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INVESTIGATION OF BUFFER LAYERS, FRONT AND BACK CONTACTS FOR $Zn_xCd_{1-x}S$/CdTe PHOTOVOLTAIC

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ABSTRACT

A numerical analysis was executed utilizing Analysis of Microelectronic and Photonic Structures (AMPS 1D) simulator to explore the possibility of higher efficiency and stable $Zn_xCd_{1-x}S$/CdTe cells among several cell structures with indium tin oxide (ITO) and cadmium stannate (Cd_2SnO_4) as front contact, zinc stannate (Zn_2SnO_4) and zinc oxide (ZnO) insertion as buffer layer and antimony telluride (Sb_2Te_3) insertion with Nickle (Ni) as back contact was conducted in the conventional (SnO_2/CdS/CdTe/Ag) CdTe cell structures in which CdS is replaced by zinc cadmium sulphide ($Zn_xCd_{1-x}S$) as window layer. Efficiency as high as 18.0% has been found with 80 nm of $Zn_xCd_{1-x}S$ window layer for x=0.05, 1 μm of CdTe layer and 100 nm Zn_2SnO_4 buffer layer without Sb_2Te_3 back contact. However, ZnO insertion shows low conversion efficiency of 7.84% and 12.26%, respectively with and without Sb_2Te_3 back contact. Moreover, it was found that the cell normalized efficiency linearly decreases with the increasing operating temperature at the temperature gradient of -0.25%/°C.

Keywords:Zn_2SnO_4, buffer layer, $Zn_xCd_{1-x}S$, AMPS1D

1. INTRODUCTION

Thin film polycrystalline cadmium telluride (CdTe) based solar cell is one of the most potential candidates for photovoltaic energy conversion. It showed long-term stable performance (Romeo *et al,* ,1999; Batzner *et al.,* 2001) and high efficiency (Wu. *et al.* 2001; Amin *et al.,* 2002; Ferekides *et al.,* 1993) under AM1.5 illumination for terrestrial usage. Moreover, CdTe has a direct optical bandgap of 1.45 eV which is very close to the optimum bandgap for solar cells. Accordingly, the thickness required for an absorption layer of CdTe cells makes the price of material relatively low (Amin *et al.,* 1999; Amin *et al.,* 2007). However, homojunction CdTe solar cells have not shown encouraging efficiencies because of the short optical absorption length and the complexity of establishing a shallow junction with a high conductivity surface layer. Hence, these types of solar cells are usually heterojunction structures in which a transparent conducting semiconductor (window layer) is used as the hetero partner. Cadmium sulfide (CdS) has been found to be best matched for thin film CdTe solar cells. However, it is not indication that it is the only best. The bandgap energy of CdS is comparatively small for CdS/CdTe solar cells, since 100nm CdS layer absorbs more than 35% of the incident photons with energy higher than 2.42 ev and there exists too much pinholes in CdS film of ≤100nm which causes significant amount of forward leakage current. consequently, the conversion efficiency of the cells decreases. Thus, wide and variable band-gap window layers are desirable. $Zn_xCd_{1-x}S$ is attaining prominence as good candidate for wide band-gap material in the field of optoelectronic devices. Its bandgap can be tailored from 2.42 eV (CdS) to 3.6 eV (ZnS) and it affords a more transparent window layer without compromising the thickness which considerably decreases the absorption of incident photons although the thickness of $Zn_xCd_{1-x}S$ is ≤100nm. The n-type $Zn_xCd_{1-x}S$ compounds have been applied as a window layer to form heterojunction solar cell with different p-type materials such as Si (Abouelfotouh *et al.,* 1982), Cu_xS (Chandrasekhar *et al.,* 1985), $CuInSe_2$ (Ram *et al.,* 1986), $CuGaSe_2$ (Reddy *et al.,* 1992), Cu(In,Ga)Se_2 (CIGS) (Bhattacharya *et al.,* 2006) and CdTe (Oladeji *et al.*, 2000).

