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HIGH EFFICIENCY CIGS SOLAR CELL WITH $Zn_xCd_{1-x}S$ WINDOW LAYER

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ABSTRACT

This work conduct the numerical modeling of $Zn_xCd_{1-x}S$/CIGS solar cells using the AMPS-1D software aiming to boost the efficiency and thermal stability of the solar cells. The substitute of typical cadmium sulfide (CdS) window/buffer layer with ternary ZnxCd1-xS window layer in Cu (In, Ga)Se_2 (CIGS) solar cells have been analyzed by AMPS-1D. The prospects of zinc (Zn) incorporation in CdS as window layer for CIGS absorber layer is investigated here. The main goal of this work is to enhance the performance of thin film $Zn_xCd_{1-x}S$/CIGS solar cells with submicron absorber, which could lead to significant reduction of production cost and wider commercial usage. Analysis shows that 0.5-0.6 μm CIGS absorber layer gives good performance with suitable back surface field (BSF). The specific BSF material selected to be investigated here is As_2Te_3. The best calculated ultrathin $Zn_xCd_{1-x}S$/CIGS solar cell with suggested value of 'x' from the simulation result with a 100 nm of As_2Te_3 BSF layer should have an absorber layer thickness of 0.6 μm (efficiency 31.096%), higher stability in most extents, as it was found that the cells have relatively lower negative temperature coefficient (TC)with a TC of -0.031%/°C in the operating temperature range 45°C to 100°C and efficiency remains almost unchanged from 25°C to 45°C.

Keywords: CIGS, stability, buffer layer, BSF, As2Te3

1. INTRODUCTION

Polycrystalline thin film solar cells based on $CuInGaSe_2$ (CIGS) stand out as high-efficiency solar cells and they have significant contributions in photovoltaic technology due to their lower cost, flexible modules, and high energy conversion efficiency of more than 21% (Bernal-Correa et al. 2016), (Jackson et al. 2007), (Green et al. 2016), (Friedlmeier et al. 2015), (Asaduzzaman et al. 2016), (Jackson et al. 2007). Additionally, the CIGS thin film hetero-junction solar cell is a promising option in industrial productivity due to its lower manufacturing cost and higher efficiency (Rampino et al. 2015), (Minemoto et al. 2003), (Powalla and Dimmler, 2001). The absorber semiconductor (CIGS) with chalcopyrite structure and band gap between 1.04–1.67 eV is well known for its long thermal stability and high optical absorption coefficient (Udai and surya, 2010), (Ramanathan et al. 2005), (Zachmann et al. 2009). The CIGS layers for solar cells have been obtained by various physical and chemical techniques (Babu et al. 2015), (Shin Ma et al. 2015), (Jia-wei et al. 2013), (Wang et al. 2014), (Liu et al. 2013), (Benslim et al. 2010), (Kaelin et al. 2004). The optimization of solar cell parameters based on theoretical models has become a powerful tool since it permits for the swift assessment of the elements and materials forming the solar cell (Fu-Ling et al. 2014), (Kim, 2014), (Olopade et al. 2014), (Morales-Acevedo et al. 2012). In the previous decade, a large number of publications about modelling thin-film solar cells (Richter et al. 2015), (Fucheng et al. 2014), (Back et al. 2014), (Shou-Yi et al. 2014), (Abdel-Rahman et al. 2014), (Osborne, 2014) have appeared. However, there are still major scopes for further efficiency improvement by optimizing parameters such as the window/buffer layers and the CIGS layer thickness. Several window layers are used to boost the efficiency of CIGS solar cells (Chelvanathan et al. 2010), (Hariskos et al.2005), (Khoshsirat et al. 2015). ZnS buffer layer having a wider band gap (Eg = 3.68 eV) has shown significant efficiency in the thin-film technology for the replacement of CdS (Nguyen et al. 2015), (Islam et al. 2009), (Nakada and Mizutani, 2002), (Nakada et al.1999). However ZnS is exceedingly resistive and very hard to dope and could considerably increase the cell's series resistance (Capper, 1997). Atomic layer-deposited (ALD) $Zn_{1-x}Sn_xO$ (ZTO) has also been used for the replacement of CdS, and the best cell efficiency of the CIGS solar cell with a ZTO buffer layer has been recorded as 18.2% (Lindahl et al. 2013). The wider band gap of ZTO is used as it permits transmitting the photons having lower wavelength into the absorber (Lindahl et al. 2016), (Asaduzzaman et al. 2017). Hence, the current generation is also increased owing to using ZTO as a buffer. Zinc oxide (ZnO), is also used as an alternative to the CdS buffer layer as it has a band gap of 3.3 eV, which is 0.88 eV wider than that of CdS (Eg = 2.42 eV) (Zhang et al. 2016), (Mikami et al. 2003). ZnO with its wider band gap of 3.3 has been used as window layers in CIGS solar cells (Lindahl et al. 2013). But with the ZnO buffer layer, the cell does not show the light soaking effect (Mikami et al. 2003). To subside the light soaking effect, the CIGS surface is doped or etched with Zn (Chaisitsak et al. 2001).

