Effect of Acceptor Concentration on Performance of CdTe Solar Cell from Numerical Analysis

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***Abstract*— In this study, the absorber layer of Cadmium Telluride (CdTe) ultra-thin solar cell was analyzed by using the one dimensional simulator Analysis of Microelectronic and Photonic Structures (AMPS 1D) software. A novel structure of ultra-thin CdS:O/CdTe solar cell is suggested in this research that emphases on conversion efficiency. The maximum conversion efficiency of ~ 26.24% (J_{SC} = 27.05 mA/cm^2, V_{OC} = 1.2 V, *FF* = 0.886) is achieved with 600 nm CdTe absorber layer at the acceptor concentration of 5 × 10^{19} cm^{-3}. The temperature effect is also examined with an aim to realize the environmental impact on performance of the cell. Our outcomes offer innovative research guidelines for resolving persistent challenges of CdTe photovoltaics.**

Keywords*— *Carrier concentration; CdTe solar cell; numerical analysis; AMPS 1D

I. Introduction

Polycrystalline cadmium telluride (CdTe) has already been found wide acceptance as an absorber material for thin film solar cells owing to its ideal band gap energy (1.45 *eV*), excellent absorption coefficient (> 5 × 10^5 cm^{-1}) and good electronic properties [1,2]. Moreover, the layer of CdTe solar cells can be deposited using various cost effective methods, including chemical bath deposition (CBD), sputtering and close-spaced sublimation (CSS) etc. [3]. Oxygenated cadmium sulphide (CdS:O) appears to be an attractive candidates for window layer. It should be noted that nanocrystalline CdS:O has larger optical band gap (2.5-3.1 *eV*) and excellent lattice match with the absorber layer of CdTe which decrease inter-diffusion affinity at the PN junction [4]. The first CdTe solar cell was fabricated by Bonnet and Rabenhorstin 1972 with efficiency ~ 5% [3]. In 1982, Tyan et al. [5] prepared CdTe/CdS thin-film solar cells and reported an efficiency of around 10%. Then, an efficiency of 15.8% has been achieved by Britt and Ferekides [6]. The current record one-of-a-kind laboratory research cell was fabricated in 2015 by First Solar (FSLR) and has an efficiency of 21.5%. Indeed, the key focus of today's PV study is to using fewer semiconductor materials by producing the thinner cells. Thinning will save materials usage thus reduce the fabrication cost required to make the cells. All of these factors mentioned above may lead to produce inexpensive and affordable solar cells. Careful investigation of the reported results display that high efficiency CdTe cells (say >10%) have doping concentrations between ~1.0 × 10^{14} and ~5.0 × 10^{15} cm^{-3} [1,6]. However, to mitigate the manufacturing cost of this cell a lower thickness is required along with appreciable conversion efficiency. So, if the doping concentration of the CdTe layer can be raised above 5 × 10^{15} cm^{-3} the maximum conversion efficiency can be found with a thinner absorber layer.

Hence, the aims of the present investigation is to find out an optimum carrier concentration for more stable and high efficient ultra-thin CdTe based solar cells. In addition, the influence of temperature is also considered to realize the environmental impact on performance of the cell. All of the simulations was done using AMPS 1D program.

II. Modeling and Simulaion

Numerical models have already been widely accepted as important tools for the fabrication of any kind of feasible solar cells. Numerical modeling of ultra-thin solar cells is a significant approach to test the possibility of suggested physical explanations and to expect the effect of physical changes on cell performance. Assumed the complex nature of CdS:O/CdTe ultra-thin solar cells, the requirement for numerical modeling is obvious. Numerical simulations give understanding into the mechanism of structures, thus allowing the fabrication of novel structures with good performance and

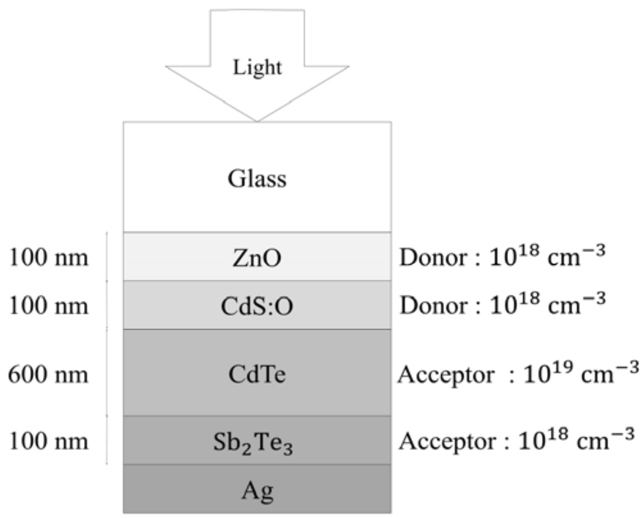

Fig. 1 Schematic structure of the CdTe solar cell.

