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A Numerical Optimization of an Efficient Double Junction InGaN/CIGS Solar Cell

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ABSTRACT

An efficient double junction InGaN/CIGS solar cell can be simulated using Silvaco ATLAS software. In this study, a thin CdS top cover layer is used as the anti-reflector layer. To reach the current matching condition, changing the thickness of this CdS layer, we can enhance the short-circuit currents of both the top and bottom cells. To gain a desired efficiency, different design parameters, such as the doping concentrations and the thicknesses of the various layers of the cell are optimized. This cell is designed to be used in a real environmental situation. Considering the proposed structure and the simulation results, an optimum efficiency of 41.87% is achieved and also the obtained fill factor is equal to 75.16%.

1. Introduction

In recent decades, the traditional sources of energy such as fossil fuels are not sufficient for the increasing energy needs because of their low efficiency and high pollution and price. One alternative of clean, cheap and available energy source is the solar cells. The first generation of solar cells was single-junction cells which convert the solar energy to electricity. The advantage of these cells is their simple structure, but the Shockley 'Queisser limit' limits their efficiency [1]. The second generation of solar cells, includes the thin-film solar cells. These cells are extremely thin and the cost of used materials is low in this generation, but the efficiency is low too [2-4].

The third generation of solar cells is consisted of multi-junction cells [5-13], sensitized solar cells [14-15], nanostructured solar cells [16], Intermediate band cells [17-18] and Split spectrum solar cells [19].

In this generation, multi-junction structures were designed to achieve high efficiency. So far, different semiconductor materials have been studied to be used in solar cell structures such as various types of Silicon (Si) [20-21], Gallium Arsenide (GaAs) [22-23], Indium Gallium Nitride (InGaN) and so on [24-30].

This paper proposes a dual-junction InGaN/Si cell with a thin layer of CdS as the anti-reflector layer. Since solar cells are designed for use in real circumstances, only structural parameters such as the band gap of semiconductors, thickness of layers and impurity are optimized in this work, and temperature, mobility of electrons and holes and other environmental parameters are not optimized.

The design parameters and the structure of the proposed dual junction cell are presented in the next section, and the results of the numerical simulation are presented in Section 3. Finally, the conclusion is given in the last section.

2. Double junction InGaN/CIGS Solar Cell

The final optimized structure of our proposed double junction InGaN/CIGS is shown in Figure 1. the proposed structure is consisted of a 251.2 nm CdS layer as the anti-reflector layer, a 200nm P-type 1×1018 cm^{-3} uniformly doped InGaN layer as the top cell's absorber layer, a 350nm N-type 1×1021 cm^{-3} uniformly doped InGaN layer as the top cell's buffer layer, a 100 nm vacuum layer as a tunnel junction, a 100nm P-type 1×1021 cm^{-3} uniformly doped CIGS layer as the bottom cell's absorber layer, and a 399.8nm N-type 7×1013 cm^{-3} uniformly doped CIGS layer as the bottom cell's buffer layer.

Since the light passes through the top cell before it enters the bottom cell, some photons that are matched to the high forbidden energy gap are captured and absorbed in the top cell, so the light entering the bottom cell of all, there is no radiation spectrum. Therefore, the absorption rate of photons and the production of electron-hole pairs, followed by short-circuit current in the bottom cell, will be lower than that for the top cell. To compensate this effect, the thickness of the bottom cell layers is greater than that for upper cell, which compensates the effect of low short circuit current and allows matching the flow in the final doping cell.

In the bottom cell, the main role is duty of the N-CIGS layer, which acts as the layer for producing electron-hole pairs. The P-CIGS layer is used in practice to create a P-N bond to separate these pairs. Therefore, it is not necessary to exactly select the thickness of the P-CIGS layer. Setting large thicknesses on this layer does not increase the solar cell efficiency, however, by increasing the amount of semiconductors, it increases the cost of making the cell.

