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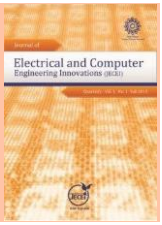

Design and Simulation of a Highly Efficient InGaN/Si Double-Junction Solar Cell

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ABSTRACT

A solar cell is an electronic device which not only harvests photovoltaic effect but also transforms light energy into electricity. In photovoltaic phenomenon, a P-N junction is created to form an empty region. The presented paper aims at proposing a new highly efficient InGaN/Si double-junction solar cell structure. This cell is designed to be used in a real environmental situation, so only structural parameters are optimized. In the present structure, a thin layer of Cd-S is used as the anti-reflector window layer. The cell is simulated using ATLAS-SILVACO software and its maximum efficiency is computed to be 37.23%. Considering the supposed structure, the findings show that the efficiency of this solar cell, which is 37.32%, is so far the highest reported efficiency amongst all solar cells.

1. Introduction

A solar cell is an electronic device which harvests photovoltaic effect and transforms light energy into electricity. In photovoltaic phenomenon, a P-N junction is created to form an empty region. Throughout this region, Fermi levels of the two semiconductors employed, are balanced to be the same level. Under such conditions, if sunlight is transmitted, photons with energies higher than the energy of the semiconductor band gap, is absorbed, making the electrons move from their places and hence electron-hole pairs are produced. In such a situation, electron-hole pairs created in or near the empty area, have a great chance to get separated from the bonding area before recombining. Under the influence of this internal electric field, the negative charge density in the N region and the positive charge density in the P region are increased. This load density is measurable in the form of a voltage at the two ends of the bond. If this voltage is applied to a consumer, the electrical energy can then be used.

The initial idea of using solar energy with the photovoltaic effect was first introduced in 1839 by a French physicist known as, Becquerel [1]. Using selenium, Adams and Day made the first solid-state solar cell in 1876 [2]. However, the first solar cell that was really applicable to produce energy was created in 1954 by Chapin, Fuller and Pearson with a yield of 6% [3]. Since then, a wide variety of solar cells have been designed. There are various types of solar cells such as, multi-cellular cells [4], intermediate-bonded cells [5], thermo-photovoltaic cells [6], color-sensitive cells [7] and hot carriers cells [8].

Basically, multi-junction cells use several layers of semiconductors with different forbidden energy bands to maximize the amount of solar energy absorbed by the cell. Given the likelihood of being trapped, electrons and holes in the layers accumulated on each other in these structures, increase the flow density and subsequently the efficiency of the solar cells. Therefore, the maximum efficiency of single junction cells can never compete with the efficacy of the multi junction cells. In fact, these cells are more commercialized [9].

Using the InGaN and Si semiconductor, Hsu et al. (2008) designed a double-junction cell [10]. The cell efficiency was 31%. Following this, in 2013, Li and his colleagues managed to achieve a return of 35.2% [11].

Then, in 2014, Feng et al. reported an optimized structure of a double-junction cell based on the above mentioned semiconductors, with a return of 36.5% [12].

There are two key parameters affecting the performance of a solar cell: efficiency and construction cost. The efficiency of a solar cell is maximized by optimization of the structural parameters such as the thickness and impurity of different layers of the cell. But there are two ways to design an economical and cost effective solar cell:

1) Using cheap semiconductors with large volumes;
2) Using expensive semiconductors with small volumes.

Regarding the current cell design in this paper, the cheap semiconductor is Si which is used to form the thickest layers in the cell, while the expensive one is InGaN, which is used to form a thin P-N junction in the top-cell.

In the present paper, in Section 2, the proposed solar cell structure is presented. In Section 3, the results of the simulation are displayed and finally in Section 4, comparison and conclusions are made.

2. Proposed Solar Cell Structure

The proposed solar cell structure consists of different layers of semiconductors with various thicknesses and impurities. As shown in Figure 1, the proposed structure consists of a CdS layer as an anti-reflector window layer with a thickness of 61nm, an InGaN layer with a thickness of 233nm and impurity of P =$5\times10^{16}cm^{-3}$, an InGaN layer with a thickness of 0.4μm and impurity of N =$7\times10^{20}cm^{-3}$, a vacuum layer of 0.1μm thickness, a thin layer of silicon with a thickness of 0.1μm and impurity P=$3\times10^{20}cm^{-3}$, and finally, a silicon layer with a thickness of 70μm with impurity N=$3\times10^{12}cm^{-3}$.

