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Impact of Back Surface Field (BSF) Layers in Cadmium Telluride (CdTe) Solar Cells from Numerical Calculation

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Abstract: ***In this study, numerical simulation has been executed using Solar Cell Capacitance Simulator (SCAPS-1D) to study the prospect of favourable efficiency and stable CdS/CdTe cell in various cell configurations. A basic structure of CdS/CdTe cell is studied with 4 µm CdTe as absorber layer, 100 nm tin oxide (SnO_2) as front contact and 25 nm cadmium sulfides (CdS) as buffer layer. Four back surface fields (BSF) layers namely ZnTe, ZnTe: Cu, Cu_2Te and $MoTe_2$ are investigated to reduce the minority carrier recombination at back contact. The cell structure of glass/SnO_2/CdS/CdTe/$MoTe_2$ has shown a nearly ohmic contact with CdTe with the highest efficiency of 17.02% (Voc=0.91 V, Jsc=24.79 mA/cm^2, FF=75.41). Simulation results have verified that $MoTe_2$ as BSF layer is appropriate for an efficient CdS/CdTe cell. Moreover, it is found that a few nanometres (about 40 nm) of BSF layer are enough to achieve high efficiency. For $MoTe_2$ layer, more than 17% efficiency has been achieved compared to other BSF layers.***

Keywords: Back Surface Field Layers, Cadmium Telluride and Solar Cell

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I. INTRODUCTION

The investigations for feasible solar cell structure which can be replaced with fossil fuel has admitted CdTe solar cell as a compatible alternative to reach the desired affordable photovoltaic device. Among different semiconductors, CdTe is an utmost favourable material in thin film solar cell technology. CdTe has appeared to be a remarkable thin film technology with significant interest from scientific and commercial view point. CdTe is superior PV material for its affordability, simple fabrication and great absorption coefficient. CdTe's band gap is about 1.5 eV which is adjacent to the desired amount for the effective photo conversion [1-5]. The basic superstrate design of CdS/CdTe solar cell is commonly consist of four layers: transparent conducting oxide (TCO), n-CdS film, p-CdTe and a back contact.

Apparently, one of the first objectives of recent studies is to reduce the price of semiconductor material through thinner cell. Thinning will reduce the production cost via fewer ingredients and less production time. The main difference between thin films and thicker films is that the back contact interface will be deposited very close to the CdS/CdTe junction. This surely results in some effects in thin CdTe cells. It can have a key impact on the short-circuit current (Jsc) and open-circuit voltage (Voc). Detracting the high flow of surface recombination is typically accomplished by adding a passivating layer to the basic structure. Thus, back contact selection has a great influence on the overall cell functionality. A low contact resistance is vital for better functionality and sustainability [6]. Nevertheless, it is not easy to apprehend ohmic contact to p-CdTe as it has high work function (5.7 eV) compared to other metals [7]. A metal is needed having the work function > 5.7 eV, yet there is no metal available in this range. The common procedure to rectify the present Schottky barrier is to propose a highly doped p-CdTe using chemical etching [8, 9] and add a BSF layer among CdTe and the metal. BSF is a higher doped layer at the rear surface in the cell. The joint between the highly doped and low doped area functions as a p-n junction and an electric field created at the interface which acts as an obstacle to minority carrier flow through the back surface. The minority carrier concentration will be retained in higher level in an undoped region and the BSF has a great effect of passivating the rear surface. This can lead to an efficient band alignment to fade the barrier width at the back contact layer.

An effective BSF is a basis component to accomplish efficient solar cells. The key duty of BSF is to create limitation for the photo-generated minority carriers and restrict inside of the p-n junction limit for effective collection. This process is done without increasing the series resistance. Moreover, photon limitation proficiencies are an exciting additional trait for an efficient BSF layer.

