HIGH-EFFICIENCY ULTRA-THIN CADMIUM TELLURIDE SOLAR CELL WITH ARSENIC TELLURIDE BSF

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Abstract: The polycrystalline cadmium telluride (CdTe) has long been recognized as a leading photovoltaic (PV) material for the possibility of fabricating high-efficiency and low-cost thin film solar cell. The CdTe has a high absorption coefficient over 5×10^5/cm and it has a direct band gap of 1.45 eV which is very close to the optimum band gap for solar cells. In this work, numerical analysis was done utilizing AMPS (Analysis of Microelectronic and Photonic Structures) simulator to investigate the possibility of ultra-thin absorber layer of CdS/CdTe solar cells. The CdTe absorber layer was reduced and found that 1 μm CdTe is enough for acceptable range of cell conversion efficiencies. The viability of this ultra-thin CdTe absorber layer was examined, together with 0.1 μm As_2Te_3 back surface field (BSF) layer to reduce the barrier height in valence band and recombination losses at the back contact of the CdS/CdTe cell. It was found that the proposed ultra-thin cells have conversion efficiency of 16.65% (V_{oc} = 0.89 V, J_{sc} = 23.91 mA/cm^2, FF = 0.78) without BSF and with 100 nm As_2Te_3 BSF conversion efficiency increased to 19.9% (V_{oc} = 0.93 V, J_{sc} = 25.87 mA/cm^2, FF = 0.823) with only 0.6 μm of CdTe layer. Moreover, the normalized efficiency of the proposed cells linearly decreased with the increasing operating temperature at a gradient of -0.4%/°C, which indicated better stability of the cells with and without BSF. In addition, it was found that the CdTe thickness can be further reduced to submicron level with acceptable cell performance.

Keywords: Solar Photovoltaic, CdS/CdTe Solar Cells, Ultra Thin CdTe Absorber, As_2Te_3 BSF, AMPS Simulator.

1. INTRODUCTION

Long-term stable performance and high efficiency has been shown by CdTe thin film solar cells under AM1.5 illumination for terrestrial usage [1]. The main technical issues of CdS/CdTe solar cell research are related to the lesser material usage and stable back contact formation. These two problems will be addressed and numerically analyzed to explore the hidden potentiality of the CdS/CdTe material system for higher cell performance. The polycrystalline CdTe has good electronic property, high absorption coefficient over 5×10^5/cm and has direct band gap of 1.45 eV which is very close to the optimum band gap for solar cells. However, the lesser thickness required for CdTe absorbing layer can lead to reduced cell material usage and lower cost of cell fabrication. In 2001, Xuanzhi Wu reported a record efficiency of 16.5% [2] for CdS/CdTe solar cell. This 16.5% efficient champion cell has used the modified CdS/CdTe cell structure of CTO/ZTO/CdS/CdTe/Cu:HgTe:Cu_xTe with 10 μm of CdTe and 100 nm CdS layers. It was fabricated using three different technologies for the different layers. This best cell efficiency (16.5%) is little greater than half the theoretical limit (29%) of CdTe based cells, but it was estimated in 2005 that practical CdTe cells with 19% efficiencies might be feasible in the near future [3]. The polycrystalline n-CdS (2.42 eV) window layer is the best suited hetero-junction partner with p-CdTe absorber. This work targets ultra-thin CdTe cells with BSF layer insertion for higher conversion efficiency.