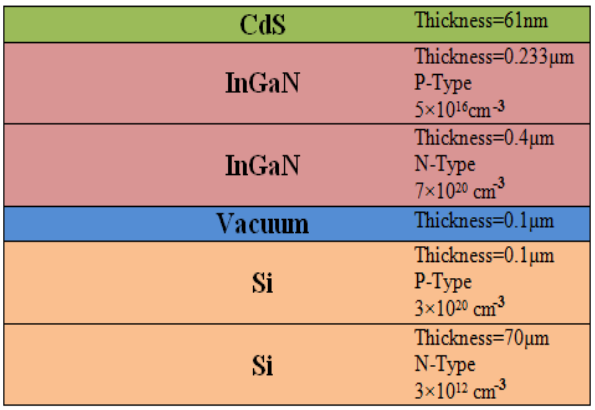

Figure 1: The proposed solar cell structure.

The specifications of the semiconductors used in the designed cell are summarized in Table 1.

Table 1
Electrical Properties of Semiconductors Used in the Designed Cell

Semiconductor properties	CdS	InGaN	Si
Band gap Eg (eV)	2.4	1.68	1.12
Electron Afinitty Xe (eV)	4.5	5.38	4.05
Effective density of states of the conduction band, Nc (cm^{-3})	2.2×10^{18}	1.287×10^{18}	3.5×10^{20}
Effective density of states of the valance band, Nv (cm^{-3})	1.9×10^{19}	3.795×10^{19}	3.5×10^{20}

3. The Results of Simulations of the Proposed Structure

A few parameters are used to describe a solar cell. These parameters are the short-circuit current density (J_{SC}), open circuit voltage (V_{OC}), fill factor (FF), and most importantly, efficiency, which are described briefly and calculated for the proposed structure.

The first parameter describing a solar cell, short-circuit current density, or J_{SC}, is equal to the cell's cathode current at zero voltage, divided by the solar cell area.

This flow is equal to the current of the first point plotted in the characteristic curve of the cell, which is the maximum current generated by a solar cell. In the proposed structure, the short-circuit current density is equal to $J_{SC} = 1.627 \times 10^{-8}$ (mA/cm^2).

The second parameter is the open circuit voltage or V_{OC}. Accordingly, it is believed that if this voltage is applied to the two ends of the solar cell, the current flow will be equal to zero.

In simulating the proposed structure, the open circuit voltage V_{OC}=2.89V was obtained.

According to the aforesaid parameters, as well as the maximum available power density of a solar cell ($P_m = V_m \times J_m$), the Fill Factor for the proposed structure is calculated as follows:

$$FF = \frac{J_m \times V_m}{J_{SC} \times V_{OC}} = 0.7917 \quad (1)$$

Finally, based on the previous calculated parameters, the proposed structure efficiency is calculated as follows:

$$\eta\% = \frac{J_{SC} \times V_{OC} \times FF \times 100}{1000\left(W/m^2\right) \times Cell\ Area(m^2)} = 37.32\% \quad (2)$$

Since the present cell is going to be used in real and practical conditions, none of the environmental

parameters such as temperature, excitation of electrons and holes have been optimized. Besides, their standard values at room temperature are used in the simulations.

The optimized parameters are: InGaN semiconductor forbidden energy band, and thicknesses and impurities of different layers of the structure. In Figures 2, 3, and 4, the maximum available interest graph is shown in terms of the individual optimization parameters, and a brief explanation is given below for each diagram.

In the final structure, the values of each parameter is set equal to the optimal value in the corresponding graph. Band gap energy of $In_xGa_{1-x}N$, which is a combination of two GaN and InN materials, can be varied. In fact, it can be tuned by changing the ratio of x, which expresses the In/Ga ratio used in the final composition [11].

