Chalcogenide Letters Vol. 8, No. 3, March 2011, p. 263 - 272

A NUMERICAL STUDY ON THE PROSPECTS OF HIGH EFFICIENCY ULTRA THIN $Zn_xCd_{1-x}S$/CdTe Solar Cell

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In this study, a new CdTe solar cell structure was proposed, where Zinc Cadmium Sulfide ($Zn_xCd_{1-x}S$) was used as window layer with an added advantage of variable bandgap. By varying the composition of the zinc content, the bandgap was varied between 2.42- 3.7 eV, thereby increasing the cell's performance in the lower wavelength region, resulting in higher efficiency. The CdTe absorber layer was decreased to the extreme limit of 1 µm and at this thickness the proposed cell has shown acceptable range of efficiency. Moreover, the thickness of $Zn_xCd_{1-x}S$ window layer was reduced to 60 nm with a suitable buffer layer either with zinc oxide (ZnO) or zinc stannate (Zn_2SnO_4) to prevent forward leakage current of ultra thin $Zn_xCd_{1-x}S$ layer. The Analysis of Microelectronics and Photonics Structures (AMPS) 1-D software was used to simulate and analyze the cell's performance (efficiency, *FF*, *Voc*, *Jsc*, temperature stability) with different variables. The results have shown that an efficiency of up to 19.5% is feasible of cost-effective ultra-thin $Zn_xCd_{1-x}S$/CdTe solar cell structure with 1 µm of CdTe, 60 nm of $Zn_xCd_{1-x}S$ and 100 nm of ZnO or Zn_2SO_4 buffer layers. The cells stability with temperature and other material properties was also studied and analyzed.

(Received March 28, 2011; Accepted April 20, 2011)

Keywords: - CdTe thin film solar cells, $Zn_xCd_{1-x}S$, AMPS 1D, ultra-thin, stability.

1. Introduction

Solar cells based on thin films of polycrystalline materials are very promising in order to achieve better efficiency/cost ratios than the other counterparts. Among the thin film cells, CdTe based solar cells is the most promising candidate for photovoltaic energy conversion because of the high potentiality to realize low cost, high efficiency, reliable and stable solar cells. Firstly, the CdTe cell is produced from polycrystalline materials on glass, which are potentially much cheaper and involve simpler processes. Secondly, the polycrystalline layers of a CdTe solar cell can be deposited using a variety of different low cost techniques, such as close-space sublimation (CSS), chemical vapor deposition (CVD), chemical bath deposition (CBD), and sputtering [1]. Thirdly, CdTe has a high absorption coefficient of over 5×10^5/cm, which means that all the potential incident photons with energy greater than the bandgap will be absorbed within the first few microns of CdTe absorber layer [2]. And finally, CdTe has a direct optical bandgap of 1.45 eV which is very close to the optimum bandgap for solar cells. Hence, the thickness required for an absorption layer of CdTe cells makes the cost of material relatively low [3, 4]. Clearly one of the main goals of today's solar cell research is using less semiconductor material by making the cells

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thinner. Thinning will not only save material, but will also reduce the recombination loss as well as lower production time, and the energy needed to produce them. All of these factors will decrease the production cost. Moreover, the CdTe thin film solar cells have shown long-term stable performance [5] and high efficiency [6, 7, 8] under AM1.5 illumination for terrestrial usage.

However, conversion efficiencies of homojunction CdTe solar cells have not shown encouraging results. Thus, heterojunction cell structure with wide and variable band-gap n-type semiconductor ($Zn_xCd_{1-x}S$) and p-CdTe creates research interest in recent years. $Zn_xCd_{1-x}S$ is gaining 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). The ternary n-type $Zn_xCd_{1-x}S$ compounds have been used as a window layer to form heterojunction solar cell with different p-type materials such as Si [9], Cu_xS [10], $CuInSe_2$ [11], $CuGaSe_2$ [12], $Cu(In,Ga)Se_2$ (CIGS) [13] and CdTe [14]. As a promising photovoltaic absorber material for thin film solar cells, CdTe commonly forms junction with CdS. The highest efficiency of the laboratory-device in 2004 has reached 16.5% [2]. However the CdS window layer has a lower bandgap, which causes considerable absorption in the short-wavelength region (below 500 nm). To maximize the blue response in CdS/CdTe solar cells, the CdS thickness is usually kept to a minimum, typically ≤ 100 nm so that higher short circuit current (*Jsc*) can be achieved. However, reducing the CdS thickness can adversely impact device open-circuit voltage (*Voc*) and fill factor (*FF*) due to the consumption of the CdS layer and excessive pinhole formation. Developing an alternative window layer with a higher band-gap 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 short-wavelength region. As demonstrated by Oladeji et al. [14] and several other researchers [15, 16], the spectral response in the blue region (400-600 nm wavelength region) can be significantly improved using $Zn_xCd_{1-x}S$/CdTe cell structures. The substitution of $Zn_xCd_{1-x}S$ instead of CdS in a CdS/CdTe heterojunction solar cell results no enrgy spike in the conduction band of the heterojunction. Moreover, $Zn_xCd_{1-x}S$ films can be deposited in various ways: Vacuum evaporation [17], metal organic chemical vapor deposition (MOCVD) [18], spray pyrolysis [19], successive ionic absorption and reaction (SILAR) [20], photochemical deposition [21] and chemical bath deposition [22]. The publication of Yin et al. [19] reported on $Zn_xCd_{1-x}S$/CdTe junctions in which the zinc concentration was chosen to be around 10%. Oladeiji's et al. [14] showed improved Quantum Efficiency (QE) compared to CdS device. However, there are still major rooms for improvement in balancing the effects of $Zn_xCd_{1-x}S$ on cell output parameters *Voc*, *Jsc* and *FF* for optimum composition of Zn and Cadmium (Cd) by modified design using standard numerical technique. 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. It is a useful tool to explore the performance of a solar cell of certain design and thus examine its viability. Numerical simulations for solar cells are done through solving the basic equations related to semiconductors like Poisson's equation, continuity equations for free electrons and free holes, etc. Given the complex nature of $Zn_xCd_{1-x}S$/CdTe thin film polycrystalline solar cells, the need for numerical modeling is apparent. Numerical simulations give insight into the mechanism of structures, thereby enabling the design of new structures with better efficiency and performance. Many researchers have carried out simulations with CdTe based solar cells, and a list can be found in the references given in the review by M. Burgelman et al. [23].In this work, the strategies for improving $Zn_xCd_{1-x}S$/CdTe cell performance were explored utilizing AMPS 1D simulator [24].

