High Efficiency and Ultra Thin $Zn_xCd_{1-x}S$/ZnCdTe Solar Cell With Cu_2Te BSF

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Abstract— **The main motivation of this work was to obtain high efficiency at reduced ZnCdTe absorber layer thickness and replacing $Zn_xCd_{1-x}S$ as window layer in conventional CdS/CdTe solar cells. The initial step of the analysis was to decrease the ZnCdTe absorber layer to the extreme limit of 1 µm and at this thickness the proposed cell has shown satisfactory level of efficiencies. The front contact of the best cell was adapted to the proposed cell and the $Zn_xCd_{1-x}S$ window layer thickness was reduced with a buffer layer. The ultimate step was to insert a suitable back surface field (BSF) with Cu_2Te to reduce the back contact barrier height and back surface recombination loss of the ultra thin cell. All the analysis was done using the widely used simulator Analysis of Microelectronic and Photonic Structures (AMPS 1D). The conversion efficiency of 17.77% (*Voc* = 0.894 V, *Jsc* = 25.48 mA/cm^2, FF = 0.78) without BSF and efficiency of 19.95% (*Voc* = 0.93 V, *Jsc* = 25.84 mA/cm^2, FF = 0.83) and 20.26% (*Voc* = 0.94 V, *Jsc* = 25.97 mA/cm^2, FF = 0.83) with Cu_2Te BSF were achieved for the proposed cells of 1 µm and 0.6 µm ZnCdTe absorber layer respectively. Moreover, the normalized efficiency of the proposed ultra thin cells linearly decreased with the increasing operating temperature at the gradient of -0.38%/°C, which indicates better stability of $Zn_xCd_{1-x}S$/ZnCdTe solar cell.**

Keywords-; High efficiency; ZnCdTe; $Zn_xCd_{1-x}S$; AMPS 1D; Cu_2Te BSF

I. INTRODUCTION

The CdTe thin film solar cells have shown promising efficiency [1] and long-term stable performance [2] under AM1.5 illumination for global usage. However, conversion efficiencies of CdTe solar cells with homojunction have not shown encouraging results. Thus, in CdS/CdTe solar cells incorporate of zinc (Zn) in both the window layer (CdS) and absorber layer (CdTe) are very promising in order to achieve high efficiency, reliable and stable solar cells than the other counterparts [3]-[4]. Clearly one of the main goals of today's solar cell research is using less semiconductor material by making the cells thinner. Thinning will not only save material, but will also reduce production time, and the energy requires producing them. All of these aspects will decrease the manufacturing cost of cells. $Zn_xCd_{1-x}S$ is gaining prominence as good candidate for wide band-gap material in the field of photovoltaic solar cells. The CdS window layer has a lower bandgap, which causes significant absorption in the short-wavelength region which is below 500 nm. Substituting $Zn_xCd_{1-x}S$ as an alternative window layer with a higher band-gap than CdS is a promising approach. In this study, $Zn_xCd_{1-x}S$ has been substituted for CdS as it can provide a more transparent window in the blue region (<500nm). As demonstrated by Oladeji et al. [5] and several other researchers [6]-[7], the spectral response in the blue region can be significantly enhanced using $Zn_xCd_{1-x}S$ as a window layer in CdTe solar cells. Moreover, $Zn_xCd_{1-x}S$ films can be deposited in a variety of ways: Vacuum evaporation [8], metal organic chemical vapor deposition (MOCVD) [9], spray pyrolysis [10], successive ionic absorption and reaction (SILAR) [11], photochemical deposition [12] and chemical bath deposition [13]. The publication of Yin et al. [10] reported on CdZnS/CdTe junctions in which the Zinc concentration was chosen to be around 10%. Oladeiji's et al. [5] showed improved Quantum Efficiency (QE) in comparison to CdS device. CdTe semiconducting material has shown great potentials as an absorber material for thin film solar cells with solar cells based on this material attaining a maximum efficiency of 16.5%. However, for this thin film technology to compete with other conventional energy sources, its efficiency needs to be improved. In an attempt towards a higher efficiency thin film solar cell structure, this study proposes the use of a ternary semiconductor cadmium zinc telluride (CdZnTe) as an absorber layer to form $Zn_xCd_{1-x}S$/ZnCdTe solar cell

There are much works to be done for improvement the conversion efficiency of $Zn_xCd_{1-x}S$/ZnCdTe solar cells in matching the effects of $Zn_xCd_{1-x}S$ on cell output parameters *Voc*, *Jsc* and *FF* for suitable composition of Zn (x) using modified design through standard numerical technique.