Zinc telluride (ZnTe) is one of the semiconductors used in optoelectronic devices that attracted a considerable attention in recent years for its direct band gap 2.26 eV at room temperature and the valence-band deviation between ZnTe/CdTe is only about 0.05 eV [10]. It has been used in tandem and flexible panels. Also, doping is done using group V, Cu, Ga and Sb to improve the properties and reduce the resistivity of ZnTe [11]. Moreover, Cu is utilized to reduce degradation and form a low resistance back surface. Normally, promising back contacts is acquired via adding a thin Cu layer on Te rich layer. ZnTe:Cu is the appropriate choice as a BSF for CdTe cell due to its work function and suitable valence band alignment [12]. Cu_2Te has also been mentioned in literature as a beneficial BSF layer due to increased carrier concentration [13]. Hence ZnTe:Cu and Cu_2Te are proposed in this study to be compared with the conventional structure. Molybdenum di-Telluride ($MoTe_2$) is also a leading back contact choice for CdTe thin film solar cell. It is affordable and abundant with direct band gap (1.1 eV) and work function (4.7 eV). $MoTe_2$ crystals are recognized to show clean photoluminescence spectra, high carrier mobility, and insignificant number of defects [6]. $MoTe_2$ is also selected as BSF because of matching thermal expansion coefficient with CdTe and its ability to prevent the spike or shunting between metal and CdTe which may lead to degradations [6].

Numerical simulation is a very effective approach to estimate the performance and to inspect the feasibility of the proposed structure. Numerical analysis of the structural performance and understanding the physics of solar cells have been a convenient means of attaining relevant insight into the possible characteristics of such structures in real life conditions. Numerical modelling techniques might predict the changes in material properties and provide the supplementary hints to vary designs and parameters. Therefore, numerical simulation is a first move to find out the optimized design. Simulation result is required for the most logical back contact material and their efficient thickness for CdTe solar cells [14]. As a result, developing high efficiency cell, simulation based on SCAPS-1D is presented to find a suitable material as a BSF and look over the desired thickness of BSF layer. Here, high band gap BSF such as ZnTe and ZnTe: Cu and lower band gap BSF such as Cu_2Te and $MoTe_2$ are utilized as BSF to lessen minority carrier recombination loss at the back contact. In this research, the maximum efficiency without BSF is achieved around 17%. Moreover, the suggested structures are resulted in improved efficiency and stability in most extents by using $MoTe_2$ as BSF. Experiment and simulation outputs verified that higher carrier density can quantitatively make way for the improved open circuit voltage (Voc) and Fill Factor (FF).

II. NUMERICAL MODELING

SCAPS is simulation software utilized to analyse mostly CdTe and CIGS based solar cells with a distinctive method to illustrate simulation yield [15]. This simulation computes results from the elementary semiconductor equations in 1-D scale [16]. In this research, SCAPS is utilized to evaluate the performance of CdTe based solar cells. SCAPS is widely used for its matching between the experiment output and the simulation outcome. The proficiency of numerically simulated solar cell is usually investigated in terms of its open circuit voltage (Voc), short circuit current (Jsc), fill factor (FF) and efficiency (η). The maximum attainable Voc is the built-in voltage (Vbi) of the p-n junction that makes up the solar cell. The maximum obtainable Jsc is the total photo-current. Voc and Jsc are the resulting performance parameters after the loss mechanism is considered. Numerical simulation is basically a process whereby the modelled solar cell is virtually operated under the standard condition and the performance parameters can be extracted.

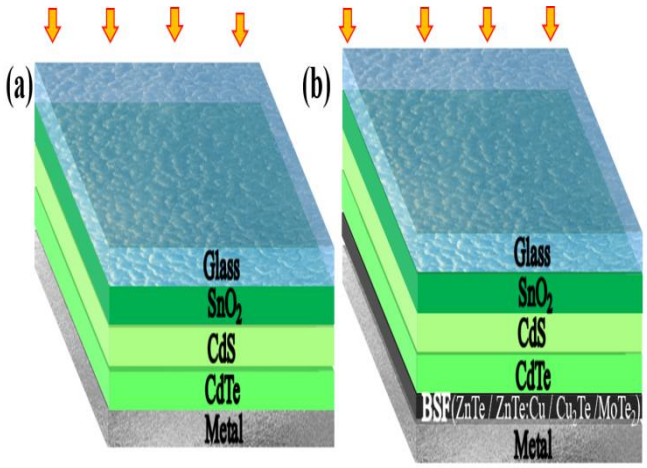

Fig. 1 Schematic diagram of (a) conventional CdTe solar cell and (b) proposed CdTe solar cell structures

A typical CdTe solar cell design comprises a glass substrate, SnO_2 transparent conducting oxide layer, CdS window layer and CdTe absorber layer as illustrated in Fig. 1(a). Fig. 1(b) represents the proposed CdTe solar cell structures by adding different BSF to the conventional cell structure. The impact of BSF thickness variation on the performance of CdTe solar cell output parameters (efficiency, Voc, Jsc and FF) are studied. Moreover, overall cell functionality for temperature variation from 300 K to 400 K is explored. It is crucial to minimize the quantity of variable parameters by keeping at an acceptable value. It is a difficult to choose the proper parameters. Plenty of the parameters rely on fabrication methods and deposition procedures and may thus alter in different designs. All the simulation parameters for conventional and proposed CdTe solar cell structures are summed up in Table 1. All parameters through simulation process are fixed except places otherwise mentioned.