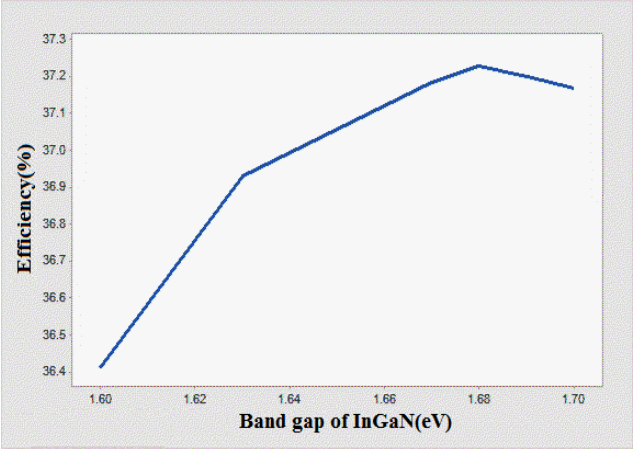

Figure 2: The efficiency graph of the proposed solar cell as a function of the band gap energy of InGaN semiconductor.

The range of the energy gap energy of this semiconductor varies from 0.7eV to 3.4eV. Based on the results of the simulations, as it is shown in Figure 2, the maximum available output in the proposed structure is achieved in the forbidden energy gap being equal to 1.68eV.

Optimizing the structural parameters of the top cell, i.e., the thicknesses and degrees of impurities of the P-InGaN and N-InGaN layers, it is observed that the maximum efficiency of the proposed solar cell is achieved with 0.233μm thickness and the impurity level of $P=5\times10^{16}(cm^{-3})$ for the P-InGaN layer and with thickness of 0.4μm and the impurity of $N=7\times10^{20}(cm^{-3})$ for the N-InGaN layer.

Figure 3 shows the efficiency graph as a function of these structural parameters.

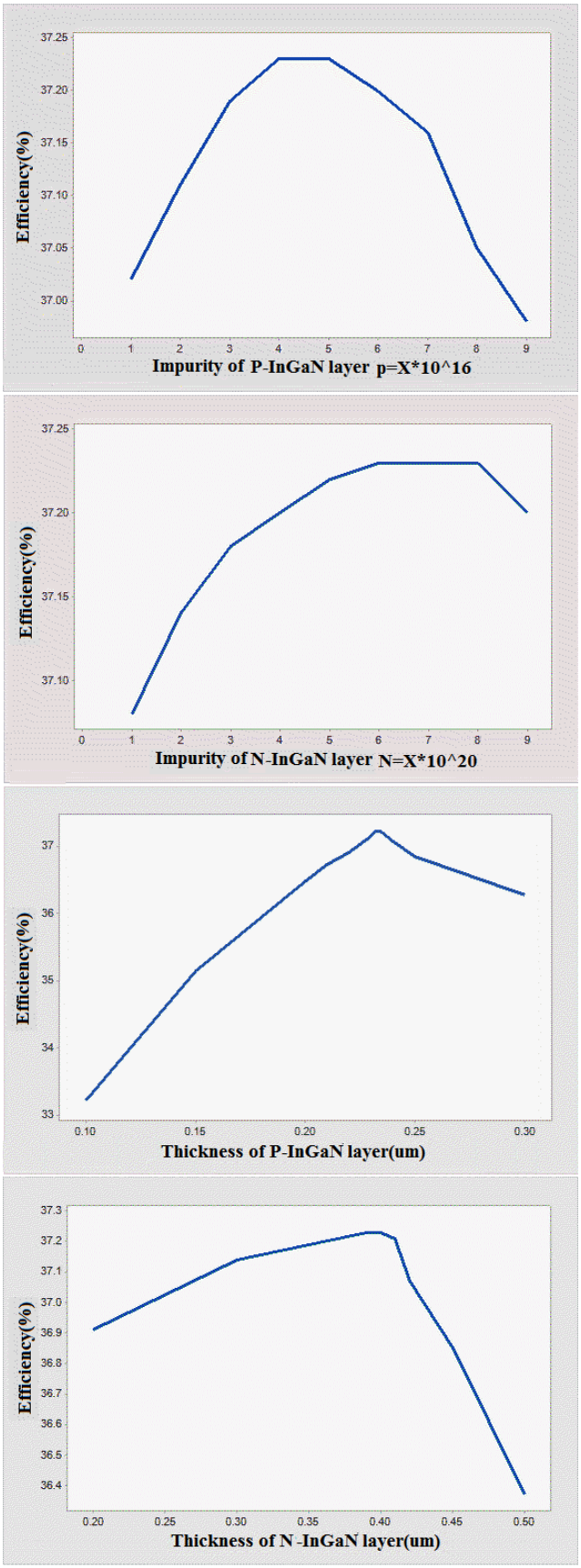

Figure 3: The efficiency graph of the proposed solar cell as a function of the thicknesses and impurities of N-InGaN and P-InGaN layers.