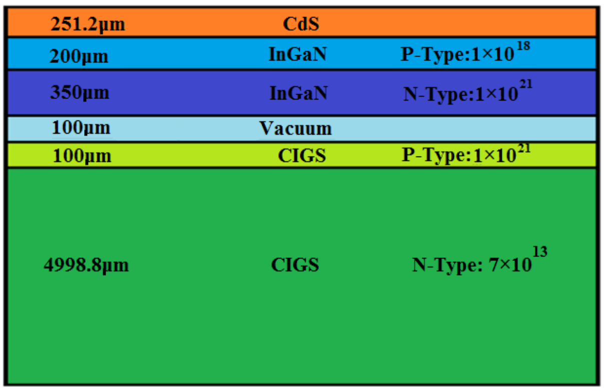

Figure 1: The final structure of the double junction InGaN/CIGS solar cell.

Table 1 shows the photovoltaic characteristics of the materials that are used in our proposed structure.

The meshing structure and the doping profile of the structure are shown in Figures 2 and 3.

3. Results and Discussion

The most effective parameter determining the possibility of using a solar cell in real applications is its efficiency.

TABLE1
PHOTOVOLTAIC CHARACTERISTICS OF THE MATERIALS THAT ARE USED IN THE PROPOSED STRUCTURE

Photovoltaic characteristic	CdS	CIGS	InGaN
E_g(eV) : Band gap	2.4	1.699	1.68
X_e(eV) : Electron affinity	3.75	3.89	5.3887
ε_r(F cm^{-1}) : Relative permittivity	10	13.6	19.07
N_C(cm^{-3}): Conduction band effective density of states	2.2×10^{18}	2.2×10^{18}	1.287×10^{18}
N_V(cm^{-3}): Valance band effective density of states	1.8×10^{19}	1.8×10^{19}	3.795×10^{19}

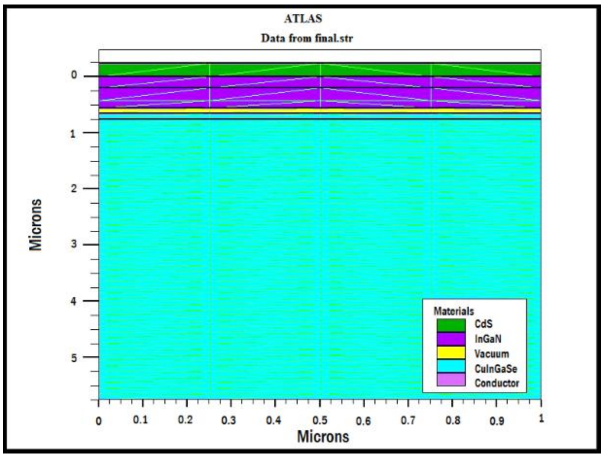

Figure 2: Meshing structure.

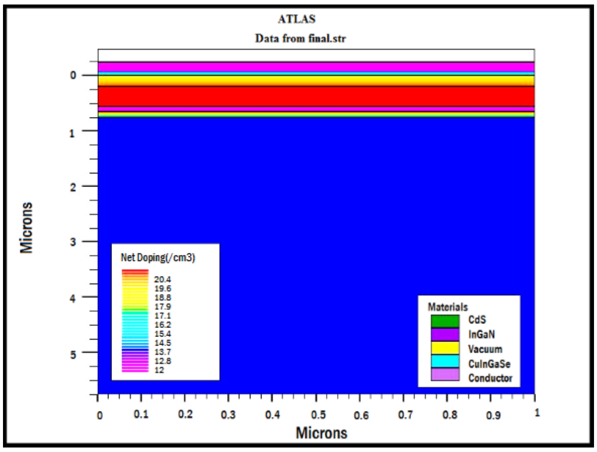

Figure 3: Doping profile.

Many structural and environmental parameters affect the efficiency of a solar cell. Structural parameters are the number of layers, the number of junctions, semiconductors used in the structure, doping concentration and thickness of each layer, while the environmental parameters are temperature and the angle of light incidence.

Since in this work the goal is to propose an efficient structure to be used in real applications, there is no control on the environmental parameters and only structural parameters are optimized.