2. Analysis of conventional and modified structures

To demonstrate the influence of the ultra thin layers on the characteristics of a $Zn_xCd_{1-x}S$/CdTe solar cell, the study started from a set of baseline parameters of $Zn_xCd_{1-x}S$/CdTe cells, and then varies a few selected parameters, while all other parameters retain their baseline values. Before modeling novel CdTe cell structures, following issues of conventional CdTe cells were addressed. High-efficiency CdTe devices are generally fabricated with a buffer layer structure. In this work, a highly conducting layer of Indium tin oxide (ITO) was used for front contact and a much thinner highly-resistive layer of suitable TCO material was used for buffer layer. CdTe cells usually have lower open circuit voltage (V_{oc}) than their counterparts like CIGS or

CIS cells. The *Voc* of the cells can be improved by higher carrier density of CdTe (~10^{15} cm^{-3}) and higher absorber lifetime (>1 ns) and by reducing the back-contact barrier height. The fill factor (FF) might be improved by reducing the thickness of CdTe absorber material whose usual value is 5-10 µm. The short circuit current density (*Jsc*) of the cell can be improved by replacing CdS with $Zn_xCd_{1-x}S$ and by reducing the carrier recombination loss at the back contact with inserting suitable back surface reflector (BSR).

The starting point of this work was the base line case as reported by Gloeckler et al. [25]. This structure was modified with appropriate front contact and BSR. Fig. 1 illustrates the schematic of the proposed ultra thin $Zn_xCd_{1-x}S$/CdTe cell [Glass/ITO/ZnO or (Zn_2SnO_4)/$Zn_xCd_{1-x}S$/CdTe/Cu_2Te/Ni] modified from the baseline cell for higher conversion efficiency.

As can be seen in Fig. 1, the modified structures have an extra layer (ZnO or Zn_2SnO_4) between ITO and $Zn_xCd_{1-x}S$ window layer to support ultra-thin $Zn_xCd_{1-x}S$ window layer for better performance. Thus, the front contact consists of ITO along with a buffer layer. The doping concentration used in the baseline case (~10^{14} cm^{-3}) has been changed to ~10^{15} cm^{-3} for achieving higher efficiency as discussed before. To investigate the back contact issue and stability problem back contact material Nickle (Ni) and BSR (Cu_2Te) have been inserted in the modified cells. Considering the simplicity and low cost feature, Ni is used as back contact material with back contact barrier height (Φ_{bL}) of 1.25 eV in the proposed cell. The polycrystalline cells are complicated in structures, and the effects of some particular phenomenon, mechanism or materials parameter are often beyond perception or simple rules of a thumb. Numerical simulation can then be used to provide insight, to interpret measurements and to assess the potential merits of a proposed cell structure. Numerical simulation programs for solar cells are matured and are available to the research community to assist in interpreting the electrical and the optical behavior of the proposed structure. Solar cell simulation could be useful for time saving and cost consumption [26]. The number of parameters that can be varied in a particular solar-cell model is larger than 50 [23]. Values of these parameters depend on fabrication techniques, deposition methods, ambient condition etc. However, a model with 50 variables is inherently unreliable and as such it is necessary to fix many of these parameters at reasonable values. In this work, AMPS 1D simulator was used to explore the conventional CdTe baseline cell and modified cells for achieving ultra thin CdTe and $Zn_xCd_{1-x}S$ layers with higher conversion efficiency. The AMPS program has been developed to realistically simulate the electrical characteristics of the thin-film heterojunction solar cells. It has been tested for thin film CdTe and CIGS solar cells [23].