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Table I

Values of different parameters used in simulation [7].

Parameters	ZnO	CdS:O	CdTe	Sb_2Te_3
$\varepsilon/\varepsilon_0$	9.00	10.00	9.40	55.00
μ_N – cm^2 /Vs	100	100	320	1094
μ_P – cm^2 /Vs	25	25	40	320
N_A - 1/cm^3	-	-	5.0×10^{16} – 5.0×10^{22}	6.8×10^{19}
N_D - 1/cm^3	1.0×10^{18}	1.0×10^{18}	-	-
E_g – eV	3.30	2.75	1.50	0.42
N_C - 1/cm^3	2.2×10^{18}	2.2×10^{18}	7.5×10^{17}	1.0×10^{16}
N_V - 1/cm^3	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}	1.0×10^{17}
χ –eV	4.50	4.50	4.28	4.15
W (nm)	100	100	100-2000	100

efficiency. The accepted methods to enhance the performance of CdS:O/CdTe cells have been explored using AMPS 1D. The key functional aspect of AMPS 1D is to solve the fundamental semiconductor equations, such as Poisson's equation and carrier continuity equations. Fig. 1 shows the modified cell structures for superior conversion efficiency which have been used in our present investigation.

In this study, we used the one dimensional (1D) simulation software AMPS to examine the effect of acceptor concentration of absorber layer on the performance of CdTe ultra-thin solar cells with modified structure. The effect of temperature and thickness of absorber layer on the performance of CdTe cells are investigated. Here, ZnO and Sb_2Te_3 have been used as the front contact and back surface field (BSF) layer, respectively. The thickness of the ZnO is kept 100 nm. During the simulation, the hole concentration of absorber layer is varied from 5×10^{16} to 5×10^{22} cm^{-3}, the CdTe layer thickness is ranging from 100 to 2000 nm and operating temperature range of 298 to 500 K. The short-circuit current (J_{SC}), open circuit voltage (V_{OC}), fill factor (FF) and efficiency was investigated with respect to the variation of doping concentrations, temperature and the thickness of CdTe layer. The values of different material parameters used in 1D software AMPS are illustrated in Table 1.

III. Result and Discussion

A. *Effect of acceptor concentration*

The acceptor concentration of the CdTe layer has been changed from 5×10^{16} to 5×10^{22} cm^{-3} and simulated results is illustrated in Fig. 2 for the fixed CdTe thickness of 600 nm. It

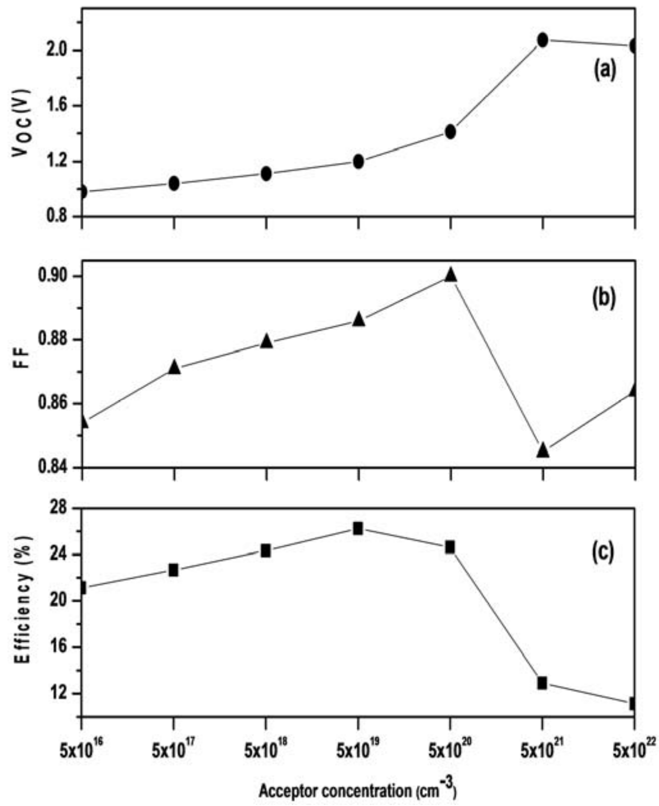

Fig. 2 Effect of acceptor concentration on (a) V_{OC}, (b) FF and (c) efficiency.