Still, there are major scopes to enhance the efficiency of CdTe solar cells in balancing the effects of $Zn_xCd_{1-x}S$ with different buffer layers, front and back contacts on cell output parameters by improving open circuit voltage (*Voc)*, short circuit current density (*Jsc)* and fill factor (*FF*). In this analysis, the conventional superstrate structure SnO_2/CdS/CdTe/Ag (Gloeckler *et al.,* 2003) was modified and investigation was performed for several modified structures by inserting different front and back buffer layers, front and back contacts by replacing window layer CdS with $Zn_xCd_{1-x}S$. Five layers were emphasized in the modified structures: a transparent and conducting oxide (TCO) which acts as a front contact, a n- $Zn_xCd_{1-x}S$ film which is the so-called window layer, buffer layers in between TCO and window layer, a p-CdTe film which is the absorber layer made on top of window layer and the back contact on top of the CdTe layer. A little bit of pinholes may be formed in $Zn_xCd_{1-x}S$ window layer but it can be fully removed by inserting a very thin resistive buffer layer in between TCO and window layer. The formation of pinholes is not as excessive as in CdS window layer in CdS/CdTe solar cells when the CdS layer thickness is reduced to <100 nm to enhance the blue response and the pinholes can't be fully eliminated by incorporating a thin resistive buffer layer. In addition, buffer layer improves window layer film morphology and ultimately increases conversion efficiency of the CdTe devices (Arturo *et al.,* 2006). The stability of the cells can be improved by applying stable back surface reflectors (BSR) like Sb_2Te_3. There are few reports about the application of $Zn_xCd_{1-x}S$ film for CdTe solar cells. Hence, in this study a systematic investigation of the junction structure, electrical and photovoltaic properties of $Zn_xCd_{1-x}S$/CdTe solar cells are reported through simulation. We have designed and modeled several cell structures by implementing all of the above ideas utilizing AMPS 1D simulator aiming to achieve the best possible structure for $Zn_xCd_{1-x}S$/CdTe PV for optimum value of x which showed low resistivity of $Zn_xCd_{1-x}S$ film.

2. MODELING AND SIMULATION

The distinctive superstrate structure of $Zn_xCd_{1-x}S$/CdTe solar cell and the modified structure to analyze of different buffer, front and back contact materials proposed in this analysis to explore the effect of electric field on the performance of the cells is shown in Fig. 1.

It is apparent from Fig. 1 that in the modified cell structure CdS window layer was replaced by $Zn_xCd_{1-x}S$ to explore effect of Zn concentration on cell output parameters such as open-circuit voltage (*Voc*), short-circuit current (*Jsc*) and fill factor (*FF*). Besides, the modified structure has TCO layer (ITO/Cd_2SnO_4) and buffer layer (ZnO/Zn_2SnO_4) in between glass substrate and $Zn_xCd_{1-x}S$ window layer at the back contact Ni with Sb_2Te_3 or Ag has been inserted. In this work, AMPS-1D was used to analyze the performance of the different cell structures possibilities of higher conversion efficiency. Four basic layers that have been focused in

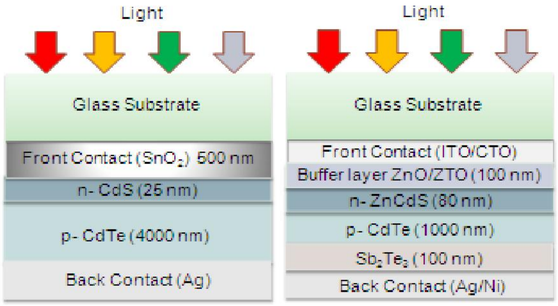

Fig. 1 Structures of the CdTe solar cells:
(a) Conventional structure and (b) modified structure

Table 1 Material parameters for simulation of ZnxCd1-xS/CdTe solar cells.

Paramers	n-Zn_2SnO_4	n-$Zn_xCd_{1-x}S$(x=0.05)	p-CdTe	p-Sb2Te3
Thickness (um)	0.10	0.1	1.00	0.10
Dielectric coefficien	9.0	9.3	9.4	55
Electron mobility (cm^2/Vs)	32	100	500	1094
Hole mobility(cm^2/Vs)	3	40	60	320
Acceptor concent. (cm^{-3})	0	0	10^{17}	$6.8x10^{19}$
Donor (cm^{-3})	10^{19}	3.0×10^{16}	0	0
Bandgap (E_g)	3.35	2.48	1.50	0.30
Density states CB (cm^{-3})	$1.8x10^{19}$	2.1×10^{18}	$7.5x10^{17}$	$1.0x10^{15}$
Density states VB (cm^{-3})	$2.4x10^{18}$	1.7×10^{19}	$1.8x10^{18}$	$1.0x10^{16}$
Electron Affinity (eV)	4.50	4.47	4.28	4.15

