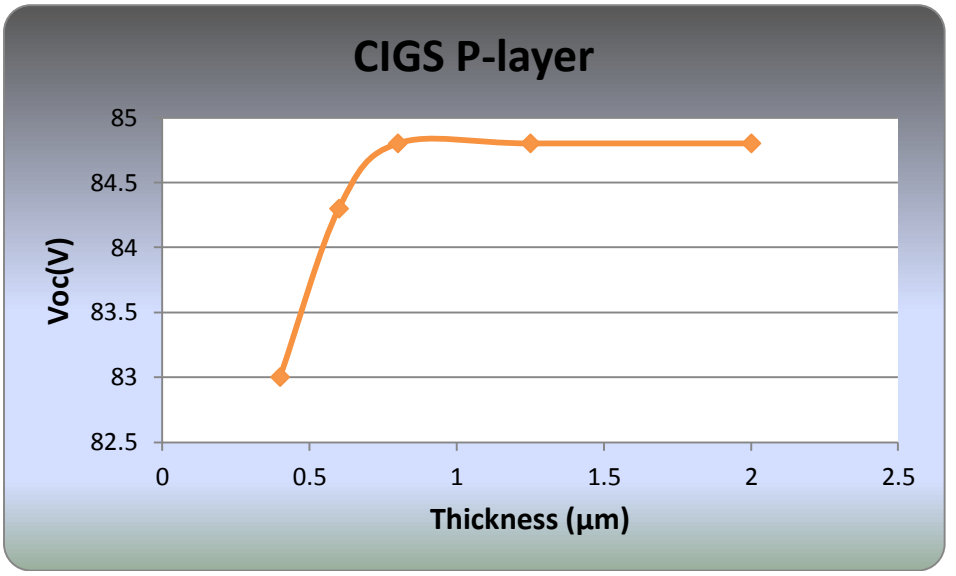
200 nm.

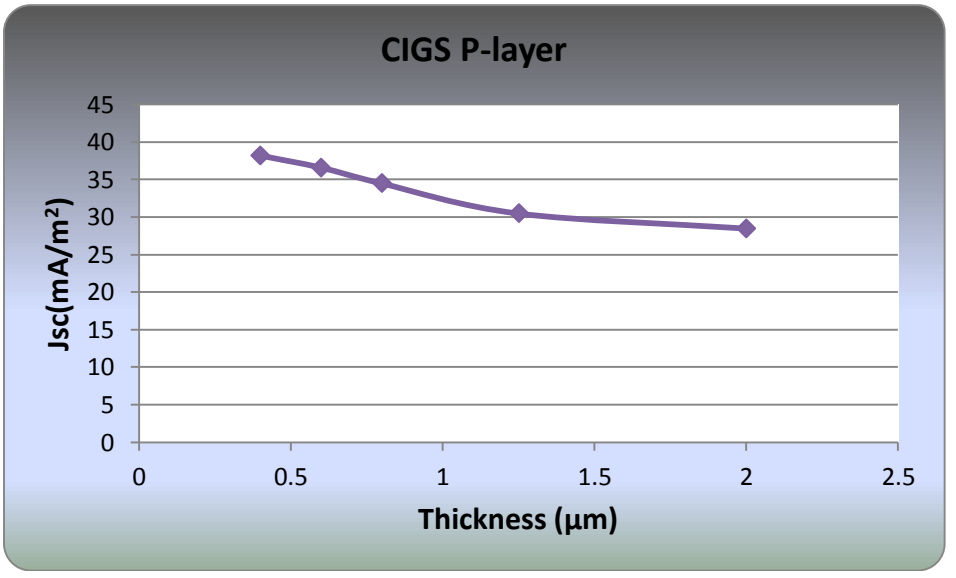
As a result of our previous numerical simulation, we know that the most optimal solar cell should have a thickness of n-CIGS layer equal to 3000 nm. In our simulation, we kept it constant and the thickness of p-CIGS layer varied in the range from 400 nm to 2000 nm. Upper buffer layer serves to provide greater absorption of the blue part of the solar spectrum. The photons, which are not absorbed in the upper layers, would be absorbed in the lower absorbent layer and produce electron- hole pairs. As a result of the overall efficiency of the solar cell, this is the total efficiency of the upper and lower elements which is increased.

Table 1: Material parameters which have been used in this CdS/ CIGS multi-junction tandem solar cells simulation.

Material	Band Gap (eV)	Conductivity Type	Conduction Band	Valence Band	Electron Affinity (eV)	Electron Mobility (cm^2/v/s)	Hole Mobility (cm^2/v/s)	Free Carrier Concentration (cm^{-3})	Relative Permittivity
ZnO	3.30	n	$2.2*10^{18}$	$1.8*10^{19}$	4.10	100.0	25.0	$1.0*10^{18}$	9.0
CdS	2.40	n	$2.2*10^{18}$	$1.8*10^{19}$	4.0	100.0	25.0	$1.1*10^{18}$	10.0
CdS	2.40	p	$2.2*10^{18}$	$1.8*10^{19}$	4.0	100.0	25.0	$1.1*10^{18}$	10.0
CIGS	1.15	p	$2.2*10^{18}$	$1.8*10^{19}$	4.5	100.0	25.0	$2.0*10^{16}$	13.4
CIGS	1.15	n	$2.2*10^{18}$	$1.8*10^{19}$	4.5	100.0	25.0	$2.0*10^{16}$	13.4

The graphs (Fig.2) show the dependence of the open circuit voltage (Voc), short-circuit current (Jsc), fill factor (FF) and efficiency (ŋ) on the thickness of CIGS p- layer, that were obtained in numerical experiments. The results show that the most optimal solar cell with the CIGS p-layer thickness of 600 nm at a standard sunlight of AM 1.5 is the element with the highest efficiency equal to 48.3%. This efficiency is more than twice the efficiency of CdS/CIGS single-junction solar cell under similar conditions.