Considering the above discussion, we have chosen $Zn_xCd_{1-x}S$ as an alternative window structure in CdTe solar cells. Its bandgap can be tailored from 2.42 eV (CdS, x=0.0) to 3.7

eV (ZnS, x=1.0). In heterojunction solar cells, the use of $Zn_xCd_{1-x}S$ with controlling Zn instead of CdS can lead to an increase in photocurrent by providing a match in the electron affinities of the window and absorber material (Ray et al. 1998), (Menner et al. 1988). $Zn_xCd_{1-x}S$ are known to have properties in between those of CdS and ZnS. In CIGS solar cells, the replacement of CdS with the higher bandgap ternary $Zn_xCd_{1-x}S$ film can lead to a decrease in window absorption losses and has resulted in an increase in the short circuit current (Yamaguchi et al. 1996).

2. METHODOLOGY

The main aim of numerical simulation of solar cells is to evaluate its performance. In solar cell, a cell model is a theoretical structure created to represent real processes and parameters that might influence cell performance. Modeling is widely used in analysis of silicon solar cells. For thin film polycrystalline solar cells, the need for numerical modeling methods is higher due to the complex nature (Burgelman et al. 2004). Numerical modeling would help to understand the solar cells behavior and should give the additional ideas to control the fabrication parameters to improve the cell performance. In this study, AMPS-1D one dimensional software packages are used to simulate the thin-film $Zn_xCd_{1-x}S$ /CdTe solar cells. The AMPS-1D is a one-dimension online simulator to analyze the electrical and optical properties of silicon based solar cells, CdTe, CIGS CZTS solar cells and so on was developed by Prof. S. J. Fonash et al. in the Electronic Materials and Processing Research Laboratory at Pennsylvania State University, USA, BETA version 1.0, which was revised in 2007, is used here. It can analyze the transport in a variety of crystalline, polycrystalline, or amorphous solar-cell materials and device structures including homo junction, heterojunction, or multifunction solar cells and detectors (Gloeckler et al. 2003), (Tripathi et al. 2006), (Kanevce et al. 2005).The properties of the conventional CdS and its alternative material $Zn_xCd_{1-x}S$ and its effects on the performance of the n-SnO_2/$ZnSnO_4$/ $Zn_xCd_{1-x}S$ /CIGS/Cu solar cell are emphasized in this study. The effects of Zn concentration in window/buffer layer, the window layer thickness, the CIGS absorber thickness and range of operating temperature to measure thermal stability of the solar cell are taken into account during the simulation to observe the change in efficiency (η), open-circuit voltage (Voc), short-circuit current (Jsc), and fill factor (FF).