Table. 1 Simulation parameters used in SCAPS-1D

Parameters	SnO_2	CdS	CdTe	ZnTe	ZnTe:Cu	Cu_2Te	$MoTe_2$
Thickness (nm)	100	25	4000	20	20	20	20
Band gap (ev)	3.6	2.4	1.5	2.26	2.2	1.19	1.1
Electron affinity (ev)	4	4	3.9	3.1	3.2	4.1	4.2
Dielectric permittivity (relative)	9	10	9.4	14	11	10	13
CB effective density of states (cm^{-3})	$2.2x10^{18}$	$2.2x10^{18}$	$8x10^{17}$	$7x10^{17}$	$7.8x10^{18}$	$7.8x10^{17}$	$1x10^{15}$
VB effective density of states (cm^{-3})	$1.8x10^{19}$	$1.8x10^{19}$	$1.8x10^{19}$	$1.5x10^{19}$	$1.7x10^{19}$	$1.6x10^{19}$	$1x10^{18}$
Carrier density (cm^{-3})	$1x10^{17}$	$1.1x10^{18}$	$2x10^{14}$	$1.6x10^{19}$	$1.5x10^{20}$	$1.6x10^{19}$	$2x10^{17}$
Electron mobility (cm^2/Vs)	100	100	320	100	400	500	426
Hole mobility (cm^2/Vs)	25	25	40	50	100	100	110

III. RESULTS AND DISCUSSION

To prove the accuracy of the simulation, a basic CdTe solar cell structure has been considered. Here, CdTe thickness of 4000 nm, CdS thickness of 25 nm and SnO_2 thickness of 100 nm have been used. After that, BSF layer thicknesses are changed from 20 nm to 100 nm to examine the impacts on photovoltaic parameters such as Jsc, Voc, FF and efficiency. From Fig. 2, it is clearly seen that all the output parameters are almost stable after BSF layer thickness of 40 nm. Hence, the optimum thickness for BSF layers is selected as 40 nm. BSF layer of 40 nm leads to an increase of Jsc and efficiency of the proposed cells. This result may be related to the electric field generated on the back surface. The electric field can boost the minority carriers to escape from recombination process. It is important to understand that Jsc and Voc are influenced by the series resistance (Rs), shunt resistance (Rsh) and the recombination. The increased Rs and decreased Rsh resulted in an improved efficiency for solar cells with $MoTe_2$ BSF layer [6]. Moreover, FF increment shown in Fig. 2(c) might be because of increasing thickness of BSF layer as well as lower series resistance [17]. However, there is no noteworthy effect on FF for BSF layer thickness above 40 nm. ZnTe introduce two important parts that could enhance device performance: one is better adjustment between ZnTe and CdTe valence band and the other is better ZnTe/CdTe lattice mismatch which occur nearly 5% dislocation misfit [17].

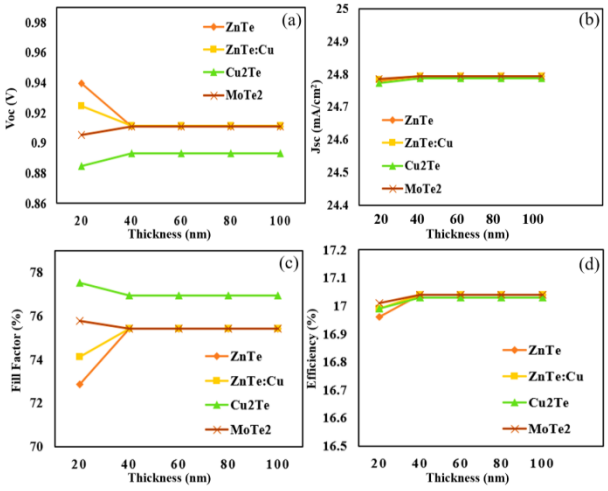

Fig. 2 Effect of BSF layer thickness on (a) Voc (b) Jsc (c) Fill Factor and (d) efficiency