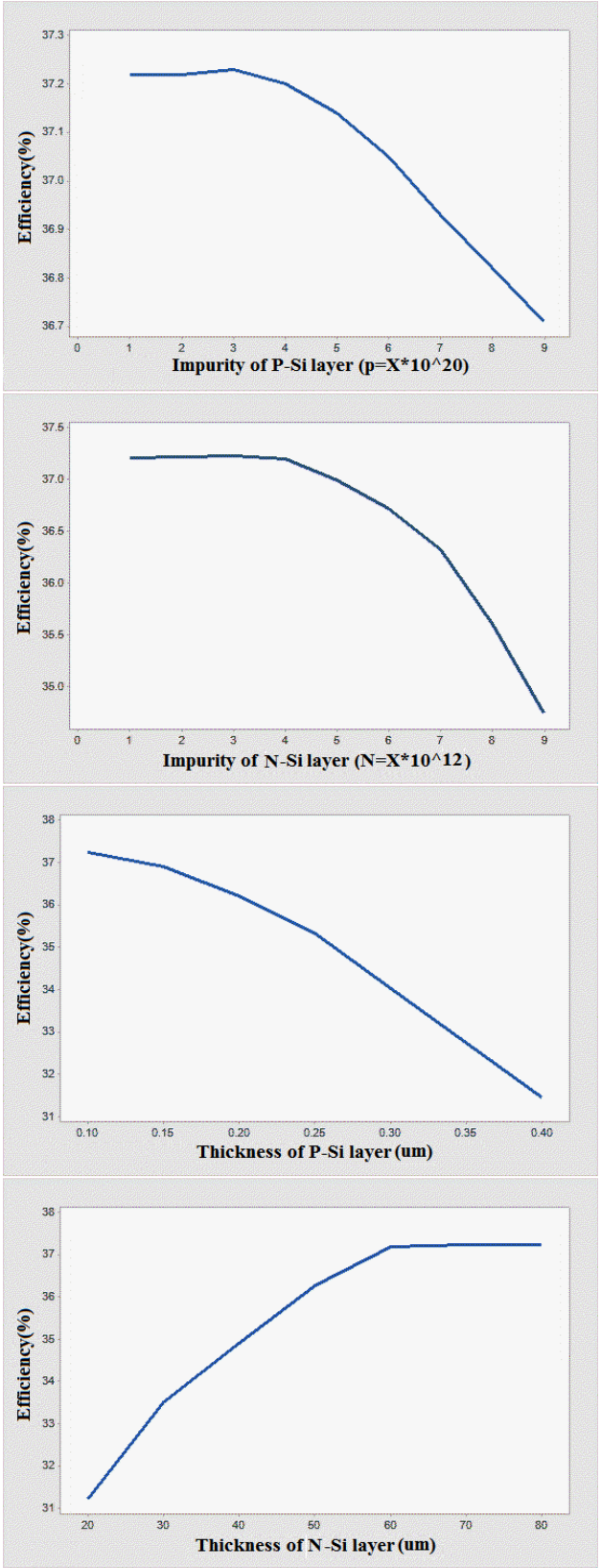

Figure 4: The efficiency graph of the proposed solar cell as a function of the thicknesses and impurities of N-Si and P-Si layers.

At the last step in the design, the current matching is done by tuning the thickness of the CdS window layer.

The density diagram of the top and bottom cells' flows in terms of different thicknesses of this layer is shown in Figure 5.