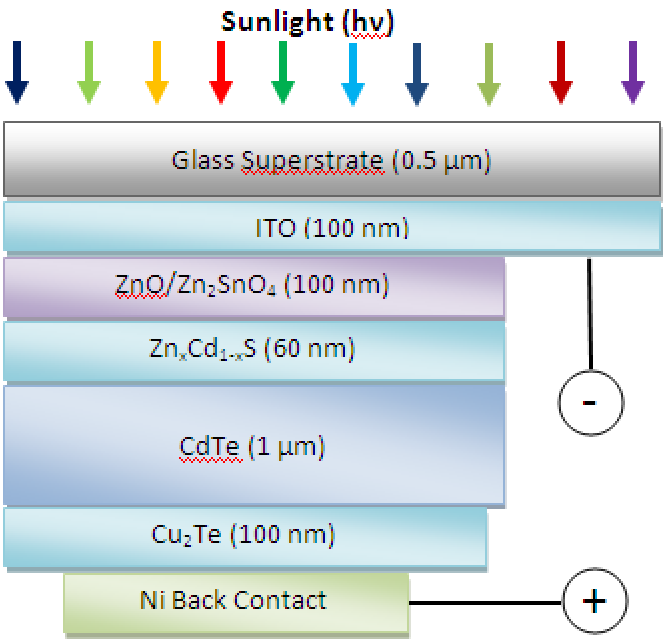

Fig. 1: Schematic structure of the proposed ultra thin $Zn_xCd_{1-x}S$/CdTe solar cell.

Table 1: Material parameters used in the numerical analysis for the $Zn_xCd_{1-x}S$/CdTe cell.

Parameter	n-ZnO/n-Zn_2SnO_4	n-$Zn_xCd_{1-x}S$ (x=0.05)	p-CdTe	Cu_2Te
Thickness, W (µm)	0.01-0.5	0.02-0.2	0.2-7.0	0.1-0.5
Dielectric ratio, $\varepsilon/\varepsilon_o$	9.0	9.3	9.4	10
Electron mobility, μ_n (cm^2/Vs)	100/32	100	320	500
Hole mobility, μ_p (cm^2/Vs)	25/03	40	40	100
Carrier concentration, n/p (cm^{-3})	10^{19}	3×10^{16}	5×10^{15}	10^{21}
Bandgap, E_g (eV)	3.0/3.35	2.48	1.45	1.18
Density of states, N_C (cm^{-3})	2.2×10^{18}	2.1×10^{18}	8.0×10^{17}	7.8×10^{17}
Density of states, N_V (cm^{-3})	1.8×10^{19}	1.7×10^{19}	1.8×10^{19}	1.6×10^{19}
Electron affinity, χ (eV)	4.35/4.50	4.47	4.28	4.20

Four basic layers that were emphasized in this modeling are the buffer layer (ZnO/Zn_2SnO_4), n-$Zn_xCd_{1-x}S$ layer, p-CdTe layer and BSR (Cu_2Te) layer. Table 1 shows the values of the cell parameters used in this work. Table 1 shows the cell parameters used in this work. These values were chosen on the basis of theoretical considerations, experimental data and existing literature or in some cases reasonable estimations. In this modeling, the CdTe layer thickness from 20 nm to 7 µm, $Zn_xCd_{1-x}S$ window layer thickness from 20 nm to 0.2 µm and ZnO and Zn_2SnO_4 buffer layer thickness from 10 nm to 0.5 µm was varied by keeping all other parameters in fixed values of Table 1 aiming to reach the efficient and thinner $Zn_xCd_{1-x}S$/CdTe solar cell.

3. Results and discussion

AMPS 1-D simulation was done to find the appropriate concentration of Zn and Cd using the number of variable parameters related to electrical and optical behavior of $Zn_xCd_{1-x}S$ which was adopted from [15, 27, 28, 29, 30]. It was observed that for x=0.05 the efficiency is highest for reasonable values of cell output parameters (*Voc*, *Jsc* and *FF*) A three layer device model of baseline case (SnO_2/CdS/CdTe) is the starting point for the analysis of ultra thin cell and it was slightly modified to explore the possibility of efficient and thinner cells. In this work, first of all the conventional CdTe baseline structure (SnO_2/CdS/CdTe) [26] was investigated and a conversion efficiency of 14.03% (*Voc* = 0.82 V, *Jsc* = 24.47 mA/cm^2, FF = 0.69) was found with 4 µm CdTe absorber layer, 100 nm-CdS window layer and with Ag back contact (Φ_{bL}=1.35 eV). It was found that the conversion efficiency increases up to 15.94% (*Voc* = 0.82 V, *Jsc* = 30.17 mA/cm^2, FF = 0.70) by replacing CdS with $Zn_xCd_{1-x}S$ for x=0.05. Moreover, numerical simulation has been done by adopting CdTe doping concentration (5×10^{15}) and higher life time (1.5 ns) parameters and a conversion efficiency 18.39% (*Voc* = 0.89 V, *Jsc* = 30.41 mA/cm^2, FF = 0.75) has been achieved which mainly improves *Voc* and FF. Theoretically the minimum thickness required for CdTe films to absorb 99% of the incident photons with energy greater than E_g is approximately 1-2 µm [2, 4]. To date almost all the high efficiency CdTe solar cells have been fabricated with more than 5 µm thick CdTe absorber layer. However, further numerical analysis has been performed aiming to conserve the material required and cost of $Zn_xCd_{1-x}S$/CdTe solar cells by reducing the thickness of CdTe and $Zn_xCd_{1-x}S$ layers. The CdTe thickness was varied from 20 nm to 7 µm to explore thinner absorber layer and the results obtained from the AMPS simulation are shown in Fig. 3.

