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Towards Ultra Thin and High Efficiency ZnxCd1-xS/CdTe Solar Cell by AMPS 1D

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Abstract. The main motivation of this work was to obtain high efficiency at reduced CdTe absorber layer thickness and replacing $Zn_xCd_{1-x}S$ as window layer in conventional CdS/CdTe solar cells. The conventional CdTe baseline case was the starting point of this investigation to analyze ultra thin and high efficiency $Zn_xCd_{1-x}S$/CdTe solar cell for optimal value of x. The initial step of the analysis was to decrease the CdTe absorber layer to the extreme limit of 1 μm and at this thickness the proposed cell has shown satisfactory level of efficiencies. The ultimate step was to insert a suitable back surface field (BSF) with As_2Te_3 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 18.02% (*Voc* = 0.89 V, *Jsc* = 25.34 mA/cm^2, FF = 0.78) without BSF and an efficiency of 20.3% (*Voc* = 0.93 V, *Jsc* = 25.97 mA/cm^2, FF = 0.825) with As_2Te_3 BSF were achieved for the proposed cells from 1 μm and 0.6 μm CdTe absorber layer respectively. Moreover, the normalized efficiency of the proposed ultra thin cells linearly decreased with the increasing operating temperature at the gradient of -0.35%/°C, which indicates better stability of the ultra thin cells.

Introduction

The Photovoltaic solar cells based on thin film CdTe are very promising in order to achieve better efficiency/cost ratios, reliable and stable solar cells than the other counterparts because of the high potentiality for the following reasons. 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. Moreover, the CdTe thin film solar cells have shown high efficiency [1] and long-term stable performance [2] under AM1.5 illumination for comprehensive usage.

As a potential photovoltaic absorber material for thin film solar cells, CdTe typically forms junction with CdS. The CdS window layer has a lower band gap, which causes significant absorption in the short-wavelength region which is below 500 nm. Substituting 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). Its band gap can be tuned from 2.42 eV (x=0 for CdS) to 3.6 eV (x=1 for ZnS). As demonstrated by Oladeji et al. [3] and several other researchers [4]-[5], the spectral response in the blue region can be significantly enhanced using cell structures of $Zn_xCd_{1-x}S$/CdTe. Hence, there are still much works for improvement the conversion efficiency of $Zn_xCd_{1-x}S$/CdTe solar cells in matching the effects of $Zn_xCd_{1-x}S$ on cell output parameters *Voc*, *Jsc* and *FF* by using modified design

This works targets ultra thin CdTe cells with $Zn_xCd_{1-x}S$ window layer for optimal value of x instead of CdS to achieve higher conversion efficiency with a proper BSF through standard numerical technique. The main purposes of BSF are to reduce the back surface recombination losses and to reduce the barrier height at back contact. The particular BSF materials selected to investigate in this work is Arsenic Telluride (As_2Te_3).

Methodology

Numerical modeling of polycrystalline thin-film solar cells is an important strategy to test the viability of proposed physical structure, predicting the effect of changes in material properties and geometry on cell performance, and fitting of modeling output to experimental results. In this work, modeling and simulation were done utilizing AMPS-1D simulator [6] to explore the possibilities of ultra thin CdTe absorber with improved cell output like open circuit voltage (*Voc)*, the short circuit current density (*Jsc)* the fill factor (FF) and ultimately the conversion efficiency. The baseline case of CdTe cell [7] 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 60 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 and a better lattice match with CdTe absorber layer. The front contact of the modified cells consist of a highly conducting layer of 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 [8]. This CTO/Zn_2SnO_4 has replaced the SnO_2 as front contact layer of the conventional cell. The next modification was to replace $Zn_xCd_{1-x}S$ window layer with CdS and to change the CdTe doping concentration of 2×10^{14} cm^{-3} used in the baseline case to 5×10^{15} cm^{-3} which is now reachable for p-CdTe material. The further modification is to reduce the CdTe absorber thickness to the extreme limit for achieving ultra thin CdTe cell and inserting As_2Te_3 BSF to lessen the barrier height and the minority carrier recombination loss at the back contact of the ultra thin CdTe cell.