The temperature has significant effect on the cell functionality and characteristics which will determine the stable output power of the solar cells under working conditions. It is considered that the solar panels will be heated by sun at high temperature about 350 K to 400 K in tropical countries. In most simulations, the optimum operating temperature used in is 300K. At high temperatures, solar cell parameters like electron/hole mobility, carrier concentration and the band gap will be affected leading to lower efficiency [5]. Therefore, to investigate the effects of temperature, temperature from 300 K to 400 K has been varied. An inspection is executed on the conventional and proposed structures to study the influence of changing temperature on each parameter for every solar cell design. During the temperature variation, all BSF layers thickness are fixed at 40 nm. Fig. 3 signifies that the efficiency and fill factor declined with the increase in temperature from 300K to 400 K. Furthermore, it has been found that $MoTe_2$ has higher efficiency rate and stability compared with other BSF layers. As Voc is very sensitive to the changes in temperature, the increase in temperature also declines the Voc. This leads electrons to get greater energy at high thermal condition and more recombination will happen before they can attain the depletion area and be collected [5].

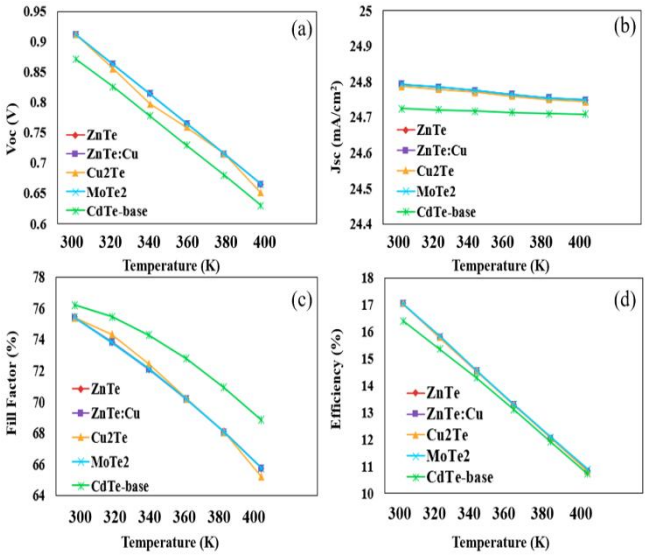

Fig. 3 Effect of temperature on (a) Voc (b) Jsc (c) Fill Factor and (d) efficiency

The impact of high temperature is investigated by temperature coefficient that determines the variations of output power for increment or decrement in temperature per degree centigrade [5]. An investigation on normalized efficiency is done to evaluate the impact of high temperature on the output cell conversion efficiency with temperature from 25°C to 125°C as presented in Fig. 4. Normalized efficiency is calculated for each of the proposed structures with different BSF materials (40 nm thick) to be compared with the CdTe basic structure. It is clear from Fig. 4 that the efficiency linearly declines with temperature at different temperature coefficients for different BSF indicating the capacity of the solar cell's stability at higher temperature. For conventional CdTe cell structure, efficiency decreases with a gradient of -0.377%/°C. The efficiency is reduced for the structures using ZnTe, ZnTe:Cu, Cu_2Te, $MoTe_2$ BSF with a gradient of -0.367%/°C, - 0.358%/°C, - 0.372%/°C and -0.348%/°C, respectively.

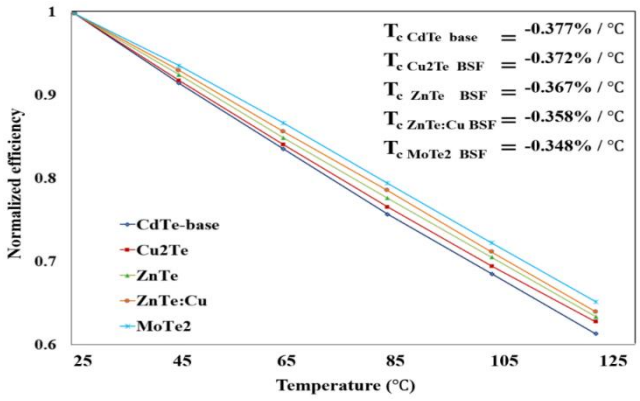

Fig. 4 Temperature gradient of CdTe with and without BSF layers

The effect of adding BSF layer is also remarkable when the structures are compared with respect to the J-V curve under the AM1.5 illumination condition. Fig. 5 presents the J-V curve for conventional and proposed CdTe solar cell structures. It is visible in Fig. 5 that the current density (J) improved with different BSF layers.