It is clear from the figure that all the cell output parameters are almost constant above the CdTe thickness of 1.5 µm. The short circuit current density (*Jsc)* slowly decreased but the *Voc* and *FF* remained unaffected with reduction of CdTe thickness from 1.5 µm to 1 µm. Below 1 µm of

CdTe absorber all the cell output parameters were decreased drastically as the minority carrier diffusion length is about 1 µm for this material system. As a consequence, the conversion efficiency showed very slow decreasing trend with the reduction of CdTe thickness until 1 µm but below 1 µm of CdTe thickness the cell output parameters decreased quickly. Thus, it indicates that 1 µm thick CdTe cell is possible with a small decrease or loss in efficiency than the thicker cell. A conversion efficiency of 17.6% (Voc = 0.89 V, Jsc = 29.25 mA/cm^2, FF = 0.743) was achieved for 1 µm thick CdTe cell, which shows compromise of efficiency is only about 0.8% (18.39% to 17.6%) with 25% CdTe absorber material from the baseline case. These results are in good agreement with related literatures [3, 31, 32].

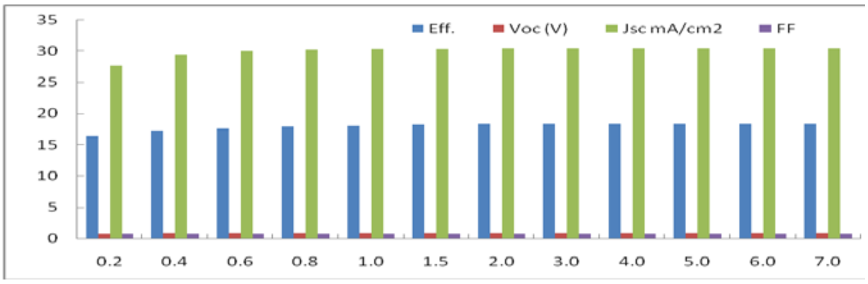

Fig. 3: Effect of CdTe film thickness on the cell output parameters.

The spectral response (SR) with different CdTe absorber layer thickness is shown in Fig. 4. It is evident that the SR starts decreasing at the operating wavelength of 460 nm until 820 nm with decreases of the CdTe layer thickness. It also signifies that the thicker CdTe layer has higher SR and higher conversion efficiency; thicker CdTe absorber layer means more CdTe materials required and more cost involves. Thickness reduction of the CdTe absorber layers would not only be useful to reduce the material cost in the production process but could also lead to better solar cell properties by reducing recombination losses in the bulk [4]. However, control of the film growth and recrystalsation due to post-deposition treatment is necessary to obtain thin films which are compact and free of pinholes. Recrystallisation is known to be critically affected for example by the type and structure of the front contact material [33] or the deposition temperature [34]. Employing the CSS technique; this is the best technique of deposition the CdTe layer as it provides high rates and good film quality while the material yield is very high. CSS-CdTe films can consist of large grains being useful for the electronic transport properties. However, the actual film thickness needed may be larger than the absorption depth due to the possibility of increased shunting in thinner films. Thus, considering all these consequences the CdTe layer thickness was selected at 1 µm for this investigation.

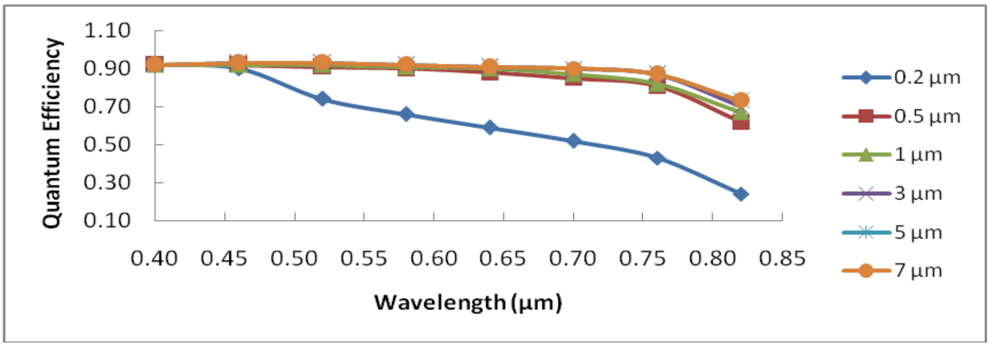

Fig. 4: Effect of CdTe thickness on the quantum efficiency.

However there are possibilities of increasing SR and cell conversion efficiency further more if the $Zn_xCd_{1-x}S$ window layer thickness (100 nm) can be reduced with proper buffer layer insertion in between front contact (ITO) and $Zn_xCd_{1-x}S$ layer. The Fig. 5 in the next page shows the effects in details of $Zn_xCd_{1-x}S$ layer thickness reduction from 20 nm to 0.2 µm on the cell output parameters from AMPS simulation, with CdTe layer thickness of 1 µm, and other values were kept at constant as shown in table 1. When the $Zn_xCd_{1-x}S$ layer thickness was reduced, the absorption loss in the blue region due to thin $Zn_xCd_{1-x}S$ layer also reduces, which improves mainly *Jsc* and consequently the cell conversion efficiency.

It is evident from Fig. 5, *Jsc* has improved greatly with reduced $Zn_xCd_{1-x}S$ layer, a bit decrease in *Voc* and FF is almost unaffected. As a result, cell conversion efficiency was increased with reduced $Zn_xCd_{1-x}S$ layer. The SR of $Zn_xCd_{1-x}S$ layer thickness variation from 20 nm to 0.2 µm was investigated through AMPS simulation and it was noticed when the wavelength was in between 400-540 nm the quantum efficiency (QE) is much affected with the increasing $Zn_xCd_{1-x}S$ layer thickness which influences the cell conversion efficiency. These results are in good agreements with other literature [32]. However, in considering fabrication challenges and to fabricate good quality cells we have selected the $Zn_xCd_{1-x}S$ film thickness of 60 nm with conversion efficiency of 17.68% (*Voc* = 0.89 V, *Jsc* = 29.35 mA/cm^2, FF = 0.744). The improvement in conversion efficiency was achieved due to the improvement of *Jsc* with reduced $Zn_xCd_{1-x}S$ layer.