The formation of a stable, low resistance, non-rectifying back contact to p-CdTe is one of the major and critical challenges of efficient and stable CdTe solar cells [4]. Metals with a high work function ($\varphi_m \geq 5.9$ eV) are required to make an ohmic back contact but most of the metals do not have such high work functions to make good ohmic contacts to p-CdTe, instead tend to form Schottky or blocking barriers [5]. Due to the high electron affinity and high band gap of p-CdTe, the non ohmic contacts usually show high resistance and thus make a significant contribution to the high series resistance (*Rs*) of the solar cells which in turn badly affect the fill factor (FF) of the cell. Using any suitable BSF material as the interlayer between CdTe and the metal back contact may reduce the contact resistance (*Rc*). If there is no energy discontinuity in the valence bands of CdTe/BSF interface which would block the hole current will definitely increase the FF of the cell. Other advantage is that the doping of p-type BSF ($>10^{18}$ cm^{-3}) is possible to be p++ layer just before metal back contact. Moreover, when suitable BSF layer was first numerically applied to the champion and baseline case CdTe solar cells, it was found that the insertion of BSF is more effective when these cells are with thinner CdTe absorber layer. Therefore, BSF was applied to the proposed ultra-thin CdTe cells and the primary results found were very much encouraging. A typical approach to overcome the contact problem at the back of CdTe cells is to either reduce the barrier height or moderate its width by heavily doping extra layer such as BSF in between the p-CdTe and final metal back contact. The specific BSF material chosen to investigate in this work is Arsenic Telluride (As_2Te_3). Recently N. Romeo et al., has proposed the As_2Te_3 material as a suitable BSF; it is a p-type semiconductor with forbidden energy gap of 0.6 eV and exhibits resistivity of 10^{-3} Ω-cm at room temperature [6]. It melts at 360 °C and can evaporate at temperatures higher than 250°C in vacuum; The authors have reported an efficiency of 15.8% for CdTe cell using As_2Te_3 BSF.

In this work, specific numerical analysis was done to explore the possibility of ultra-thin CdS/CdTe cell with As_2Te_3 BSF utilizing AMPS [7] simulator to improve the open circuit voltage (*Voc)*, the short circuit current density (*Jsc)* and FF of the CdS/CdTe cells. The numerical analysis showed that 1 μm CdTe absorber layer with ITO/Zn_2SnO_4 front contact and As_2Te_3/Mo as BSF are suitable materials for higher efficiency (19.9%) ultra-thin and stable CdS/CdTe cells.

2. MODELING AND SIMULATION

Numerical modeling is increasingly being used to obtain insight into the details of the physical operation of solar cells. Modeling and simulation were done in this work to explore the possibilities of ultra-thin CdTe absorber layer for low-cost solar cell. The baseline case of CdTe cell [8] was utilized to approximate the highest efficiency of CdS/CdTe solar cell, and it was modified to investigate the possibility of efficient ultra-thin solar cells with suitable BSF insertion.

Before modeling the 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 (CTO/ITO) was designed for front contact and a much thinner highly resistive layer of suitable TCO material was designed for buffer layer. The CdS/CdTe cells usually have lower open circuit voltage (*Voc*) than their counterparts like CIGS or CIS cells. The *Voc* of the cells can be improved by higher carrier density ($>5\times10^{15}$ cm^{3}) of CdTe and higher absorber lifetime (>1 ns) and by reducing the back contact barrier height with suitable BSF. The FF might be improved by ohmic back contact and reducing the thickness (<1 μm) of CdTe absorber material whose usual value is around 5–10 μm. The short circuit current density of the cell can be improved by reducing the carrier recombination loss at the back contact with suitable BSF. The stability of the cell might be improved by applying stable BSF.

In this design, the first modification of typical CdS/CdTe cell was to reduce 100 nm CdS layer to 50 nm CdS:O layer with Zn_2SnO_4 buffer layer. Now the front contact of the modified cells consists of a highly conducting layer of ITO for contact and lateral current collection. Moreover, a much thinner (0.1 μm) high resistive buffer layer of Zn_2SnO_4 prevents forward leakage current through pinhole of ultra-thin CdS:O window layer. Thus, this

ITO/Zn_2SnO_4 will replace the 500 nm SnO_2 as front contact layer of the conventional CdS/CdTe cell. The second modification was to change the CdTe doping concentration (~10^{14} cm^{-3}) used in the baseline case to ~10^{15} cm^{-3} which is now achievable for p-CdTe material [9]. The third modification is to reduce the CdTe absorber thickness to the extreme limit for achieving ultra-thin CdS/CdTe solar cell. The fourth modification was to insert As_2Te_3 BSF to reduce minority carrier recombination loss at the back contact of the ultra-thin CdS/CdTe cell.