CIGS P-layer
Voc(V)
85
84.5
84
83.5
83
82.5
0
0.5
1
1.5
2
2.5
Thickness (µm)


CIGS P-layer
Jsc(mA/m²)
45
40
35
30
25
20
15
10
5
0
0
0.5
1
1.5
2
2.5
Thickness (µm)

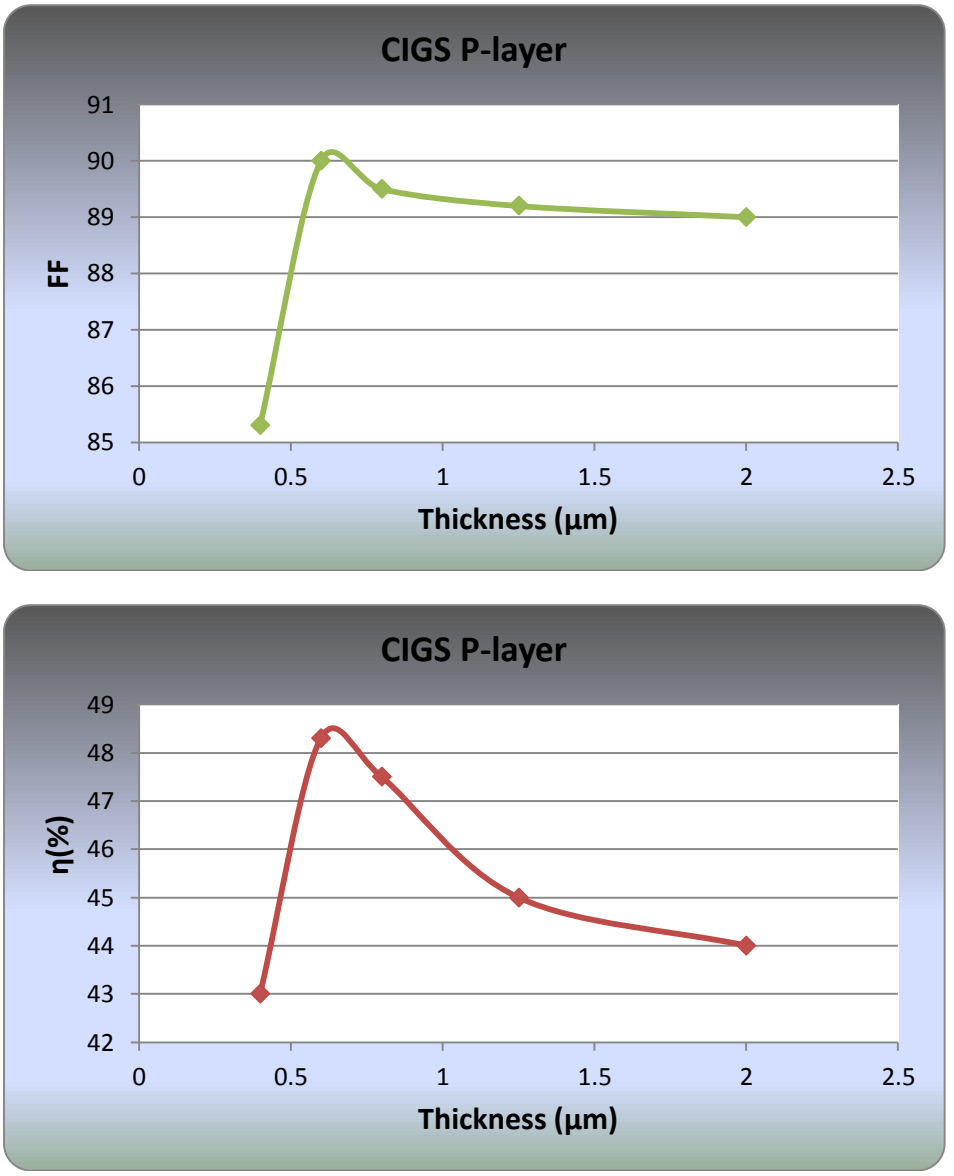


Fig 2. The dependence of the output parameters (short circuit current density Jsc, open-circuit voltage Voc, the fill factor FF and the efficiency EFF) of CdS/CIGS multijunction tandem solar cells on the p-CIGS thickness.

5. Conclusion

We developed the design and conducted the optimization of the new multi-junction numerical simulation of tandem CdS/CIGS solar cell structure by applying the results of the single-junction solar cells. Numerical simulation shows that the maximum efficiency of this solar cell is equal to 48.3% with the CIGS p-layer thickness of 600 nm at a standard illumination of AM 1.5.

In the given modeling, the p-CdS and n-CdS thicknesses were kept constant at 50nm and 200nm, respectively. The most optimal thickness for the layers that were achieved in other research was kept constant at 3000nm for CIGS n-layer and has changed from 400nm to 2000nm for the p-CIGS. The top layer of cells, Buffer layer, plays important role on the absorption of blue waves. To produce pairs of electrons and holes (electron- holes pair), photons that are not absorbed in the top layer are more attracted to a lower layer, Absorber layer. As a result, the overall efficiency of the cell which is the sum of the upper and lower cell efficiency increased. Thus, numerical simulation based on the application of one-dimensional analysis of microelectronic and photonic structures (AMPS-1D) software for the copper indium gallium diselenide (CIGS) solar cells analysis allowed us to formulate the optimal design of the new multi-junction tandem solar cell which has done its optimal performance.

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