However, this reduced $Zn_xCd_{1-x}S$ layer might allow forward leakage current to front contact through possible pinholes of ultra thin $Zn_xCd_{1-x}S$ layer although the pinholes is greatly reduced using $Zn_xCd_{1-x}S$ window layer instead of CdS in our proposed solar cell. In order to prevent this unwanted forward leakage current a high resistive buffer layer of suitable material must be inserted in between front contact and $Zn_xCd_{1-x}S$ layer. Further numerical analysis was done aiming to improve the conversion efficiency of the ultra thin $Zn_xCd_{1-x}S$/CdTe cell by inserting a suitable buffer layer. It is possible to take advantage of the different properties of two TCOs by forming a buffer layer. High-efficiency CIGS and CdTe devices are generally fabricated with such buffer layer structures. The modified proposed cell structure consists of a highly conducting layer (ITO) for low-resistance due to contact and lateral current collection and a much thinner high-resistivity layer (called buffer layer) of a suitable material. By incorporating a very thin resistive buffer layer, the $Zn_xCd_{1-x}S$ layer thickness can be reduced to 60 nm, which significantly improves the blue response, $Zn_xCd_{1-x}S$ film morphology and conversion efficiency of the $Zn_xCd_{1-x}S$/CdTe devices.

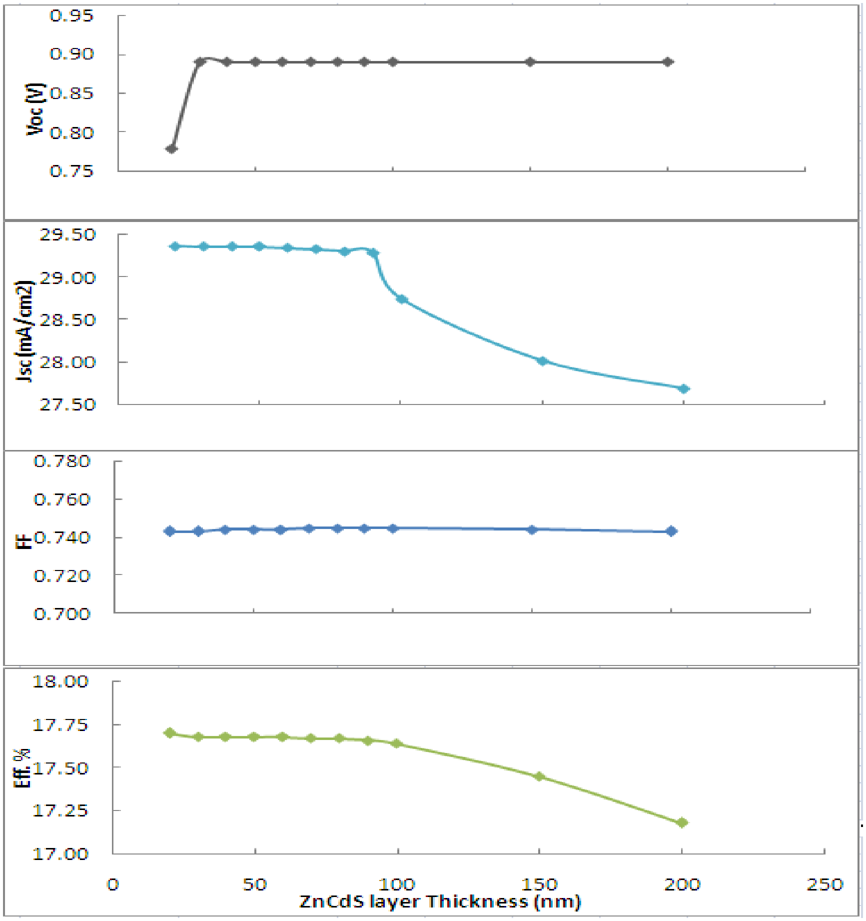

Fig. 5: Effect of the $Zn_xCd_{1-x}S$ film thicknesses on cell Output Parameters.

The presence of the smoother high-resistive buffer layer also improves the $Zn_xCd_{1-x}S$ film morphology by providing large grains during CBD process. Two potential buffer layer materials ZnO and Zn_2SnO_4 were investigated in this work. The ZnO or Zn_2SnO_4 as a buffer layers were inserted in the ultra thin $Zn_xCd_{1-x}S$/CdTe cell with CdTe layer thickness of 1 µm, $Zn_xCd_{1-x}S$ layer thickness of 60 nm and with all other cell parameter as shown in table 1. The proposed ultra thin $Zn_xCd_{1-x}S$/CdTe cells with buffer layer shows acceptable range of cell output parameters such as *Jsc*, *Voc* and FF. It was observed that the ZnO insertion shows almost the same performance as Zn_2SnO_4 buffer layer. The thicknesses variation of 20-500 nm for ZnO/Zn_2SO_4 buffer layer shows no change in the solar cell output parameters and conversion efficiency. Moreover, it was found that the SR has no effect for ZnO/Zn_2SnO_4 thickness variation of 20-500 nm. Considering the difficulties in fabrication of ultra thin layer less than 100 nm with acceptable qualities, we have selected the ZnO/Zn_2SnO_4 buffer layer thickness of 100 nm with cell conversion efficiency of 18.6% (*Voc* = 0.89 V, *Jsc* = 29.89 mA/cm^2, FF = 0.749). The improvement of efficiency was achieved from 0.64 mA/cm^2 gain of *Jsc* and a little bit gain of *FF* than without any buffer layer. Thus, the buffer layer shows higher *Jsc* and conversion efficiency along with prevention of forward shunting of the ultra thin $Zn_xCd_{1-x}S$/CdTe cells.