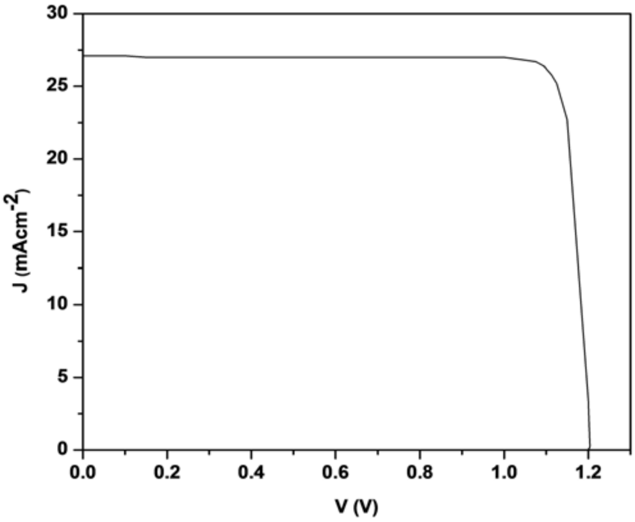

Fig. 3 Light J-V characteristics curve.

can be seen from Fig. 2 that the maximum efficiency of 26.24% is achieved for the acceptor concentration of 5×10^{19} cm^{-3}. It is important to focus that the efficiency of CdS:O/CdTe solar cell increases with the acceptor concentration from 5×10^{16} to 5×10^{19} cm^{-3}, for further increment of acceptor concentration the efficiency decreased considerably. Higher doping concentration reduces the diode's saturation current and hence increases the open-circuit voltage (V_{OC}) (Fig. 2(a)) and the fill-factor (FF) (Fig. 2(b)) [8]. However, for the acceptor concentration above 5×10^{19} cm^{-3}

the efficiency (Fig. 2(c)) decreased sharply. In this case R_S seems to decreases with increasing the doping concentration up to the optimum level, $N_A = 5 \times 10^{19}$ cm^{-3}. The *J-V* characteristics curve of CdS:O/CdTe ultra-thin solar cell is shown in Fig. 3. From this curve, it is clearly observed that the higher shunt resistance and lower series resistance with maximum J_{SC}, V_{OC} and *FF*. Compared with previously reported cells, our proposed CdS:O/CdTe solar cell exhibited superior efficiency owing to the improvement of V_{OC} (1.2 V).

B. Effect of Thickness of CdTe Layer

It is suggested that the reduction of thickness of CdTe absorber layers not only helpful to minimize the cost of materials in the process of cell production but also lead to improve the properties of cell by decreasing recombination losses in the bulk [3]. At this stage, the thickness of CdTe layer is ranging from 100 to 2000 nm to achieve the optimum thickness of absorber layer for the fixed acceptor concentration of 5×10^{19} cm^{-3}. The highest efficiency of 26.24% is achieved for 600 nm of CdTe as observed in Fig. 4(b). Further increase in the thickness causes the efficiency to decrease. Fig. 4(a) shows the highest V_{OC} of 1.2 V is found for CdS:O/CdTe cell. It signifies that although the thicker CdTe layer has greater spectral response, it increases the carrier recombination also.

C. Effect of Temperature

Operating temperature is playing a vital role in thin-film solar cell's performance and stability. It is suggested that the operating temperature on the cell surface can be prolonged from 283 to 373 K under the sun light [9]. CdTe has comparatively low temperature coefficient which can protects the cell performance at higher temperature [10]. For this cell operating temperature is varied from 298 to 500 K. Fig. 5 shows the efficiency with respect to the variation of the operating temperature on the cell. From our results the temperature coefficient is found to be 0.031% / K which shows the stability and reliability of the proposed cell. From

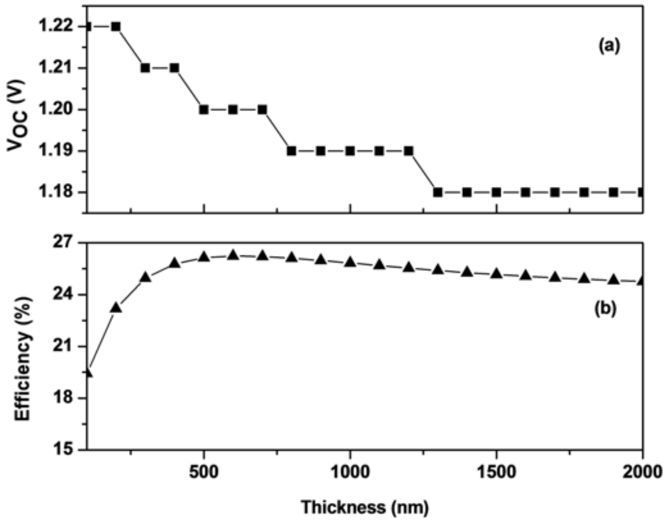

Fig. 4 Effect of thickness on (a) V_{OC} and (b) efficiency of CdTe solar cell.