Fig. 1 illustrates the conventional CdS/CdTe baseline case structure and Fig. 2 shows modified proposed CdS/CdTe solar cell (Glass/SnO_2/Zn_2SnO_4/CdS:O/CdTe/As_2Te_3/Mo) structure for higher cell performance. Thus, the four layers of the proposed cell, emphasized in this analysis, are n-Zn_2SnO_4, n-CdS:O window layer, p-CdTe absorber layer and p-As_2Te_3 BSF layer. The CdS:O layer was used with a hope that it would discard the unwanted inter-diffused layer of CdS_xTe_{1-x} and figure out a better lattice match with poly-CdTe absorber.

The CdTe absorber layer thickness was varied from 0.1 μm to 10 μm and the thickness of other layers were fixed to the usual values [10]. This modeling showed the possibility of getting a highly efficient (around 20%) CdS/CdTe solar cell with 1 μm of CdTe, 50 nm of CdS:O, 100 nm of Zn_2SnO_4 and 100 nm of As_2Te_3 layers.

The number of parameters that can be varied in a particular solar cell model is larger than 50 [11]. Obviously, a problem with 50 variables is too ambiguous to solve reliably without help of computer. It is, therefore, necessary to minimize the number of variable parameters by fixing many of them at reasonable values. It was a real challenge to choose the practically achievable parameters to be used for different layers of the proposed cells. Many of them depend on fabrication techniques and deposition methods and can thus vary even between devices fabricated in the same batch from the same technology. Table 1 shows the material parameters used in this modeling, which were selected based on experimental data, literature values, theory, or in some cases reasonable estimations.

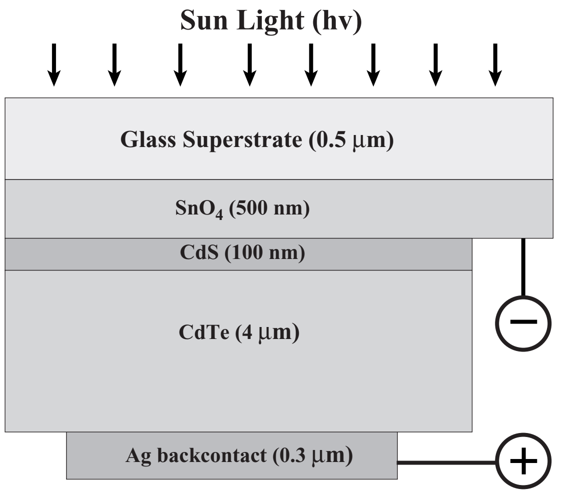

Fig. 1 The **c**onventional baseline case structure of the CdTe solar cells.

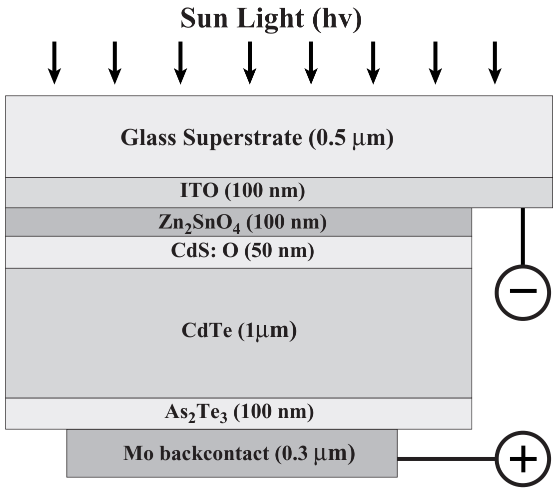

Fig. 2 The modified proposed structure of CdTe solar cell for higher performance.

Table 1 The material parameters used for the numerical analysis of the proposed cells.

Parameters	Back contact		
Φ_b [eV]	Φ_{bp} = 1.25 (Ag), 0.3 (BSF)		
S_e [cm/s]	1×10^2 - 1×10^8		
S_h [cm/s]	1×10^2 - 1×10^8		
R_f [I]	0.9 - 0.95		
Parameters	**CdS:O**	**p-CdTe**	**BSF**
W (μm)	0.05	0.1-10.0	0.1
$\varepsilon/\varepsilon_0$	10.0	9.4	20
μ_c (cm^2/Vs)	100	320	500
μ_p (cm^2/Vs)	25	40	210
n, p (cm^{-3})	10^{17}	5×10^{15}	8×10^{19}
Eg (eV)	2.8	1.45	0.6
N_c (cm^{-3})	2×10^{18}	8×10^{17}	8×10^{17}
N_v (cm^{-3})	2×10^{19}	1.8×10^{19}	2×10^{19}
χ (eV)	4.50	4.28	4.0