In this work modelling and simulation were done utilizing AMPS-1D simulator to explore the possibilities of ultrathin CIGS absorber and $Zn_xCd_{1-x}S$ window layer with improved cell output parameters and ultimately the conversion efficiency. In AMPS-1D, the optical model was set to 85% reflection without BSF and 95% reflection with BSF of As_2Te_3 at the back contact and 5% reflection for the front contact, which mean that 95% of the incoming light will be transmitted to the absorber layer. The operating temperature was set to 298K (25°C) of the solar cell. Figure 1 (a) shows the CIGS conventional structure. It was modified as (Glass/SnO_2/Zn_2SnO_4/$Zn_xCd_{1-x}S$/CIGS/As_2Te_3/Cu) in which CdS is replaced from the conventional structure by $Zn_xCd_{1-x}S$ for higher performance. By adding an extra Zn_2SnO_4 (ZTO) buffer layer in the conventional cell structure and incorporating Zn with the CdS window layer, the window layer thickness was reduced to 50 nm as well as it provide more transparent window layer in the blue region. And one of the main goals of today's solar cell research is using less semiconductor material by making the cell thinner. Thinning will not only save materials but also reduce cell production energy and time without compromising its conversion efficiency. And it also reduces absorption energy loss.

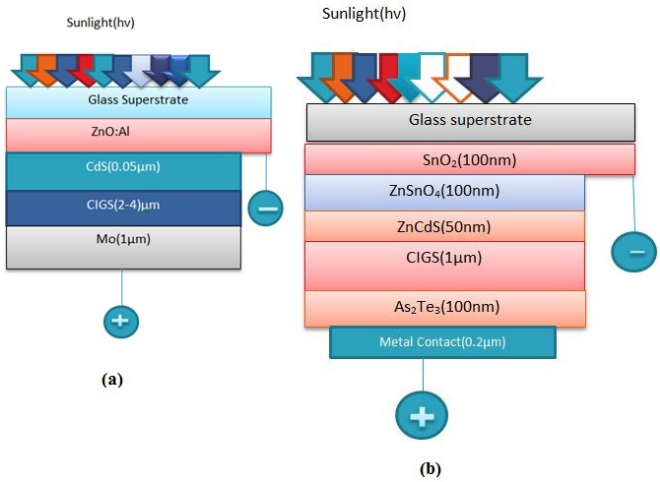

Figure 1: Structure of the (a) conventional CIGS thin film solar cell and (b) modified solar cell structure for higher performance.

Therefore in an attempt towards a higher performance thin film solar cell structure, this study proposed the use of $Zn_xCd_{1-x}S$ as a window layer to form $Zn_xCd_{1-x}S$ /CIGS solar cell. The proposed solar cell structure is shown in Figure 1 (b), which is composed of five main layers:

a) A transparent conducting oxide (TCO) which is indium doped SnO_2 (ITO) about few hundred nm which acts as a front contact generally deposited on high quality glass substrate.
b) A thin Zn_2SnO_4 (ZTO) film which is called front contact buffer layer about 100nm thickness top of the front contact TCO.
c) A thin $Zn_xCd_{1-x}S$ film which is the so-called window/buffer as n-type layer of p-n junction about 50 nm thicknesses on top of the ZTO buffer layer.
d) 1μm thick CIGS layers, which is the absorber layer and deposited on top of $Zn_xCd_{1-x}S$ to complete the p-n junction.
e) Finally, the back contact with BSF (As2Te3) to be formed on top of the CIGS layer to complete the cell. The light is incident from the glass through the front

contact into the $Zn_xCd_{1-x}S$ layer then finally to the CIGS absorber where the cell is designed to absorb most of the incident photon in the CIGS layer only.

Table 1 and 2 show the device parameters for the CIGS cell structure with $Zn_xCd_{1-x}S$ buffer used for the simulation (Asaduzzaman et al. 2016), (Chelvanathan et al. 2010), (Asaduzzaman et al. 2017), (Burgelman et al. 2004), (Gloeckler et al. 2003), (Hossain et al. 2011).