The short-circuit current (ISC) is one of the important parameters of a solar cell. ISC is defined as the current flows through the cell when the terminals of the cell are short-circuited. This current is generated by electron-hole pairs which are generated by the incoming sun light. Since applying any external voltage on solar cell's terminals, is the reason for decreasing the current, as another definition for ISC, it is the maximum current which is generated by a solar cell.

Since ISC is directly depends on the area of the cell, it is not therefore an appropriate parameter for comparing different structures. The short-circuit current density (JSC), which is defined as the ratio of the ISC to the cell area, is a better comparative parameter.

On the other hand, another significant parameter of a solar cell is its open-circuit voltage (VOC). As it is obvious from its name, VOC is the externally applied voltage to the cell's terminals, which will decrease the cell's current to zero. Both ISC and VOC parameters are obtained from the V-I characteristics of the solar cell.

In multi-junction solar cells, the most important issue is the current matching of the junctions. The short-circuit current density of all junctions of the multi-junction solar cell must be equal. The overall V-I characteristic is obtained from junctions V-I characteristics. The top cell V-I curves, bottom cell and overall curves are all shown in Figure 4.

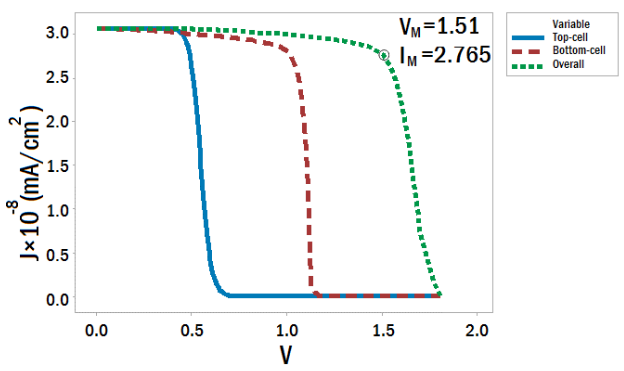

Figure 4: The top cell, bottom cell, and overall V-I curves.

The output power density of a solar cell, is defined as the product of the externally applied voltage to the terminals and the current of solar cell. By increasing the externally applied voltage, this product increases at first and after reaching a maximum value, it begins to fall down. At the maximum point, M, the output power is PM = VM×IM [2].

The fill factor, which is one of the main parameters of a solar cell, is defined as follows [2]:

$$FF = \frac{V_M \times I_M}{V_{OC} \times J_{SC}} \quad (1)$$

Finally, the efficiency (the most important parameter of a solar cell,) is defined as follows [2]:

$$\eta\% = \frac{V_{OC} \times J_{SC} \times FF}{1000[W.m^{-2}] \times CellArea[m^2]} \times 100 \quad (2)$$

In this study, some of the structural parameters of the designed solar cell have been optimized: band gap, thickness and impurity of InGaN layers, and band gap, impurity and thickness of CIGS layers. The variations of the efficiency due to these parameters are shown in Figures 5 to 10.

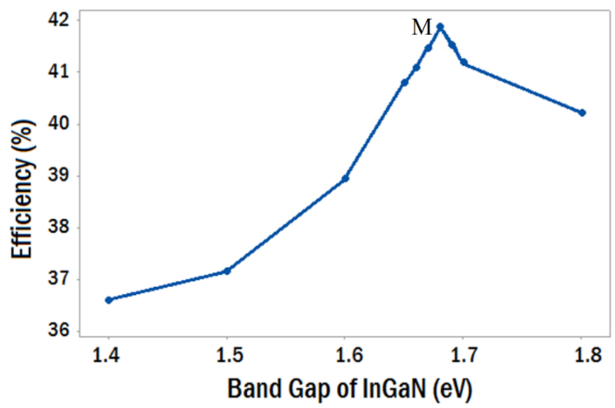

Figure 5: The effect of the band gap of InGaN on efficiency.

It is clear that the maximum efficiency occurs at 1.69eV band gap of the InGaN and by increasing the band gap, the efficiency falls down.