This study had shown the possibility of a highly efficient 20.26% (*Voc* = 0.94 V, *Jsc* = 25.97 mA/cm^2, FF = 0.83) $Zn_xCd_{1-x}S$/ZnCdTe solar cell with 0.6 µm of ZnCdTe, 80 nm of $Zn_xCd_{1-x}S$, 100 nm of Zn_2SnO_4 and 100 nm of Cu_2Te BSF layers.

II. METHODOLOGY

Numerical simulation and analysis of the structure performance and understanding the physics of solar cells and other photonic systems has been a useful means of gaining useful and relevant insight into the possible behaviour of such structures in real life conditions. Modeling and simulation were done utilizing AMPS-1D simulator to explore the possibilities of ultra thin CdTe absorber and $Zn_xCd_{1-x}S$ window layer with improved cell output like open circuit voltage (*Voc)*, the short circuit current density (*Jsc)* the fill factor (FF) and ultimately the conversion efficiency. In AMPS-1D, the optical model was set to 85% reflection without BSF and 90% reflection with BSF at the back contact and 5% reflection for the front contact, which mean that 95% of the incoming light will be transmitted to the absorber layer. The temperature was set to 298K (25°C). The baseline case of CdTe cell [14] was utilized to approximate the highest efficiency of CdTe solar cell at that time, and it was modified in this work to analyze the possibility of efficient ultra thin cells with proper BSF. The first modification was to decrease $Zn_xCd_{1-x}S$ window layer to 80 nm with Zn_2SnO_4 buffer layer. The $Zn_xCd_{1-x}S$ layer was included as an alternative of CdS layer to improve the absorption of photon energy in the short wavelength region (blue region). The front contact of the modified cells consist of a highly conducting layer of Cd_2SnO_4 (CTO) as transparent conducting oxide (TCO) for low resistance due to contact and lateral current collection and a much thinner high resistivity buffer layer of Zn_2SnO_4 to prevent small amount of forward leakage current through $Zn_xCd_{1-x}S$ layer which is significantly less than the leakage current in CdS layer in comparison to CdS/CdTe solar cell [15]. This CTO/Zn_2SnO_4 has replaced the SnO_2 as front contact layer of the conventional cell. The next modification was to reduce the ZnCdTe absorber thickness to the extreme limit for achieving ultra thin $Zn_xCd_{1-x}S$/ZnCdTe cell and inserting Cu_2Te as BSF to lessen the barrier height and the minority carrier recombination loss at the back contact of the ultra thin CdTe cell. Fig. 1 shows the CdTe baseline case structure and (Glass/Cd_2SnO_4/Zn_2SnO_4/$Zn_xCd_{1-x}S$/ZnCdTe/Cu_2Te/Al) that is the modified structure in which CdS and CdTe from baseline case are replaced by $Zn_xCd_{1-x}S$ and ZnCdTe respectively for higher performance. Four layers that were highlighted in this analysis are the n-Zn_2SnO_4 buffer layer, n- $Zn_xCd_{1-x}S$ window layer, p-ZnCdTe absorber layer and p-Cu_2Te BSF layer.

The ZnCdTe absorber layer thickness was varied from 0.1 μm to 10 μm and the other layers thickness were fixed to the optimum values found in literature [15] and is shown in Table 1 and also the material parameters used in this modelling which were chosen based on literature values.

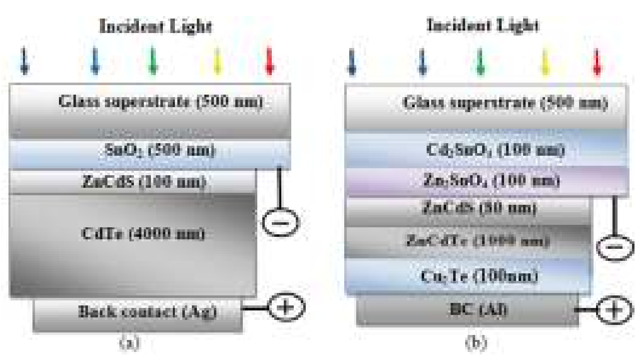

Fig. 1. Structures of the ZnCdTe solar cells: (a) Conventional baseline case structure and (b) Modified structure for higher performance.