Table1 General Device parameters

Parameter	Front	Back
Φ_b [eV]	$\Phi_{bn} = 0.1$	$\Phi_{bp} = 0.3$
S_e [cm/s]	10^7	10^7
S_h [cm/s]	10^7	10^7
Reflectivity R_f	0.05	0.85

Parameter	n-SnO_2	n-Zn_2SnO_4	n-$Zn_xCd_{1-x}S$	p-CIGS	p-As_2Te_3
W [nm]	100	100	50	600	100
$\varepsilon/\varepsilon_0$	9	9	10	13.6	20
μ_e [cm^2/Vs]	100	32	100	300	500
μ_h [cm^2/Ns]	25	3	40	36	210
n, p [cm^{-3}]	10^{17}	1.0×10^{19}	3×10^{16}	2.0×10^{20}	6.8×10^{19}
E_g [eV]	3.6	3.35	2.48	1.55	0.6
N_c [cm^{-3}]	2.2×10^{18}	2.2×10^{18}	2.2×10^{18}	2.2×10^{18}	1×10^{16}
N_v [cm^{-3}]	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}	1×10^{17}
X (eV)	4.5	4.5	4.47	4.5	4.0

Table 2 Layer Properties used in the proposed solar cell structure

3. RESULTS AND DISSCUSSION

3.1 Optimization of 'x' concentration in $Zn_xCd_{1-x}S$ Window Layer

In this step the conventional structure CdS/CIGS has modified and here CdS is replaced by ZnxCd1-xS and ZTO layer is inserted with 100 nm thickness in between ITO and window layer. To optimize the composition of 'x' of window layer ($Zn_xCd_{1-x}S$) in the modified structure, numerical simulation has been done using AMPS-1D to see the effect of Zn content on conversion efficiency from x=0 to x=1 using the parameters which was adopted from the published work of (Hossain et al. 2011).

It is clear from Figure 2, for low content of Zn (≤ 5%), the conversion efficiency (Eff), Voc, and FF are higher than that for high content of Zn (> 5%) and Jsc decreased continuously from x=0.05 to x=0.6. It is also clear that the optimum efficiency 29.452% (Voc = 1.374 V, Jsc= 26.06 mA/cm2 and FF = 0.894) has found for x=0.05. The electrical resistivity of $Zn_xCd_{1-x}S$ layer increases from 1 Ω-cm (x=0.0) to 1010 Ω-cm (x=1.0) although band gap increases with increasing 'x' (Hossain et al. 2011), (Tian et al. 2011). In consideration to fabrication complexity, band gap, resistivity and simulation results, x=0.05 was selected as optimum value for $Zn_xCd_{1-x}S$ window layer. In the following section, $Zn_xCd_{1-x}S$ has been replaced to $Zn_{0.05}Cd_{0.95}S$ for the proposed cell.