this modeling are the front contact layer (ITO/Cd$_2$SnO$_4$), buffer layer (ZnO/Zn$_2$SnO$_4$), n-Zn$_x$Cd$_{1-x}$S layer, and p-CdTe layer. Table 1 shows the arrangement of all the material parameters used in this modeling which are extracted from (Razykov, 1985; Hossain *et al.,* 2011a).

In our preceding work (Hossain *et al.,* 2011a) we have found that 1 µm CdTe films are sufficient for fully absorption of potential photons and 80 nm Zn$_x$Cd$_{1-x}$S window layer together with suitable buffer layer for high efficiency Zn$_x$Cd$_{1-x}$S /CdTe solar cells. In this work, we have investigated seven different structures to inspect cell performances and effect of electric field on high efficiency Zn$_x$Cd$_{1-x}$S/CdTe PV for optimum value of x.

Table 2 Different cell structures and cell output parameters

Structure	Voc (V)	Jsc(mA/cm^2)	FF	Eff. (%)
Structure A1 (ITO/Zn$_{0.05}$Cd$_{0.95}$S/CdTe/Ag)	0.956	25.031	0.775	17.2
Structure A2 (CTO/Zn$_{0.05}$Cd$_{0.95}$S/CdTe/Ag)	0.957	25.061	0.776	17.9
Structure A3 (CTO/ZnO/Zn$_{0.05}$Cd$_{0.95}$S/CdTe/Ag)	1.17	19.75	0.565	12.3
Structure A4 (CTO/ZTO/Zn$_{0.05}$Cd$_{0.95}$S/CdTe/Ag)	0.957	25.5	0.777	17.9
Structure A5 (CTO/Zn$_{0.05}$Cd$_{0.95}$S/CdTe/Sb2Te3/Ni)	0.975	25.559	0.7	16.4
Structure A6 (CTO/ZnO/Zn$_{0.05}$Cd$_{0.95}$S/CdTe/Sb2Te3/Ni)	0.884	18.945	0.55	7.84
Structure A7 (CTO/ZTO/Zn$_{0.05}$Cd$_{0.95}$S/CdTe/Sb$_2$Te$_3$/Ni)	0.975	25.592	0.71	16.5

3. RESULTS AND DISCUSSIONS

The conventional SnO$_2$/CdS/CdTe solar cell (Gloeckler et *al.,* 2003) was analyzed by AMPS-1D simulator initially by replacing CdS with Zn$_x$Cd$_{1-x}$S and SnO$_2$ with ITO as well as inserting different TCO, buffer layer and back contact. It was noticed that for low concentration of Zn (x ≤ 10%), the conversion efficiency (Eff), *Voc*, and *FF* are higher than for high content of Zn (> 10%) and *Jsc* was increased for x=0 to x=0.1 and almost same up to x=0.35 then started to decrease up to x=1. The electrical resistivity of Zn$_x$Cd$_{1-x}$S layer increases from 1 Ω-cm (x=0) to 10^{10} Ω-cm (x=1) (Razykov *et al.,* 1985; Hussain *et al.,* 1991). In consideration to fabrication challenges, resistivity of Zn$_x$Cd$_{1-x}$S film and simulation results in this work, x=0.05 was selected which exhibited low resistivity and high conversion efficiency in comparison to other values of x. In the following text, Zn$_x$Cd$_{1-x}$S window layer was swapped as Zn$_{0.05}$Cd$_{0.95}$S for our proposed cell structures.

The different cell structures and the cell output parameters (*Voc*, *FF* and J_{SC}) for individual structure through AMPS 1D simulation using the material parameters of Table 1, are shown in Table 2.

The efficiency *Voc*, *FF* and J_{SC} of each structure are assimilated in Fig. 2. It is clear from Fig. 2 that the cell structures containing ZnO are showing deprived performance.