Hence, it is crucial to minimize the number of variable parameters by fixing many of them at reasonable values. It was a tough challenge to select the appropriate parameters to be used for the individual layers of the cells. Many of them depend on fabrication processes and deposition techniques and can thus vary even between devices fabricated at the same chamber. The dependability of this analysis, of course relies on the selection of the material parameters that are going to be used in the simulation. Table 1 shows the material parameters used in this modeling, which were chosen based on experimental data, literature values, and theoretical study.

III. Results and Discussions

The baseline case of CdTe cell [14] was chosen as the starting point of the analysis in which CdS was replaced by $Zn_xCd_{1-x}S$. Numerical simulation was done to see the effect of Zn content of $Zn_xCd_{1-x}S$ window layer on conversion efficiency from x=0 to x=1 using the parameters related to electrical and optical behavior of $Zn_xCd_{1-x}S$ which was adopted from literature reviews and x= 0.1 was selected as it showed high efficiency and low resistivity of $Zn_xCd_{1-x}S$ window than other values of x. The conversion efficiency of 14.96% (*Voc* = 0.82 V, *Jsc* = 24.84 mA/cm^2, *FF* = 0.716) was found from the baseline case cell, where 4 μm CdTe absorber layer, 80 nm $Zn_xCd_{1-x}S$ (x=0.1) window layer, 500 nm SnO_2 front contact and Ag (Φ_{bL}=1.25 eV) as final back contact metal were used.

Table 1: Material parameters used in AMPS simulation

Typical cell properties				
Parameters	**Front contact**	**Back contact**		
Φ_b [eV]	Φ_{bn} = 0.05	Φ_{bp} = 1.25 (Ag) and 0.4 (Cu_2Te)		
S_e [cm/s]	1×10^7	1×10^3 - 1×10^9		
S_h [cm/s]	1×10^7	1×10^3 - 1×10^9		
R_f [I]	0.05	0.85 (Al) and 0.9 (Cu_2Te)		
Layer properties				
Parameter	**Zn_2SnO_4**	**$Zn_xCd_{1-x}S$ (x=0.1)**	**p-ZnCdTe**	**p-Sb_2Te_3**
W (μm)	0.1	0.06	0.1 - 10.0	0.5
$\varepsilon/\varepsilon_0$	9.0	9.3	9.4	10
μ_e (cm^2/Vs)	32	95	320	500
μ_p (cm^2/Vs)	03	35	40	100
n, p (cm^{-3})	10^{19}	2.5×10^{16}	5×10^{15}	10^{21}
Eg (eV)	3.35	2.55	1.45	1.18
N_c (cm^{-3})	2.0×10^{18}	2.1×10^{18}	7.5×10^{17}	7.5×10^{17}
N_v (cm^{-3})	1.5×10^{19}	1.7×10^{19}	1.8×10^{19}	1.5×10^{19}
χ (eV)	4.50	4.44	4.28	4.20

When the front contact of the baseline case cell was changed by introducing Cd_2SnO_4 with 100 Zn_2SnO_4 along with 80 nm $Zn_xCd_{1-x}S$ (x=0.1) layer rejecting 500 nm SnO_2 the efficiency increased to 15.78% (*Voc* = 0.82 V, *Jsc* = 26.21 mA/cm^2, FF = 0.716). The improvement of efficiency resulted from higher *Jsc* as Cd_2SnO_4/Zn_2SnO_4 has higher optical transmission than SnO_2. When ZnCdTe doping concentration (5×10^{15}) which is now attainable was implemented to the baseline case cell the conversion efficiency increased to 19.11% (*Voc* = 0.9 V, *Jsc* = 26.0 mA/cm^2, FF = 0.798). The step up of conversion efficiency is certainly due to increased

Voc and *FF* for higher doping concentration of CdTe absorber layer.

Theoretically, the minimum thickness required to absorb 90% of the incident photons with energy greater than the bandgap is nearly 1 µm which was in literature for CdTe cell. But, it is remarkable that in most high efficiency CdTe solar cells, the CdTe absorber layer is purposely kept at 5 µm and above. The key idea of this analysis is to obtain the acceptable cell output parameters using $Zn_xCd_{1-x}S$ (x=0.1) window at reduced ZnCdTe absorber thickness. This will reduce the cost of cell deposition and material usage of CdTe cells. Numerical analysis was done to lessen the thickness of ZnCdTe absorber layer to the extreme limit aiming to preserve the absorber ZnCdTe materials use and was found that all the cell output parameters were constant from 4 µm to 10 µm of ZnCdTe layer. Thus, the cell output characteristics below 4 µm ZnCdTe layer were explored and are shown in Fig. 2.