The CdTe baseline case structure was (Glass/SnO2/CdS/CdTe/Ag) which was modified to (Glass/Cd_2SnO_4/Zn_2SnO_4/$Zn_xCd_{1-x}S$/CdTe/As_2Te_3/Al) in which CdS from baseline case was replaced by $Zn_xCd_{1-x}S$ 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-CdTe absorber layer and p-As_2Te_3 BSF layer.

The CdTe 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 [8].

In modeling of solar cells, the number of parameters that can be varied is larger than 50 [9]. Clearly, a problem with 50 variables is too ambiguous to solve consistently. 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 few material parameters used in this modeling, which were chosen based on experimental data, literature values, and theoretical study.

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 0.3 (As_2Te_3)
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	0.9 (Ag) and 0.95 (As_2Te_3)

Results and Discussion

A simple structure (SnO_2/CdS/CdTe) of baseline case of CdTe cell [7] 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, 60 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. When the front contact of the baseline case cell was changed by introducing Cd_2SnO_4 with 100 Zn_2SnO_4 along with 60 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 CdTe 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 (Eg) is approximately 1 μm for CdTe cell [10]. 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 CdTe 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 CdTe absorber layer to the extreme limit aiming to preserve the absorber CdTe materials use. The range of variation of CdTe absorber thickness was from 0.1 μm to 10 μm and found that all the cell output parameters were constant from 4 μm to 10 μm of CdTe layer. Thus, the cell output characteristics below 4 μm CdTe layer were explored and are shown in Fig. 1(a) (*without BSF*).

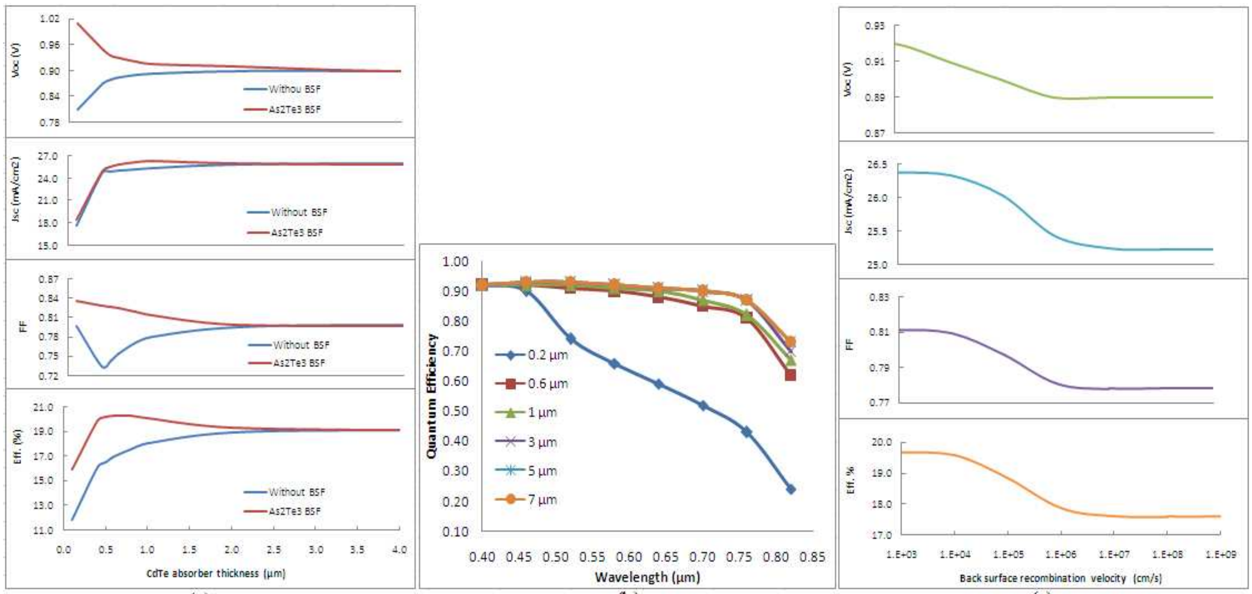
It can be seen that all the cell output characteristics were gradually decreased from 4 μm to 1 μm of CdTe layer. However, the *Voc*, *FF* and conversion efficiency decrease dramatically at thickness below 1 μm. The 1 μm thick CdTe cell showed conversion efficiency of 18.02% (*Voc* = 0.89 V, *Jsc* = 25.34 mA/cm^2, FF = 0.78). These results are in good agreements with related published works [19]. A bit efficiency of 1 μm thick CdTe absorber layer was decreased (from 19.11% to 18.02%) compared that of 4 μm thick CdTe absorber layer. Thus, the selection of 1 μm CdTe absorber layer is acceptable with a little sacrifice in efficiency but greater saving of the absorber CdTe material (from 4 to 1 μm).