3. RESULTS AND DISCUSSION

3.1 CdTe Absorber Layer Optimization

A three layer device model (SnO_2/CdS/CdTe) of the CdTe baseline case [8] was the starting point of this analysis. The conversion efficiency of 14% (*Voc* = 0.81 V, *Jsc* = 24.42 mA/cm^2, FF = 0.71) was found from the CdTe baseline case cell where CdTe absorber layer was 4 μm with doping concentration of 2×10^{14}, CdS:O window layer was 50 nm along with 100 nm Zn_2SnO_4 buffer layer and Ag as the final back contact metal. When the today's achievable CdTe doping concentration (5×10^{16}) was adopted to the baseline case cell keeping all other device parameters with the same value the conversion efficiency was found to be increased to 17.68% (*Voc* = 0.9 V, *Jsc* = 24.53 mA/cm^2, FF = 0.8).

The improvement of cell conversion efficiency was achieved mainly due to increased *Voc* and FF for higher CdTe absorber doping. It is noteworthy that in most high efficiency CdS/CdTe solar cells, the CdTe absorber layer is purposely kept around 5 μm or above. Theoretically the minimum thickness required is approximately 2 μm for CdTe layer to absorb 99% of the incident photons with energy greater than the band gap [2]. Thus, further numerical analysis was done with the modified cell to reduce the thickness of CdTe absorber layer aiming to conserve the absorber CdTe materials usages and finally the cost of cell fabrication.

The CdTe absorber thickness was varied from 0.1 μm to 10 μm keeping all other parameters at fixed values and the obtained simulated results are shown in Fig. 3. It is clear from Fig. 3 that all the cell output parameters were almost unaffected for the CdTe thickness above 2 μm as 99% of the incident photons are absorbed within 2 μm of CdTe layer.

Further reduction of CdTe thickness from 2 μm showed that *Jsc, Voc* and FF were decreased slowly until 1 μm of CdTe thickness. Meanwhile, it can be seen from spectral response simulation results shown in Fig. 4 that the quantum efficiency at the long wavelength region decreases with the decrease in CdTe absorber thickness. Therefore, insufficient absorption of photon has been occurred in the case of thinner CdTe absorber which reduces the cell output performances. From Fig. 3 it is evident that at the very lower value of CdTe absorber (<1 μm) the *Voc* and FF were significantly decreased that might be attributed to the minority carrier (electron) diffusion length was critically decreased and the minority carriers were possibly being diminished through recombination.

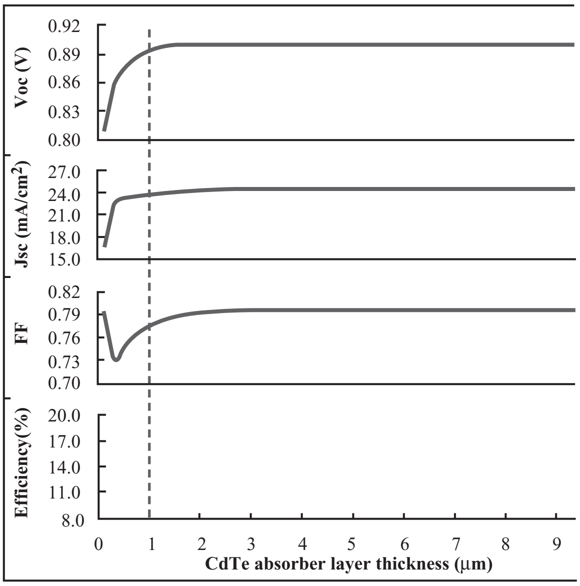

Fig. 3 The Effect of CdTe absorber layer thicknesses on cell output parameters.