The formation of a stable, low resistance, non-rectifying contact to p-CdTe thin film is one of the major and critical challenges associated with this technology in the fabrication of efficient and stable solar cells [35]. A stable back contact that is not significantly rectifying and has a low resistance is essential for good performance and long term stability of $Zn_xCd_{1-x}S$/CdTe solar cells. Since CdTe is a p-type semiconductor with a high electron affinity (χ = 4.5 eV) and high band gap (1.45 eV), a high work function metal is required to make good ohmic contact to p-CdTe. Most metals, however, do not have sufficiently high work functions and therefore form Schottky-barrier contacts to CdTe absorber layer. When the Fermi-level at the metal/CdTe interface is pinned by surface states, a metal with a reasonably high work function might not make an ohmic contact. The presence of a backcontact barrier can significantly affect the current–voltage (I-V) characteristics of a CdTe cell, primarily by impeding hole transport. This mechanism is one of the causes of the current limiting effect referred to as “rollover”. Typically, metals with a high work function ($\varphi_m \geq 5.9$ eV) are required to make an ohmic contact to CdTe but mostly they do not have such high work functions to make good ohmic contacts to p-CdTe, instead tend to form Schottky, or blocking barriers [25]. A typical approach to overcome this obstacle is to either reduce the barrier height or moderate its width by heavily doping extra layer of BSR with appropriate material in between the CdTe and final metal backcontact. The specific BSR material chosen to investigate in this work are Cuprus Telluride (Cu_2Te) with Ni back contact. Further numerical analysis was done for the proposed ultra thin cell [Glass/ITO/ZnO or (Zn_2SnO_4)/$Zn_xCd_{1-x}S$/CdTe/Cu_2Te/Ni] with 1 un CdTe, 60 nm $Zn_xCd_{1-x}S$ (x=0.05), 100 nm ITO and 100nm Cu_2Te and a cell conversion efficiency of 19.34% (*Voc* = 0.92 V, *Jsc* = 30.43 mA/cm^2, FF = 0.759) was achieved. The final J-V characteristics of the proposed cell are shown in Fig. 6

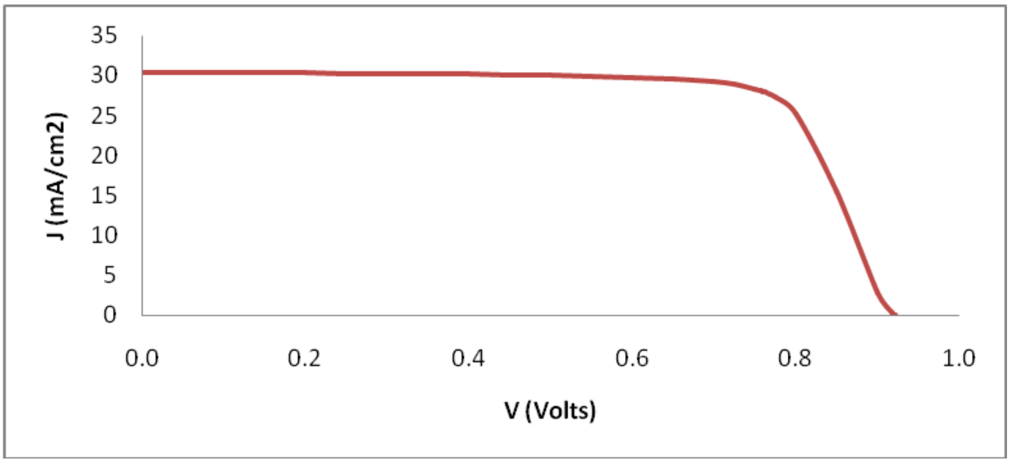

Fig.6: Final J-V characteristics of the proposed cell.