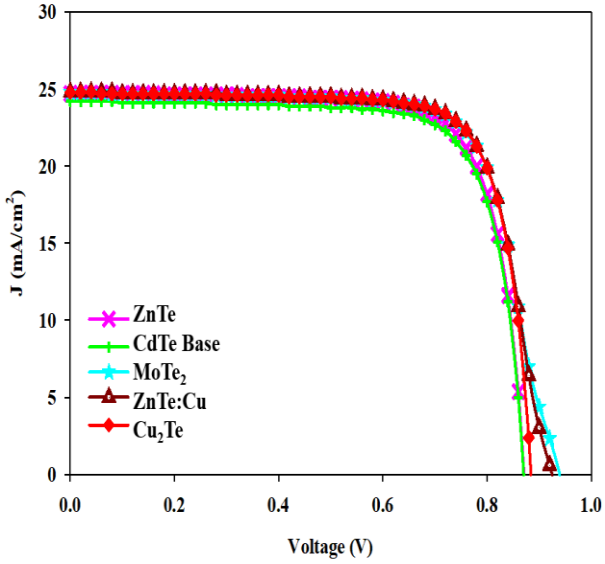

Fig. 5 J-V characteristic of conventional and proposed CdTe solar cell structures

The QE graph exemplified in Fig. 6 signifies the absorption of light for different BSF layers was good compared to the conventional CdTe solar cells. It is also obvious from QE graph that while the functioning wavelength is lower than 500 nm, the quantum efficiency (QE) is remarkably improved for $MoTe_2$ BSF. CdTe solar cell with $MoTe_2$ BSF might be less likely to have carrier recombination as a result of the reduced transportation distance, leading the increase of the minority carrier lifetime [6, 18]. So, QE of the CdTe solar cells with $MoTe_2$ BSF layer exhibits better quantum efficiency in short wavelength. With the decrease in thickness of $MoTe_2$ layer, Jsc and the efficiency are mainly increased. In addition, Table 2 shows the optimum simulation results from the cell structure using $MoTe_2$ BSF with 40 nm thickness and it is selected as the best BSF with efficiency of 17.02% (Voc=0.91 V, Jsc=24.79 mA/cm^2, FF=75.41). It is obvious that the enhanced cell efficiency has been attained mostly because of the improvement in Jsc [18, 19].

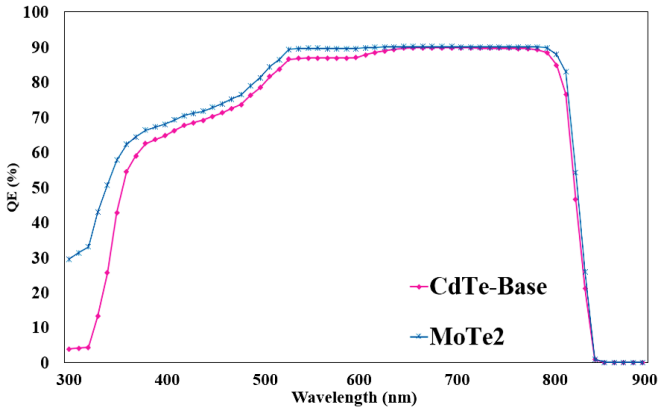

Fig. 6 EQE of CdTe conventional structure compared to Proposed CdTe with $MoTe_2$ BSF layer

Table. 2 Optimum simulation results found in this study

Parameters	Reference Cell	Proposed Cell
Efficiency, η (%)	16.41	17.02
Fill factor (%)	76.21	75.41
Short circuit current density, Jsc (mA/cm^2)	24.72	24.79
Open circuit voltage, Voc (V)	0.87	0.91

IV. CONCLUSION

In this study, impact of various BSF layers has been explored thoroughly via simulation. The key emphasis was to choose the best BSF layer among all the proposed designs with respect to their efficiency. It is revealed that $MoTe_2$ could be a great option as a BSF in CdTe solar cells. By analysing the results, it can be stated that the solar cell functionality is temperature reliant for all proposed designs with BSF in different ranges of temperature coefficients. The maximum efficiency of 17.02% is obtained for

($MoTe_2$/CdTe/CdS/SnO_2) solar cell with 4000 nm thick absorber and 40 nm thick BSF layer. Cell structure with $MoTe_2$ BSF illustrated slightly better stability in high thermal conditions with a gradient of -0.348%/°C in contrast to other BSF layers.

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