At very lower value of CdTe absorber thickness (<0.3 μm), the *Jsc* decreased sharply that might be attributed to the sharp reduction of the electric field but the FF increased due to the reduction of bulk resistance of the ultra-thin CdTe absorber layer. As a combined effect, efficiency gradually decreased with reduced CdTe thickness from 2 μm to 1 μm and below 1 μm of CdTe the conversion efficiency rapidly decreased which indicated that selection of 1 μm CdTe absorber is critically safe. The 1 μm thick CdTe absorber showed conversion efficiency of 16.65% (*Voc* = 0.89 V, *Jsc* = 23.91 mA/cm^2, FF = 0.78). These results are in good agreement with related published works [10, 12]. The carrier generation rate of CdTe cells

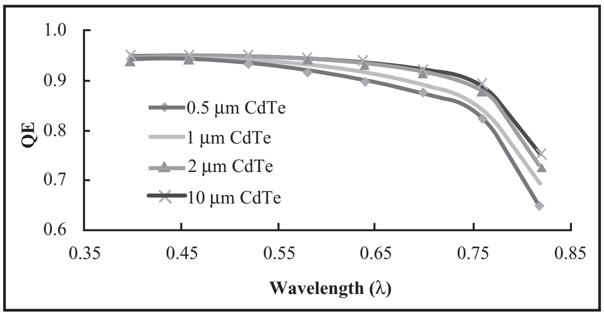

Fig. 4 Effect of CdTe absorber thicknesses on cell spectral response.

was calculated and found that the carriers were being generated in the order of 8×10^{21} $cm^{-3}s^{-1}$ in the vicinity of CdS/CdTe junction. But the carrier generation drastically decreased 1/80 times within 1 µm of CdTe absorber layer thickness which indicated the importance of thickness reduction to 1 µm of CdTe absorber layer. The loss in efficiency of 1 µm thick CdTe absorber layer is very little (from 17.68% to 16.65%) than that of 4 µm thick CdTe absorber layer. Thus, the selection of 1 µm CdTe absorber layer is justified with little sacrifice in efficiency but greater saving of the costly absorber CdTe material (from 4 µm to 1 µm).

Motivated by lower production cost, time and energy, several research groups all over the world have produced CdS/CdTe cells with thinner CdTe absorber. In a typical CdTe solar cell, the absorber thickness is usually over 4µm. Thickness reduction from 4 µm to less than 1 µm could save over 75% of the CdTe material, if the film deposition rate can be kept unchanged, the deposition time and energy could be at least four times lower. For example, CdTe absorber thinning from 4 µm to 1 µm decreased the deposition time from one hour to only 15 minutes only and required energy decreased at the same rate. Therefore, thinner solar cells without compromising much their performance should lead to lower cost PV devices, since they require less materials, less fabrication time and energy. Again keeping the CdTe thickness constant at 1 µm, the simulated back surface recombination rate variation showed that with decreased recombination rate the cell characteristics were improved. Therefore, a new configuration with As_2Te_3 BSF could be implemented to inhibit the possible recombination losses at the back contact in case of such ultra-thin (~1 µm) CdTe absorber layer.

3.2 Insertion of As_2Te_3 BSF

In order to reduce the possible recombination loss and the barrier height at the back contact of ultra-thin (1 µm CdTe) cell, a low bandgap (*Eg*) material As_2Te_3 (*Eg*=0.6 eV) was inserted at the back to reduce back surface recombination rate at the CdTe/As_2Te_3 hetero-junction. This low bandgap material would act as a BSF to bounce back the carriers (electrons) from the CdTe/As_2Te_3 junction and thus would contribute in the enhancement of carriers. One of the major differences of thin cells compared to the thicker ones is that the absorber/back contact interface is now located closer to the main junction (p-CdTe and n-CdS) of the cell and the choice of the back contact material therefore has a high impact on the thinner cell overall performance.

A numerical analysis of the modified ultra-thin cell with As_2Te_3 BSF was done by utilizing AMPS simulator to explore the hidden benefit of BSF insertion. In this numerical analysis, all the layers of the cell are similar to the previous optimized cell except one extra BSF layer of 0.1 µm of As_2Te_3 just before the final back contact metal of the proposed cell. Now the modified cell with all the cell parameters listed in Table 1 were simulated along with 1 µm CdTe, 50 nm CdS:O, 100 nm Zn_2SnO_4 and 100 nm As_2Te_3 BSF layers; the AMPS simulated results are shown in Table 2 to compare the cell performances with and without BSF layer.