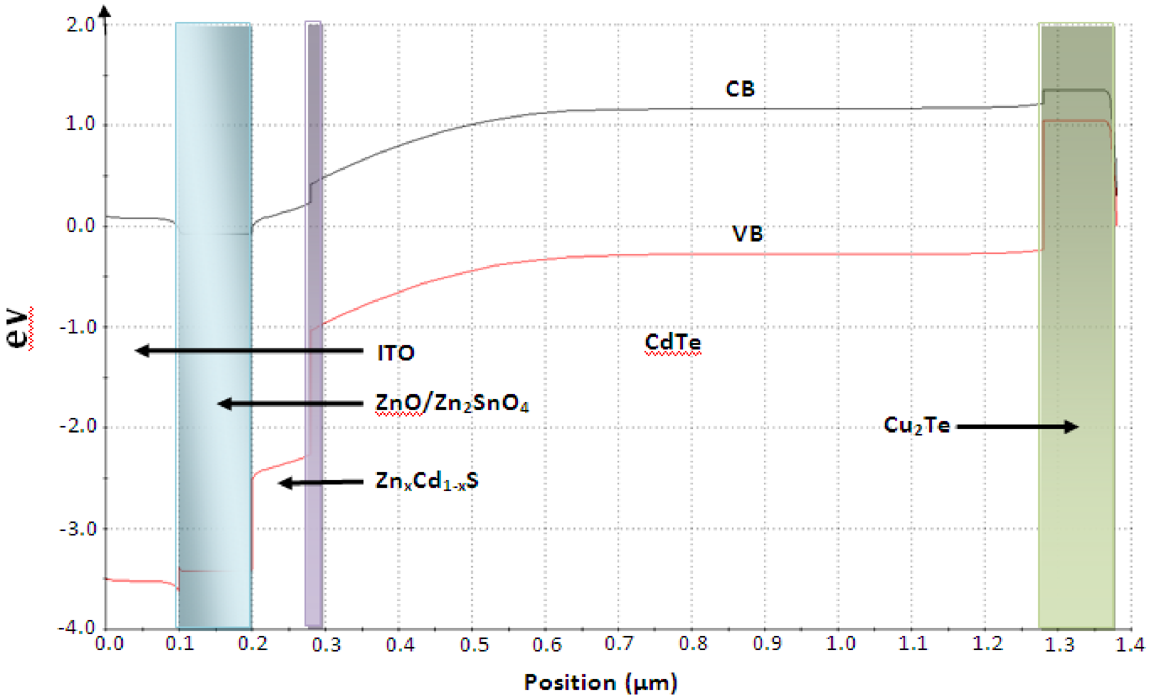

Fig. 7: The band diagram of the ultra thin proposed cell (Glass/SnO_2/ZnO/CdS/CdTe/Ag).

Fig. 7 shows the band diagram of the proposed 19.34% efficient ultra thin $Zn_xCd_{1-x}S$/CdTe cell with illumination at 0 V to investigate the band alignment and band offset. The band diagram as shown in figure indicates important features of the proposed ultra thin $Zn_xCd_{1-x}S$/CdTe cell. The front contact consists of ITO and ZnO all are well alignment in conduction band and balance band with $Zn_xCd_{1-x}S$ window layer and CdTe absorber. There is a cliff of about 0.3 eV at the conduction band of $Zn_xCd_{1-x}S$-CdTe interface, which is common and acceptable for $Zn_xCd_{1-x}S$/CdTe cells [15]. Again, there is a spike at the valance band of ZnO-ITO interface, it will work as a barrier for undesired hole flow towards the front contact. There is a negative cliff of about 0.1 eV at the conduction band of ZnO-ITO interface, which might hinder the desired electron flow to the front contact. This negative cliff can be avoided with more suitable buffer layer material with appropriate electron affinity and bandgap with the front contact material ITO or with new front contact material (CTO) which will be in the focus of our future work. One of the major differences in thin film cells compared to the thicker ones is that the absorber/back contact interface is now located closer to the p-n junction, and the choice of the back-contact materials therefore has a strong impact on the cell performance.

Fig. 8 shows the electric field distribution of the proposed ultra thin $Zn_xCd_{1-x}S$/CdTe cell with illumination at 0 V. It is clear that the cell has a negative spike at the interface of ITO and Zn_2SnO_4 or ZnO. Again there is a positive spike at the interface of $Zn_xCd_{1-x}S$ and ZnO or Zn_2SnO_4. The ZnO buffer layer produced larger spike than Zn_2SnO_4 buffer layer showing the presence of higher electric field with ZnO buffer layer.

Finally it shows the desired positive spike of 1.3 kV/cm at the p-n junction ($Zn_xCd_{1-x}S$-CdTe) with slower decreasing distribution of the electric field in the absorber layer. The electric field diminished well bellow of the selected absorber thickness, which indicates all the generated electro hole pair will be collected within the ultra thin absorber layer.