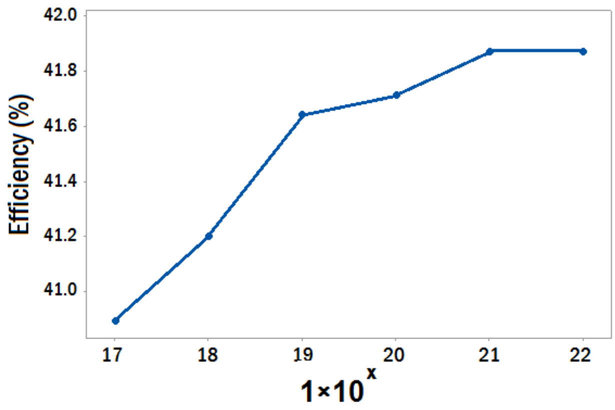

Figure 6: The effect of the impurity of N-InGaN on efficiency.

By increasing the impurity of N-InGaN from 1017 to 1021, efficiency increases. After that, increasing the impurity does not affect the efficiency any more.

Maximum efficiency occurs when the thickness of

InGaN layers is 550nm. By increasing the thickness of these layers, efficiency slightly begins to fall down.

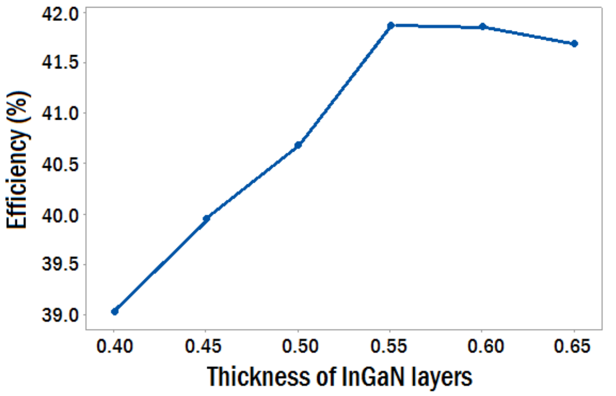

Figure 7: The effect of the thickness of InGaN layers on efficiency.

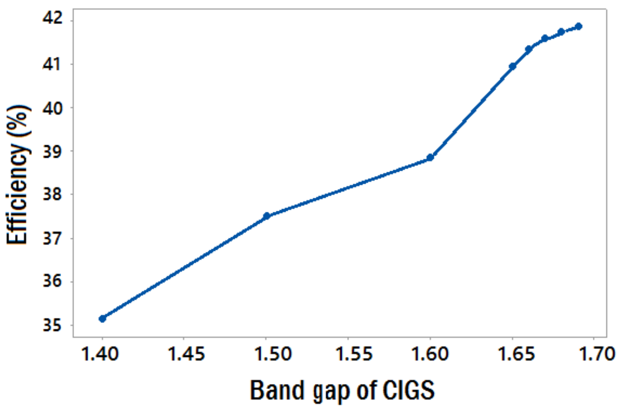

Figure 8: The effect of the band gap of CIGS on efficiency.

As the band gap of CIGS increases, the efficiency increases too. Since the maximum band gap of GIGS is about 1.7eV, we choose 1.69eV for CIGS band gap in our optimization process. As seen in the figure, the increase of the CIGS band gap energy leads to an increase in the final efficiency of the dual solar cell. This boost of productivity at the beginning is very impressive and then takes a slower process. The maximum available throughput in the forbidden energy band is 1.69 eV.

Increasing the impurity of CIGS starting from 1×10^{13} causes slight decrease in ISC density of the bottom cell, which means that the efficiency decreases as well.

The efficiency increases as a function of increasing thickness of CIGS layers. This occurs because by increasing the thickness, these layers absorb more light energy which improves the efficiency. On the other hand, the most important condition that must be considered is current matching. In multi-junction structures, the SCI of all of the cells must be matched. Altering the thickness of CdS window layer, is used to tune these current values. The variation functions of the current of the cells are shown in Figure 11.