The sacrificing of efficiency in ultra thin CdTe cell than the thicker one is mainly due the loss in *Jsc* which might be attributed at the long wavelength region as the quantum efficiency is reduced with the decrease of CdTe absorber thickness as shown in Fig. 1(b). Furthermore, keeping the CdTe thickness at constant value, the back surface recombination rate (BSRR) was changed from 10^3 cm/s to 10^9 cm/s; the simulated results are shown in Fig. 1(c). From Fig. 1(c) it is noticeable that if the BSRR decreases all the cell output characteristics increase considerably. This result is in agreement with related published work of CdTe solar cells [10]. This obviously reveals the effect that arises in the case of thin CdTe cells as result of carrier recombination near the back contact. To reduce the BSRR of this thin cell new structure with BSF was introduced. Thus, a new structure with As_2Te_3 BSF was inspected at the back contact to control the recombination losses in such ultra thin (1 μm) CdTe cell.

Further numerical analysis was done with As_2Te_3 to investigate the effects of BSF in the ultra thin cell. In this simulation, all the layers of the previous cell are same except one additional BSF layer (0.1 μm of As_2Te_3) at the back contact of the cell. The modified cell were simulated with the parameters in Table 1and other parameters along with 1 μm CdTe, 60 nm $Zn_xCd_{1-x}S$, 100 nm Zn_2SnO_4 and 100 nm As_2Te_3 BSF layers. Simulation results are shown in Fig. 1(a) (*As_2Te_3 BSF*) with variable thickness of CdTe absorber layer from 0.1 μm to 4 μm with 100 nm As_2Te_3 BSF layer and along with the $Zn_xCd_{1-x}S$/CdTe (x=0.1). It was investigated from the simulation results that the proposed cell with 1 μm CdTe without BSF gives conversion efficiency of 18.02% but with BSF 1 μm CdTe gives 20.1% and with 0.6 μm CdTe gives the highest conversion efficiency of 20.3%.