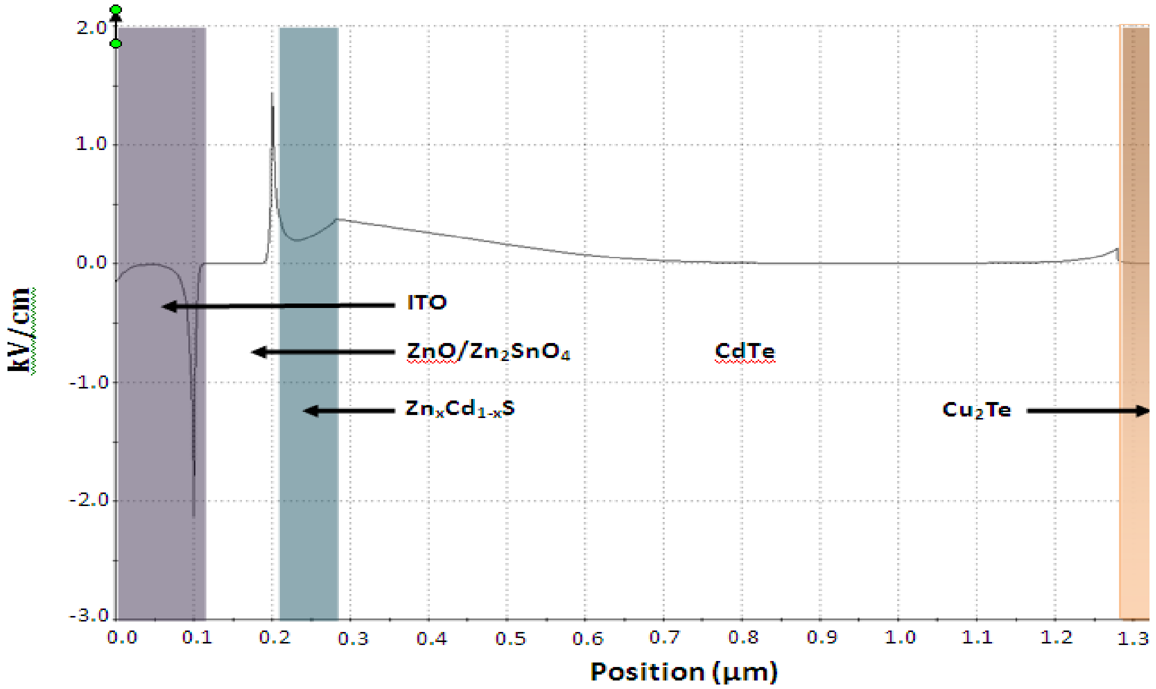

Fig. 8: Effect of electric field on the solar cell characteristics.

In real cases operating temperature plays a very important role which affects the performance and stability of the cells. At higher operating temperature, cell layers parameters such as the effective density of states, absorption coefficients, electron and hole mobility, carrier concentrations and band gaps of the materials are affected. An investigation has carried out to investigate the performance and stability of the ultra thin $Zn_xCd_{1-x}S/CdTe$ proposed cell with operating temperature ranged from 25°C to 100°C. The AMPS simulated results are shown in Fig. 9.

It is evident from the Fig. 9 that the conversion efficiency linearly decreases with increase of operating temperature at a temperature coefficient (TC) of -0.25%/°C, which also indicates the higher degree of stability of the this ultra thin cell at higher operating temperature or in stressed conditions. This is in good agreement with related works [32] of ultra thin $Zn_xCd_{1-x}S/CdTe$ cell.

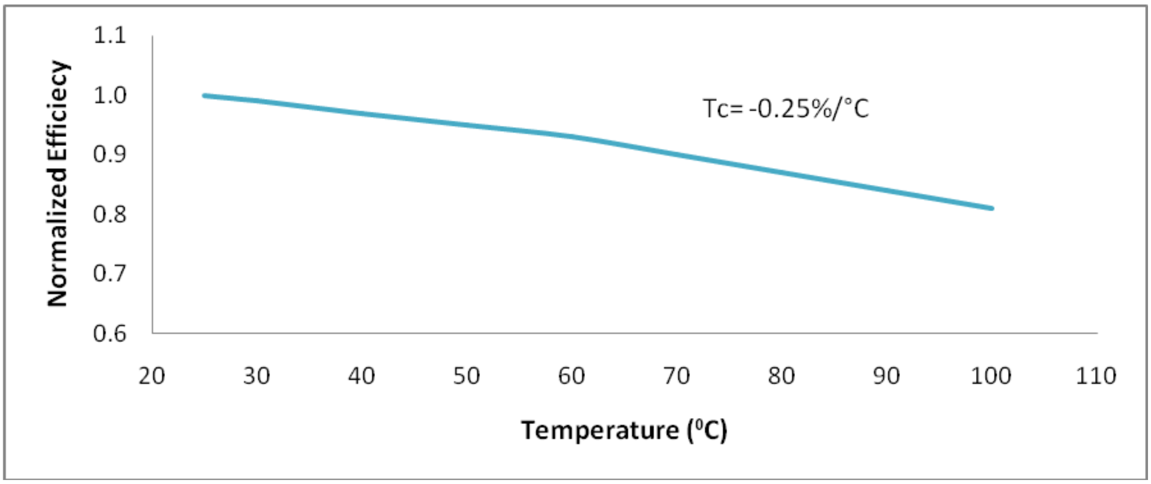

Fig. 9: Effect of operating temperature on the normalized cell efficiency.

4. Conclusions

By incorporating $Zn_xCd_{1-x}S$ (x=0.05) as a window layer, a highly efficient 19.34% (*Voc* = 0.92 V, *Jsc* = 30.43 mA/cm^2, FF = 0.759) ultra thin $Zn_xCd_{1-x}S$/CdTe solar cell was obtained from numerical analysis. It was found that 1 µm thick CdTe layer is possible with the least sacrifice of efficiency (0.8%) from the CdTe baseline case (ITO/$Zn_xCd_{1-x}S$/CdTe/ metal) of 4 µm thick CdTe layer. Moreover, an effective idea was used to increase the cell efficiency by reducing $Zn_xCd_{1-x}S$ window layer thickness with suitable buffer layer. The efficiency improvement was achieved from 100 nm ZnO/Zn_2SnO_4 buffer layer insertion to reduced $Zn_xCd_{1-x}S$ window layer thickness to 60 nm, which improves the SR of the cell at the blue region. The Zn_2SnO_4 buffer layer insertion showed almost the same results with ZnO insertion. Furthermore, the results of cell operating temperature has shown the stability to some extent of this cell at higher operating temperatures with a temperature coefficient (TC) of -0.25%/°C. Therefore, it is suggested that efficient and cost-effective ultra thin $Zn_xCd_{1-x}S$/CdTe solar cell can be realized with 1 µm of CdTe absorber layer and this proposed cell can be investigated using standard fabrication technique for practical implementation.

Acknowledgments

This work has been supported by the Department of Electrical, Electronics & System Engineering and Solar Energy Research Institute (SERI), UKM, Malaysia through the research Grant UKM-GUP-TK-08-16-057.

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