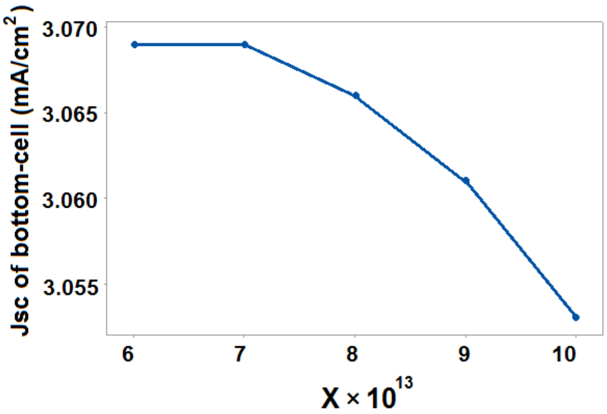

Figure 9: The effect of the impurity of CIGS on bottom cell ISC.

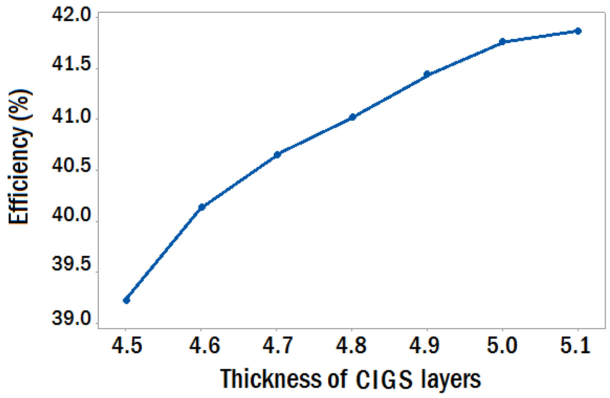

Figure 10: The effect of the thickness of CIGS layer on efficiency.

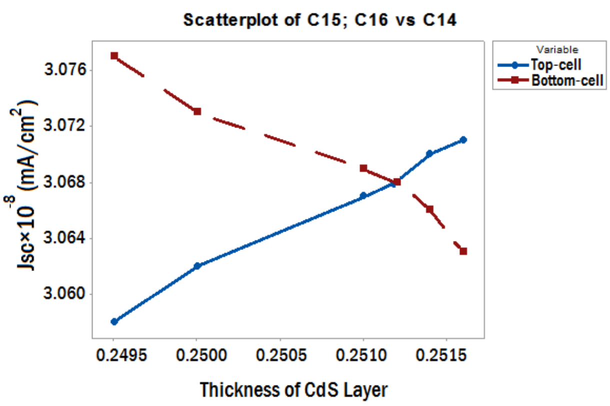

Figure 11: The effect of thickness of CdS layer on short-circuit currents.

As it can be seen in Figure11, by increasing the CdS layer thickness, which is used as the antireflection window of the cell, the ISC density of the top cell increases. At the same time, the short circuit current density of the bottom cell decreases. In this work, we set the CdS layer's thickness to 251.2nm in order to meet the current matching condition.

Table.2 compares the proposed solar cell efficiency with previously reported solar cells.

TABLE.2
COMPARISON OF THE PROPOSED SOLAR CELL'S EFFICIENCY WITH PREVIOUS WORKS

Reference	Structure	efficiency (%)
Hsu (2010)[13]	InGaN/si	31
Li (2013)[14]	InGaN/si	35.2
Feng (2014)[15]	InGaN/si	36.2
Nacer (2015)[16]	InGaN/si	38.3
Albar (2015)[19]	CIGS/CIGS	26.21
Nacer (2015)[17]	InGaN/InGaN	34.7
Farhadi (2016)[10]	InGaP/ GaAs	41.95
Naseri (2016)[20]	CIGS/CIGS	28.31
Farhadi (2016)[31]	InGaN/CIGS	40.42
Verma (2017)[24]	InGaP/ GaAs	42
This work	InGaN/CIGS	41.78

4. CONCLUSIONS

In this study, a new structure for an efficient double junction InGaN/CIGS solar cell, was proposed. In our proposed structure, a thin CdS layer is used as the anti-reflector layer. To achieve the current matching condition, by changing the thickness of this CdS layer, we can enhance the short-circuit currents of both the top and bottom cells. To get a desired efficiency, different design parameters, such as the doping concentrations and the thicknesses of various layers of the cells were optimized. Using the proposed structural parameters and under current matching condition, an optimum efficiency of 41.87% was achieved and also the obtained fill factor was equal to 75.16%.

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