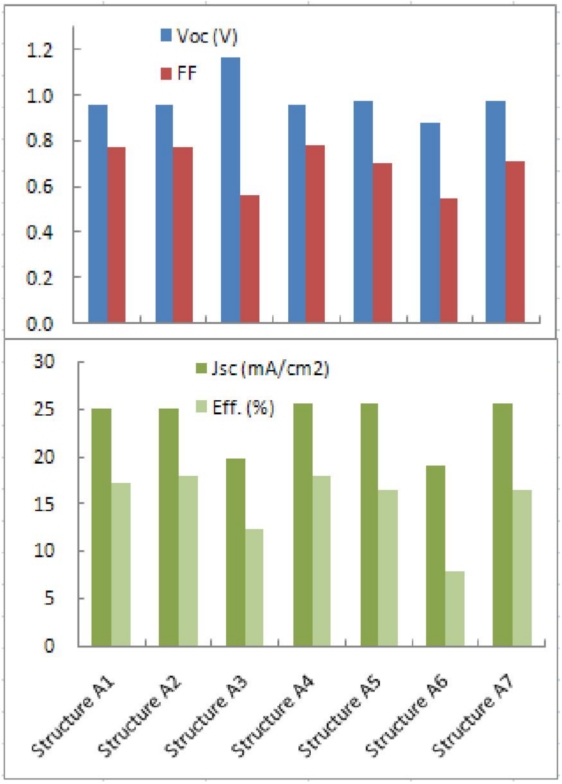

Fig. 2 Performance of all cell structures

To assist high efficiency $Zn_{0.05}Cd_{0.95}S$/CdTe PV the $Zn_{0.05}Cd_{0.95}S$ window layer has been reduced to 80 nm but thin $Zn_{0.05}Cd_{0.95}S$ layer (<100nm) may allow a small amount of forward leakage current to front contact through some pinholes of the thinner $Zn_{0.05}Cd_{0.95}S$ layer which is significantly less than the leakage current in CdS layer in comparison to CdS/CdTe solar cell (Amin *et al.,* 2010). In order to eliminate this leakage current a high resistive Buffer layer of suitable material must be inserted in between front contact TCO and $Zn_{0.05}Cd_{0.95}S$ window layer. It is possible to get benefit of the different properties of two TCOs by forming a buffer layer. High-efficiency CdTe and CIGS devices are usually fabricated with such buffer layer structures consisting of a highly conducting layer for low-resistance due to contact and lateral current collection and a much thinner high-resistivity buffer layer of an appropriate material to minimize leakage current through some possible pinholes in the $Zn_{0.05}Cd_{0.95}S$ window layer. By inserting a 100 nm thick resistive ITO, ZnO, or Zn_2SnO_4 layer, the $Zn_{0.05}Cd_{0.95}S$ layer thickness can be reduced <100 nm, which significantly improves the blue response of the $Zn_{0.05}Cd_{0.95}S$/CdTe devices. The insertion of the smoother high-resistive buffer layer also improves the $Zn_{0.05}Cd_{0.95}S$ film morphology. Among many potential buffer layer materials ZnO and Zn_2SnO_4 were implemented in this work. ZnO and Zn_2SO_4 were included as a buffer layer with its parameters as in Table I. The Zn_2SnO_4 buffer layer insertion provides better result than ZnO insertion. It was also investigated that the spectral response has no effect on QE for Zn_2SnO_4 thickness variation from 50 nm to 500 nm. In consideration of fabrication limitation, the thickness of Zn_2SnO_4 buffer layer was selected as 100 nm.

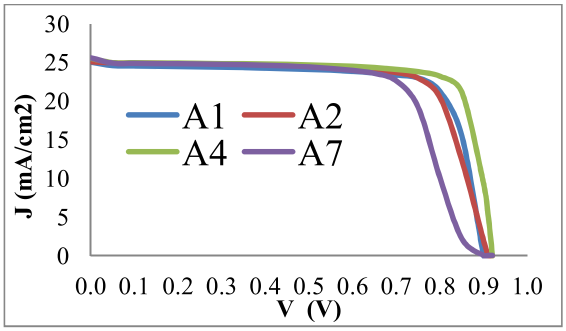

Fig. 3 The J-V curves for selected structures

The J-V curve for selected cell structures which are shown in Table 2, when utilizing all the material parameters with 80 nm $Zn_xCd_{1-x}S$ (x=0.05) and CdTe layer thickness of 1 µm is shown in Fig. 3. Structures A1, A2, A4 without BSF showed higher *Jsc* and *Voc* with good *FF* which in turn showed higher efficiency in comparison to other structures. The lowest *Voc* of structure A6 is due to combined effect of ZnO and Sb_2Te_3 in comparison to structure A3 which showed highest *Voc*. The existence of roll over was found in some of the structures with Sb_2Te_3.