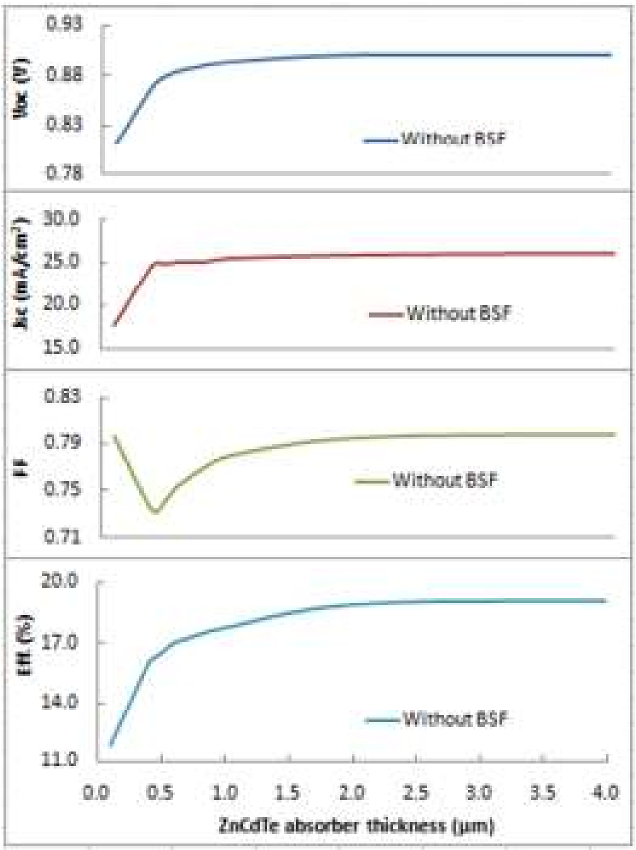

Fig.2. Effect of ZnCdTe thickness variation on the output parameters of $Zn_xCd_{1-x}S$/ZnCdTe cell.

From the figure all the cell output characteristics were gradually decreased from 4 µm to 1 µm of CdTe layer. However, the *Voc*, *FF* and conversion efficiency decrease dramatically at thickness below 1 µm. The 1 µm thick CdTe cell showed conversion efficiency of 17.77% (*Voc* = 0.894 V, *Jsc* = 25.48 mA/cm^2, FF = 0.78). A bit efficiency of 1 µm thick CdTe absorber layer was decreased (from 19.11% to 17.77%) compared that of 4 µm thick ZnCdTe absorber layer. Thus, the selection of 1 µm ZnCdTe absorber layer is acceptable with a little sacrifice in efficiency but greater saving of the absorber CdTe material (from 4 to 1 µm) as it is very expensive. Further numerical analysis was done with Cu_2Te to investigate the effects of BSF in the ultra thin cell. It was found that the proposed cell with 1 µm ZnCdTe without BSF gives conversion efficiency of 17.77% but with BSF 1 µm CdTe gives 19.95% and with 0.6 µm CdTe gives the highest conversion efficiency of 20.26%. Simulation results are shown in Fig. 3 with variable thickness of ZnCdTe absorber layer from 0.1 µm to 4 µm with 100 nm Cu_2Te BSF layer and along with the $Zn_xCd_{1-x}S$ (x=0.1). The Figure 1 is also combined here for comparison. The enhancement in efficiency with BSF resulted from the improvement of all the cell output parameters like *Jsc*, *Voc* and FF.