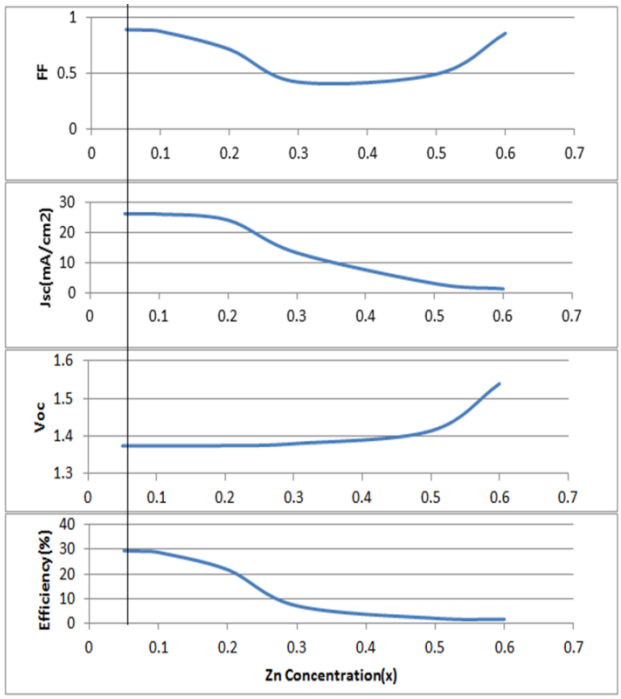

Figure 2 Effect of Zn content (x) on $Zn_xCd_{1-x}S$/CIGS cell performance

3.2 Optimization $Zn_xCd_{1-x}S$ Window Layer's Thickness

From Figure 3, it is seen that the thicknesses of $Zn_{0.05}Cd_{0.95}S$ window layer directly affect the cell performance. If the thickness is less than 50 nm, Voc as well as FF remain almost same. It is well known that very thin window layer cause for pin-hole effect and it may be happened due to this effect. To date, it is almost impractical to fabricate window layer thickness below 50 nm for high quality CIGS solar cells. On the other hand, as the thickness is more than 50 nm, the efficiency and Jsc decrease. It happened due to the light absorption by the window layer. As the thickness increases, the light absorption also increases, and as a result less efficiency. Due to fabrication limitation, $Zn_{0.05}Cd_{0.95}S$ layer thickness was selected as 50nm with conversion efficiency 29.452% (Voc = 1.374 V, Jsc= 26.36 mA/cm2 and FF = 0.894) outcomes from the simulation results as shown in Figure 3.

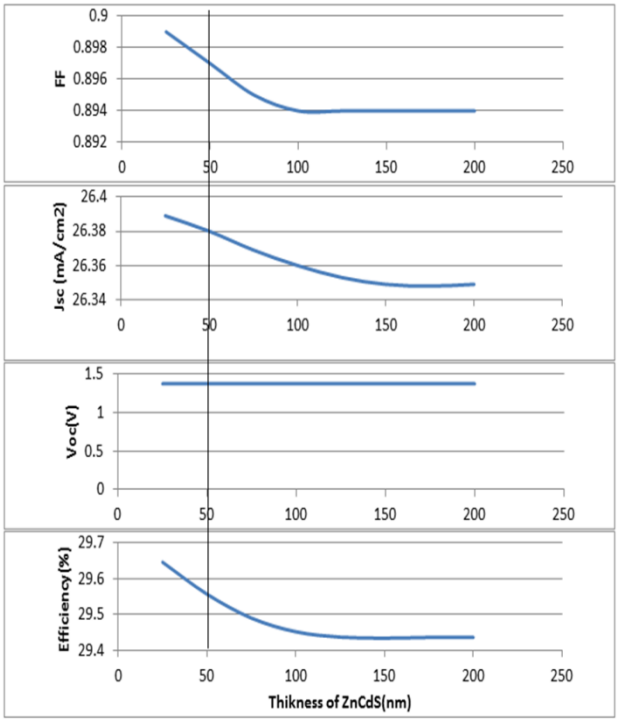

Figure 3 Effect of $Zn_{0.05}Cd_{0.95}S$ thickness on $Zn_{0.05}Cd_{0.95}S$ /CIGS cell parameters

3.3 Optimization Thickness of CIGS Absorber Layer

Theoretically, the minimum thickness required to absorb 90% of the incident photons with energy greater than the band gap is nearly 1 µm which was in literature for CIGS cell. But, it is remarkable that in most high efficiency CIGS solar cells, the CIGS absorber layer is purposely kept at 6 µm and above. The key idea of this analysis is to obtain the acceptable cell output parameters using $Zn_xCd_{1-x}S$ (x=0.05) window at reduced CIGS absorber layer thickness. This will reduce the cost of cell deposition and material usage of CIGS cells. Numerical analysis was done to lessen the thickness of CIGS absorber layer to the extreme limit aiming to preserve the absorber CIGS materials use.

It has been observed that the efficiency of CIGS solar cell varies with variation of thickness. According to graph, highest efficiency is obtained 31.096% at 600nm. It is well known that very thin absorber layer may cause pin-hole in the layer. For pin-hole effect, short circuit is occurred into the cell. To date, it is almost impractical to fabricate absorption layer thickness below 1000 nm for high quality CIGS solar cells. On the other hand, as the thickness is more than 700 nm, the efficiency and Jsc decrease. To avoid the pin-hole effect and fabrication limitation thickness of CIGS absorption layer is kept 1000nm for this work. At 1000nm, $Zn_{0.05}Cd_{0.95}S$ /CIGS solar cell efficiency is 30.169%, Jsc = 27.389mA/cm2, Voc = 1.355V and FF = 0.895.