The band diagram of some structures (A2, A4, A7) is plotted in Fig.4 which showed high efficiency and *Jsc* as point out in Table 2. The band discontinuity of 0.23 eV at $Zn_{0.05}Cd_{0.95}S$/CdTe junction is found. There is a rectifying back contact with Ag material in structure A2 which may be responsible for rollover of the cell. The electron rectifying potential caused by Sb_2Te_3 BSR in the structure A7 can also be seen from Fig. 4.

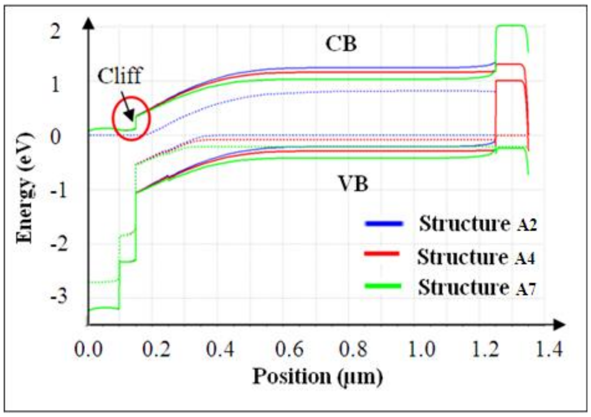

Fig. 4 The band diagram of some selected structures

Operating temperature plays important role for affecting the performance of the solar cells. At higher operating temperature, parameters such as the electron and hole mobility, carrier concentrations and band gaps of the materials are affected, which was explored in this analysis An investigation was also performed utilizing AMPS with operating temperature ranged from 27°C to 100°C to understand the effects on the cell performance for the cell structures of CTO/ZTO/$Zn_{0.05}Cd_{0.95}S$/CdTe/Sb_2Te_3/Ni and CTO/ZTO/$Zn_{0.05}Cd_{0.95}S$/CdTe/Ag, as shown in Fig. 5.

It is clear from the Fig. 4 that the conversion efficiency linearly decreased with the increase of operating temperature at a temperature coefficient (TC) of -0.25%/°C which also indicated the degree of stability of the cell with BSR at higher operating temperature. This result is in good agreement with the related work (Hossain *et al.,* 2011b, 2011c).

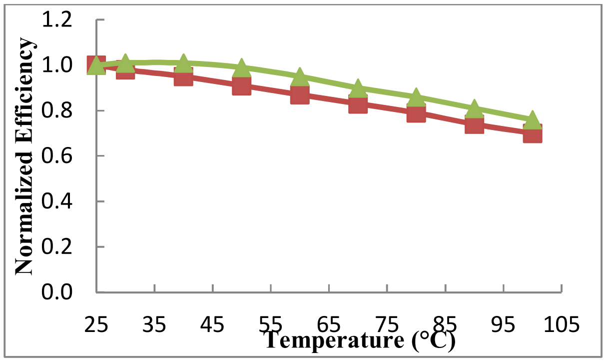

Fig. 5 Effect of temperature on structure A1 and A7

4. CONCLUSIONS

This work outcomes the best structure: A4 (CTO/ZTO/$Zn_{0.05}Cd_{0.95}S$/CdTe/Ag) in considering efficiency and good cell output parameters. If we consider the stability of the cell at higher operating temperature then the structure A6 (CTO/ZTO/$Zn_{0.05}Cd_{0.95}S$ /CdTe/Sb_2Te_3/Ni) is the best although it exhibited the lowest efficiency that was achieved from this numerical study. The computed operating temperature gradient provides some valuable hints to fabricate higher efficiency and stable $Zn_{0.05}Cd_{0.95}S$/CdTe solar cells with standard fabrication techniques which are comparable to any other reported cells.

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