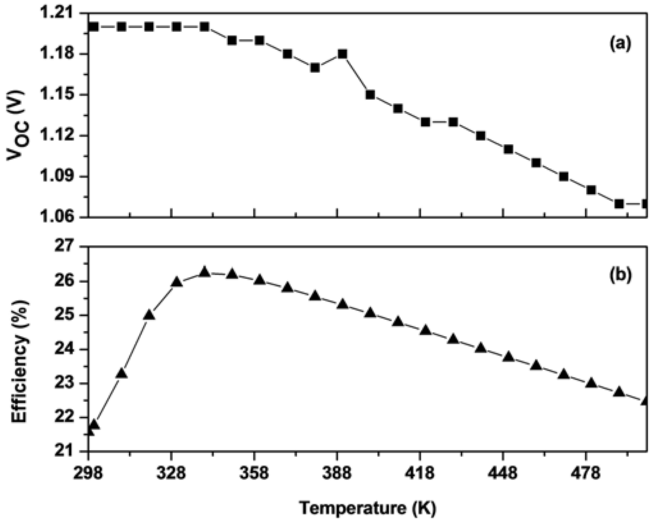

Fig. 5 Effect of temperature on (a) V_{OC} and (b) efficiency.

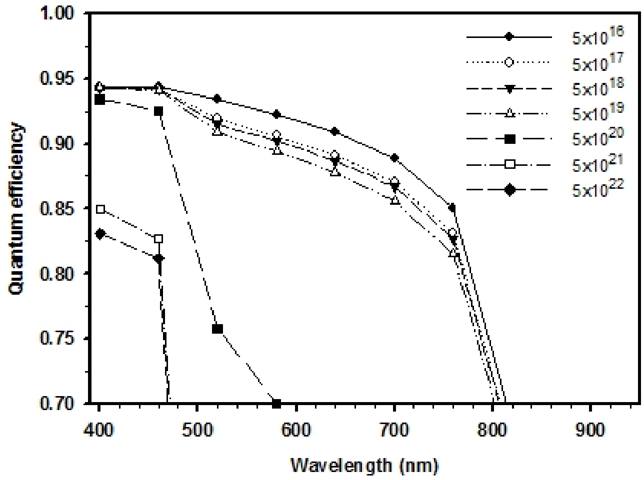

Fig. 6 Quantum efficiency of CdTe solar cell.

Fig 5(b), it can be observed that the efficiency increases with increasing the temperature and achieved highest value at 340 K, for further increment of temperature the efficiency decreased sharply. As observed the V_{OC} (Fig. 5(a)) at this stage for which the efficiency is increased. As the band gap in the semiconductor decreases with the increase of temperature which helps to enhance the cell efficiency by increasing the electrons flow rate in the material. On the other hand, the results as shown in Fig. 5 indicating that over the temperature 340 K, the carrier collision and recombination is dominated over the carrier flow rate and the efficiency start to reduce.

D. Quantum Efficiency

The quantum efficiency (*QE*) can be defined as the ratio of the current of photo-generated carriers to the incident photon flux. The *QE* of a solar cell strongly depends on the energy of the individual photon. This may be due to both the wavelength dependency of the optical absorption coefficients in semiconductors and the depth dependency of the carrier collection probability. Fig. 6 shows the *QE* vs. wavelength characteristics curve for different acceptor concentration on the absorber layer. For different concentration of CdTe layer the spectral response exhibited different characteristics. The wavelength of the cell is varied from 400 to 850 nm. For the various acceptor concentrations the *QE* exhibits almost same characteristics. The results in a change in the quantum efficiency as shown in Fig. 6 indicates that CdTe thin film solar cell provides more stable spectral response.

IV. Conclusion

In this study, an ultra-thin high efficiency CdS:O/CdTe solar cell is suggested with a reduced CdTe absorber layer thickness. The performance of CdS:O/CdTe cell was numerically simulated by using AMPS 1D package. The maximum conversion efficiency of 26.24% (J_{SC} = 27.05 mA/cm^2, V_{OC} = 1.2 V and *FF* = 88.6%) is achieved with the proposed cell consisting of 600 nm CdTe layer and with acceptor concentration of 5×10^{19} cm^{-3}. The greater values of J_{SC}, V_{OC}, *FF* as well as *QE* curves are demonstrated the lower pinholes and shallow defect density, outstanding absorption range and strength. Our findings not only open up new research instructions but also cover the way for the industrialization of very cost-efficient solar modules.

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