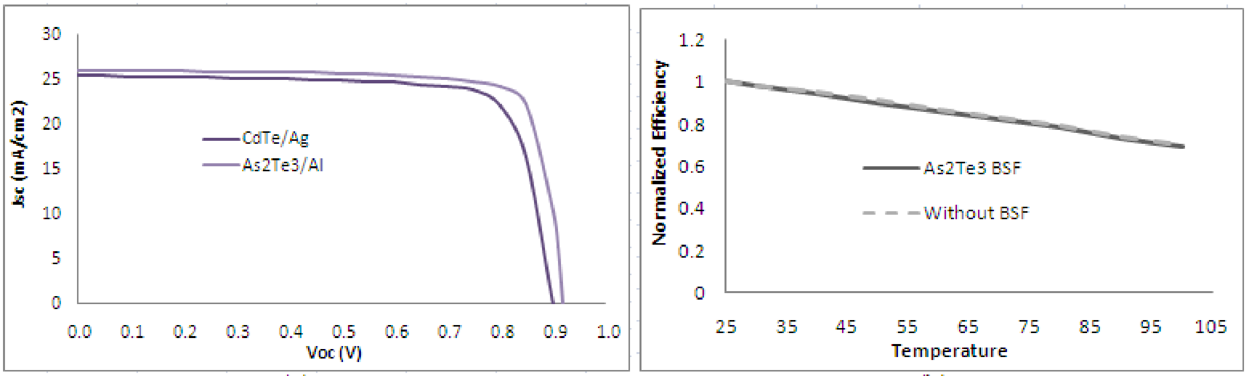
The *Jsc* with As_2Te_3 BSF has shown higher value than without BSF layer but follow the similar trend of decrease considerably below 0.6 μm of CdTe layer as without BSF. The increase in *Voc*, FF and *Jsc* are due to the minority carriers (electron) that are bounced back from the back surface of the $Zn_xCd_{1-x}S$/CdTe/As_2Te_3 (x=0.1) cell and the smother flow of hole at the back contact with reduced barrier height. These results of BSF layer are agreeable to the related published works [11]. Thus, the cell conversion efficiency show highest value of 20.3% (*Voc* = 0.93 V, *Jsc* = 25.97 mA/cm^2, FF = 0.825) at 0.6 μm of CdTe layer with BSF. Hence, it is a clear sign of further reduction of CdTe absorber layer thickness from 1 μm to 0.6 μm with BSF is possible as proved in this analysis.

The enhancement in efficiency with BSF resulted from the improvement of all the cell output parameters like *Jsc*, *Voc* and FF which will be much clearer from the J-V characteristics of the $Zn_xCd_{1-x}S$/CdTe (x=0.1) cells. The simulated J-V characteristics of the cell of 1 μm CdTe layer without BSF and 0.6 μm CdTe layer with As_2Te_3 BSF are shown in Fig. 2 (a). Before final termination of this work, it is investigated the stability of the proposed cells at higher operating temperatures. 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. 2(b). From Fig. 2(b) it is apparent that without BSF layer and with As_2Te_3 BSF layer the cells normalized efficiency linearly decreased with the increase of operating temperature at a temperature coefficient (TC) of -0.35%/°C. This TC indicates better stability of the cells at higher operating temperature, which are in good agreement with related works [11]



(a) (b) (c)

Fig. 1: (a) Effect of CdTe thickness variation on the output parameters of $Zn_xCd_{1-x}S$/CdTe cell with BSF and without BSF (b) on the SR (c) Effect of BSR velocity on proposed cell



(a) (b)

Fig. 2: (a) Effect of BSF on the J-V (b) Effect of operating temperature on cell stability

Conclusion

The main objective of this analysis was to determine the effects of CdTe thickness reduction and application of $Zn_xCd_{1-x}S$ as window layer in CdTe solar cells. The conversion efficiency shows a slight decreasing trend with a decrease of CdTe thickness up to o.6 µm. The overall performance of the $Zn_xCd_{1-x}S$/CdTe cell was affected by the back surface recombination in case of thinner CdTe absorbers. To avoid the effect of such recombination a new structure with low band-gap BSF material like As_2Te_3 was investigated. Calculations related to $Zn_xCd_{1-x}S/CdTe/As_2Te_3$ structure indicate that insertion of As_2Te_3 could nullify the back surface recombination loss and thus could contribute a significant efficiency rise even with ultra thin (0.6 µm) CdTe absorber layer. The temperature analysis of the proposed cells showed the stability to some extent at higher operating temperatures with a linear TC of -0.35%/°C. A highly efficient 20.3% (*Voc* = 0.93 V, *Jsc* = 25.97 mA/cm^2, FF = 0.825) 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 As_2Te_3 BSF layers was proposed and the proposed cells can be examined using typical existing fabrication techniques.

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