3.4 Analysis of $Zn_{0.05}Cd_{0.95}S$ /CIGS thermal stability

It is important to investigate the stability of the proposed cells at higher operating temperatures. The operating temperature plays a very important role for cell performances. At higher operating temperature parameters such as the electron and hole mobility, carrier concentrations, density of states and band gaps of the materials are affected. In order to investigate the effects of higher operating temperature on $Zn_{0.05}Cd_{0.95}S$ /CIGS solar cell. Simulation were carried out with cell operating temperature ranged from 25°C to 100°C and the calculated results are shown in Figure 5.

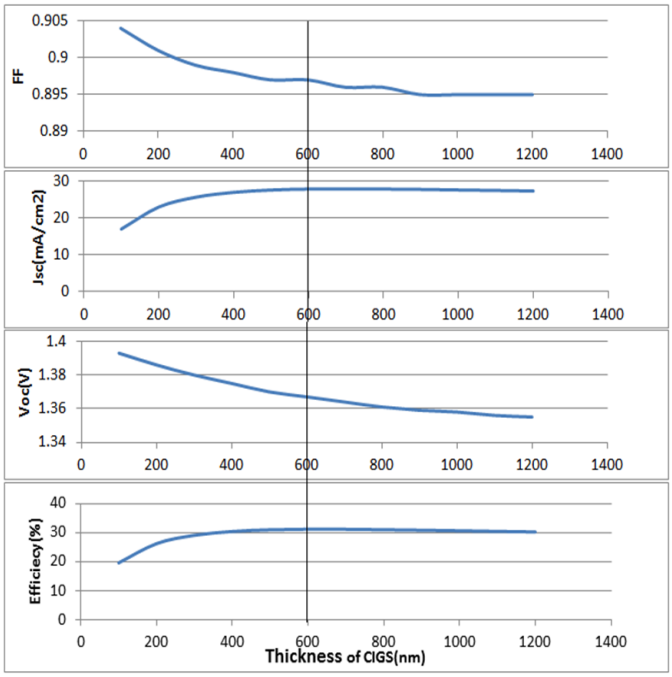

Figure 4 Effect of CIGS thickness variation on the cell output parameters

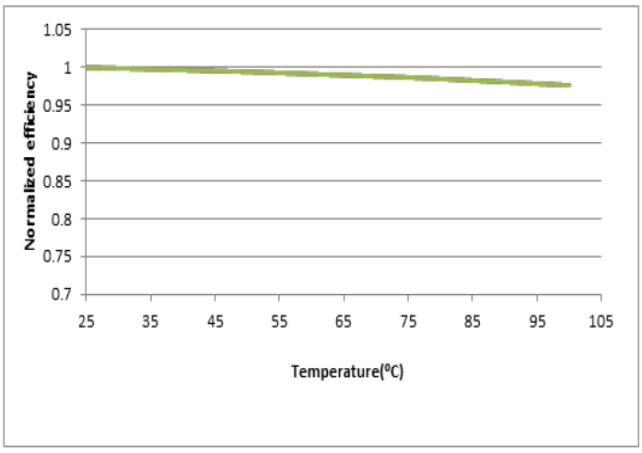

Figure 5 Effect of operating temperature on the proposed $Zn_{0.05}Cd_{0.95}S$ /CIGS solar cell

From the Figure 5, it is evident that the cells normalized efficiency linearly decreased with the increase of operating temperature at a temperature coefficient (TC) of -0.031/°C in the operating temperature range of 45°C to 100°C and no variation form 25°C to 45°C. This TC indicates high stability of the proposed cells at higher operating temperature.

Table 3 Comparison between temperature coefficients of different types of thin film solar cell.