Table 2 The output parameters of modified cells without BSF layer and with BSF layer.

Structure/ Parameters	*Voc* (V)	*Jsc* (mA/cm^2)	FF	Eff. (%)
Base case	0.89	23.91	0.78	16.65
As_2Te_3 BSF	0.92	24.97	0.81	18.60

It is evident from Table 2 that the proposed cell without BSF shows conversion efficiency of 16.65%, which is in the acceptable range for CdS/CdTe cells. The conversion efficiency increased to 18.6% with the insertion of 100 nm As_2Te_3 BSF layer. The improvement in efficiency with BSF resulted from the improvement of all the cell output parameters like *Jsc*, *Voc* and FF which would be much clearer from the *J-V* characteristics of the cells. Simulated *J-V* characteristics of both the cells are shown in Fig. 5.

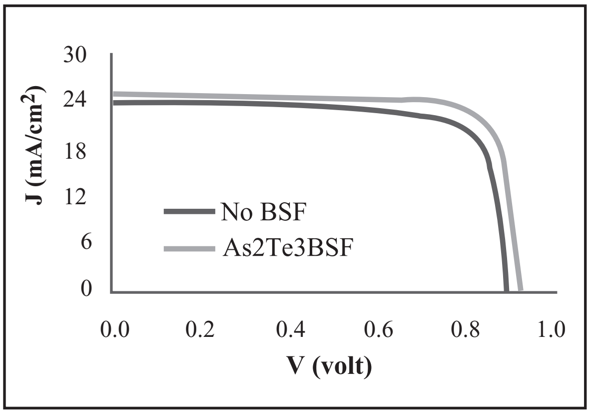

Fig. 5 *J-V* characteristics of the proposed cells.

In Fig. 5, the structure with As_2Te_3 BSF showed higher *Voc, Jsc* and FF than the same cell without BSF due to reduced back surface recombination and improved back contact formation with p-CdTe. However, the overall performance of the cell with As_2Te_3 BSF is better than that of the cell without BSF layer. Calculations have been carried out for the CdS/CdTe/As_2Te_3 configuration to find the effect of absorber CdTe thickness reduction with BSF. The simulation results for variation of the thickness of CdTe absorber layer from 0.1 µm to 4 µm with and without 100 nm As_2Te_3 BSF layer are shown together in Fig. 6.

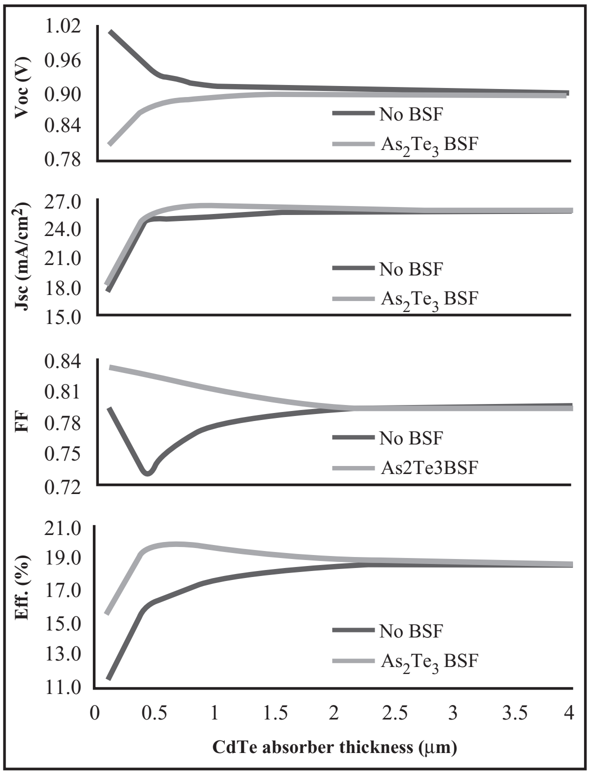

Fig. 6 Effect of CdTe thickness variation for the proposed cells with and without As_2Te_3 BSF.