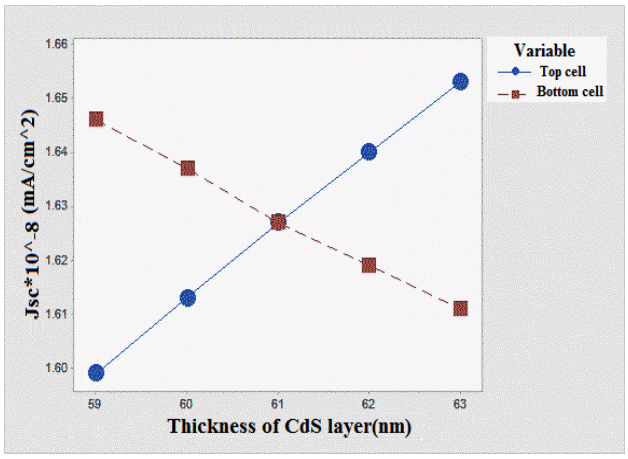

Figure 5: The short-circuit current densities of the top and bottom cells in terms of different thicknesses of CdS layer.

As shown in Figure 5, by increasing the thickness of the CdS window layer, the JSC of the bottom cell gradually decreases, but the JSC of the top cell increases.

By tuning the thickness of the CdS layer to be equal to 61nm, both the above currents have the same value, and being equal to $1.627\times10^{-8}(mA/cm^{-2})$.

Finally, the characteristic curve diagrams of the top, bottom and the overall cells are shown in Figure 6.

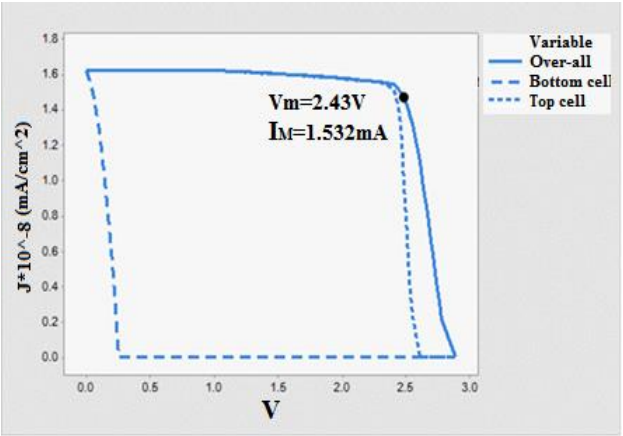

Figure 6: The characteristic curve diagrams of the top, bottom and the overall cells.

As the overall characteristic diagram of the designed double-junction cell shows, the maximum density point is the available power point in the existing design. Besides, the M point has a current density of $IM=1.532\times10^{-8}(mA/cm^{-2})$ and a voltage of VM=2.43V.

By putting the above values in the general formula for the efficiency (formula 2), the designed structure has an efficiency of 37.33%, which is the highest reported efficiency in a double-junction cell using InGaN and Si semiconductors used in real environmental conditions.

As it can be seen in Figure 6, for the designed structure with a cell area being equal to 1μm×1μm, the maximum available power density point has a current density of JM=1.532×10^{-8}(mA/cm^{-2}) and a voltage of VM=2.43V. So, the maximum available power density is calculated as:

$$P_d = J_M \times V_M = 37.23\ (mW/cm^{-2}) \quad (3)$$

As mentioned, the most important parameter describing a solar cell is its efficiency. Table 2 compares the proposed solar cell efficiency with previous solar cells designed using the above mentioned semiconductor materials.

TABLE 2
COMPARISON OF THE PROPOSED SOLAR CELL EFFICIENCY WITH OTHER SIMILAR ONES

Structure	Efficiency (%)	Reference
InGaN/InGaN	27.49	Hamzaoui et al. [13]
InGaN/InGaN	34.7	Nacer et al. [14]
InGaN/InGaN	35.1	Zhanget al. [15]
InGaN/Si	31	Hsu et al. [10]
InGaN/Si	35.2	Li et al. [11]
InGaN/Si	36.5	Feng et al. [12]
InGaN/Si	37.23	The present work

4. CONCLUSIONS

In the present study, a double-junction solar cell was designed and optimized using InGaN and Si semiconductors.

A thin layer of CdS semiconductor has been used as an anti-reflector window layer to design the structure.

According to the simulation results, the efficiency of the proposed solar cell is 37.32%, which is so far the highest reported efficiency amongst solar cells designed and simulated using the above two mentioned semiconductors.

The design is much suitable for usage in real environmental conditions.

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BIOGRAPHIES

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