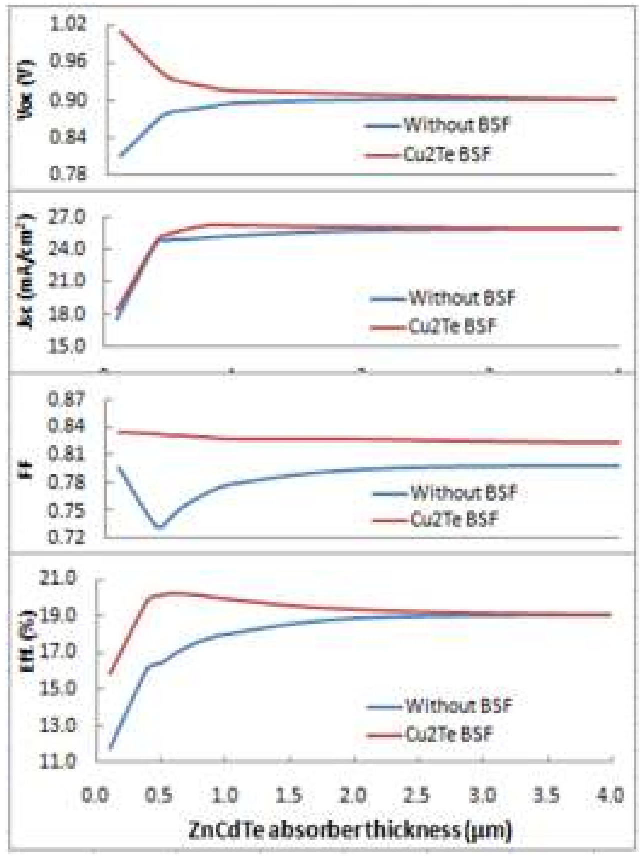

Fig.3. Effect of BSF in $Zn_xCd_{1-x}S$/ZnCdTe cell

The simulated J-V characteristics of the cell of 1 µm ZnCdTe layer without BSF and 0.6 µm CdTe layer with Cu_2Te BSF is shown in Fig. 4. The step up of efficiency with BSF resulted from the improvement of all the cell output parameters like *Jsc*, *Voc* and FF which is much clearer from J-V curves.

Before final termination of this work, it is investigated the stability of the proposed cells at higher operating temperatures.

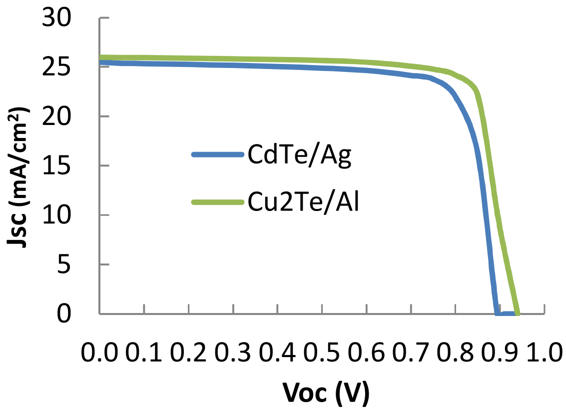

Fig. 4. J-V characteristics of the proposed cells

In order to analyze the effects of temperature on cells performances with and without BSF, simulation were carried out with cell operating temperature range of 25°C to 100°C and the simulated results are shown in Fig. 5. From the figure it is apparent that without BSF layer and with Cu_2Te BSF layer the cells normalized efficiency linearly decreased with the increase of operating temperature at a temperature coefficient (TC) of -0.38%/°C. This TC indicates better stability of the cells at higher operating temperature.

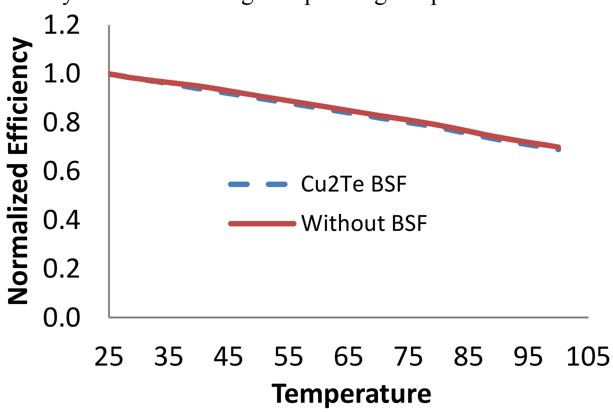

Fig. 5. Effect of operating temperature of the proposed cells.

IV. Conclusion

A highly efficient 20.26% (*Voc* = 0.94 V, *Jsc* = 25.97 mA/cm^2, FF = 0.83) cell with ultra thin (0.6 µm) CdTe absorber, 60 nm of $Zn_xCd_{1-x}S$, 100 nm of Zn_2SnO_4 and 100 nm of Cu_2Te BSF layers was proposed. This analysis had shown that Cu_2Te is a suitable back contact BSF material for higher efficiency and stable ultra thin $Zn_xCd_{1-x}S$/ZnCdTe/Cu_2Te cell. In consideration of both cell conversion efficiency and thermal stability at higher operating temperature, the structures with Cu_2Te BSF provided evidence to be improved to other reported cells, and the proposed cells can be examined using typical existing fabrication techniques.

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