The simulated results of the proposed cell without BSF layer are also shown in Fig. 6 for comparison. The *Voc* and FF show increasing trend as expected with decrease of the CdTe layer thickness in the presence of highly doped As_2Te_3 BSF, whereas both *Voc* and FF show decreasing trend for the cell without BSF. The increase of *Voc* has the largest contribution to the efficiency improvement in the case of ultra-thin CdTe absorber (<1 µm). The *Jsc* with As_2Te_3 BSF has shown higher value than that without BSF layer but follows the same trend to decrease drastically below 0.6 µm of CdTe layer as without BSF due to electric field diminished at this thickness. The increase in *Voc*, FF and *Jsc* are due to the minority carriers (electron) that are reflected from the back surface of the CdTe/As_2Te_3 conduction band offset and the smoother flow of hole at the back contact. These results of BSF layer are agreeable to the related published works [14]. Thus, the cell conversion efficiency showed highest value of 19.9% (*Voc* = 0.93 V, *Jsc* = 25.87 mA/cm^2, FF = 0.823) at 0.6 µm of CdTe layer with BSF. Therefore, it is a clear indication of further reduction of CdTe absorber layer thickness from 1 µm to 0.6 µm with As_2Te_3 BSF as found in this analysis.

Before final conclusion on the As_2Te_3 BSF performance, it is preferred to investigate the stability of the proposed cells at higher operating temperatures. The operating temperature plays a very important role on cell performances. At higher operating temperature, parameters such as the electron and hole mobility, carrier concentration, density of states and bandgaps of the materials are affected. In order to investigate the effects of higher operating temperature on the performances of the cells with and without BSF, simulations were carried out with cell operating temperature ranging from 25 °C to 100 °C and the simulated results are shown in Fig. 7. From Fig. 5 it is evident that without BSF layer and with As_2Te_3 BSF layer the normalized efficiency of the cells linearly decreased with the increase of operating temperature at a temperature coefficient (TC) of -0.4%/°C. This TC indicates better stability of the cells at higher operating temperature, which are in good agreement with related published works [9, 13]. However, the stability of cell with As_2Te_3 BSF showed the same stability as the cell without BSF. Thus, the As_2Te_3 BSF has no unfavorable effects on the cell stability at higher operating temperature.

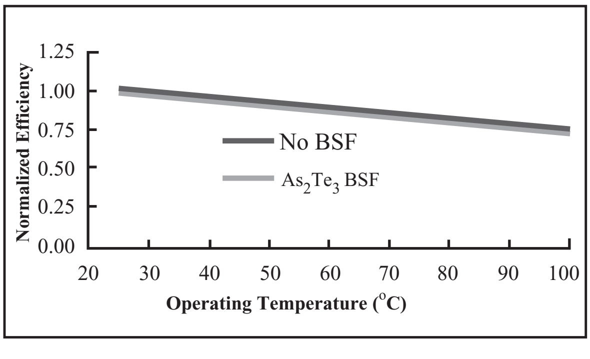

Fig. 7 Effects of operating temperature on the performances of the proposed cells.

4. CONCLUSION

The higher doping concentration of p-CdTe absorber leads to higher CdS/CdTe cell performance. It was found from the CdTe baseline case cell (SnO_2/CdS/CdTe) that 1 µm thick CdTe absorber layer is possible with acceptable range of efficiency of 16.65% (*Voc* = 0.89 V, *Jsc* = 23.91 mA/cm^2, FF = 0.78) without BSF layer. The potential BSF material As_2Te_3 was examined for the possible BSF effect with ultra-thin CdTe layer. With a 100 nm BSF layer, the highest efficiency was found with submicron CdTe thickness, where the As_2Te_3 BSF with 0.6 µm CdTe layer showed the best conversion efficiency of 19.9% (*Voc* = 0.93 V, *Jsc* = 25.87 mA/cm^2, FF = 0.823). This analysis showed that As_2Te_3/Mo BSF is a suitable back contact modification for higher efficiency and stable ultra-thin CdS/CdTe solar cell. The thermal analysis of the proposed cells showed better stability at higher operating temperatures with a linear TC of -0.4%/°C. The proposed cells can be further investigated using any standard CdTe cell fabrication techniques.

5. ACKNOWLEDGEMENTS

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