Solar cell structure	Temperature Coefficient (TC)	Published and proposed works
SnO_2/Zn_2SnO_4/ CdS/CdTe/ZnTe/Ag	-0.3%/°C	(Matin et al. 2013)
SnO_2/Zn_2SnO_4/ CdS/CdTe/Cu_2Te/Ni	-0.35%/°C	(Matin et al. 2013)
SnO_2/Zn_2SnO_4/ CdS/CdTe/Sb_2Te_3/Mo	-0.4%/°C	(Matin et al. 2013)
SnO_2/Zn_2SnO_4/ ZnCdS/ CdTe /Cu_2Te/Ni	-0.25%/°C	(Hossain et al. 2011)
SnO2/i-ZnO/ ZnCdS/CIGS/Mo	-0.32%/°C	(Chelvanathan et al. 2010)
SnO_2/Zn_2SnO_4/ ZnCdS/CIGS/As_2Te_3/Cu	-0.031%/°C	Proposed work

The temperature coefficient of ITO/ZTO/ $Zn_{0.05}Cd_{0.95}S$ /CIGS/As_2Te_3/Cu solar cell is -0.031%/°C. According to the comparison table above, it can be stated that the proposed cell structure is more thermally stable than the published works of (Chelvanathan et al. 2010), (Hossain et al. 2011), (Matin et al. 2013).

Table 4 Comparison between proposed and other published works

Proposed and published works	Eff (%)	FF	Jsc (mA/cm^2)	Voc (V)
Asaduzzaman et al. 2017	24.62	-	-	-
Benabbas et al. 2016	24.45	0.80	38.66	0.78
Yasar et al. 2016	27.00	-	-	-
Oubda et al. 2015	17.80	0.78	34.197	0.665
Mostefaouia et al. 2015	22.11	0.84	38.06	0.693
Chelvanathan et al. 2010	21.32	0.82	33.50	0.78
Proposed work	30.17	0.89	27.389	1.355

3.5 Comparison with Other Works

The proposed work is compared with other published works with respect to efficiency. The structure of Glass/ITO/ZTO/Zn0.05Cd0.95S/CIGS/As2Te3/Cu exhibits best cell efficiency of 30.169 % (Voc= 1.355 V, Jsc= 27.389 mA/cm2, FF = 0.895) with considerably high value of Voc but lower value of Jsc in comparison to the literatures mentioned in Table 4.The comparable low value of Jsc may be owing to the higher resistivity of Zn0.05Cd0.95S window layer with respect to CdS window. However, the significant value of Voc superimposes the overall efficiency of the proposed cell structure which is quite good in comparison to the cells described in Table 4. So it is suggested that our proposed cell structure can be fabricated by suitable fabrication process and reducing the resistivity of the window layer at the same time and can be analyzed for high efficiency Zn0.05Cd0.95S/CIGS solar cells with the proposed cell structures.

4. CONCLUSION

The results of this work could open new window for the use of poly-crystalline CIGS thin films solar cells using $Zn_xCd_{1-x}S$ window layer with 'x'=0.05. Due to the short optical absorption length in CIGS, the CIGS thickness of 1 µm is sufficient by incorporating Zn in the buffer layer to absorb more than 90% of the radiation with energy greater than its bandgap (1.55 eV). This work, focused on the thickness reduction of absorber (CIGS) and window ($Zn_{0.05}Cd_{0.95}S$) layers to the extreme limit with expected film quality improvement by insertion Zn in CdS and the proposed solar cells exhibit significant efficiency 30.169 % (Voc = 1.355 V, Jsc= 27.389 mA/cm2, FF = 0.895) and improved stability as its efficiency remains almost unchanged in the operating temperature range from 25°C to 45°C and then it slightly decreases with a TC of -0.031%/°C.It proves the proposed cell is highly stable in higher operating temperature and consequently the cell structure Glass/ITO/ZTO/ $Zn_{0.05}Cd_{0.95}S$ /CIGS/As_2Te_3/Cu can be fabricated to investigate the validity of simulation results using suitable fabrication methods for practical implementation.

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