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Effect of series and shunt resistance on the performance of CZTSe thin film solar cell

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Abstract: CuZnSnSe (CZTSe) is a brilliant material for solar energy systems because its essential elements, non-toxic nature, and suitable bandgap for solar energy conversion are abundant on Earth. This compound exhibits a chalcopyrite structure, which is conducive to effective light absorption and charge carrier mobility. The efficiency of solar cells, especially thin-film types, is significantly impacted by three main types of losses: optical losses, recombination losses, and electrical losses. This paper has studied theoretically the effect of electrical losses resulting from series and shunt resistance on the performance of CdS/CZTSe solar cells. Cell efficiency, fill factor, open circuit voltage, and short-circuit current density have been accurately estimated. It was found that the Values of series and shunt resistance have a significant influence on the cell performance. An increase in series resistance from 0 Ω to 25 Ω causes a dramatic decrease in fill factor from 0.803 to 0.360 and a drop in efficiency from 16% to 7%, alongside a slight reduction in open circuit voltage. Conversely, increasing shunt resistance from 2000 Ω to infinity improves the fill factor and raises efficiency modestly from 15.5% to 16%. However, maintaining fixed resistance values leads to an upward shift in performance curves, with a slight decrease in open-circuit voltage and efficiency. These results underscore the importance of optimizing resistance parameters to enhance solar cell performance and efficiency.

Keywords: CZTS, CdS, fill factor, cell efficiency, open circuit voltage.

1. Introduction

Kesterite materials $Cu_2ZnSnSe_4$ (CZTSe), Cu_2ZnSnS_4 (CZTS), $Cu_2ZnSn(S, Se)_4$ (CZTSSe), with their earth-abundant components and high theoretical efficiencies, have been considered as prospective replacements for CdTe and $Cu(InGa)Se_2$ (CIGS) absorbers in thin film solar cells. These materials offer special qualities such as an ideal optical energy gap around 1 eV, p-type electrical conductivity, low cost, and a high absorption coefficient higher than 10^4 cm^{-1} [1-3].

CZTSe cells have reached a maximum experimental power conversion efficiency of 12.6%, which is notably lower compared to the efficiencies of CdTe and CIGS, at 21% and 21.7%, respectively. [4–7]. Siebentritt and Schorr [8] suggest that compositional inhomogeneities in CZTSe solar cells contribute to a low open circuit voltage related to the band gap, thereby restricting efficiency. Additionally, this efficiency restriction may be attributed to secondary phases that may form during the preparation of the material [9].

According to Shockley-Queisser studies, thin film solar cells with a CZTSe absorber layer have a theoretical maximum efficiency of around 32–34% [10]. The efficiency of CZTSe solar cells can be affected by various losses. Reflection at the air/TCO, TCO/CdS interfaces, and CdS/absorber layers, light absorption of light in the TCO and CdS layers, and recombination at the absorber layer's front and back surfaces can all be quantitatively measured. The extinction coefficient, refractive index, and optical band gap of the materials are utilized to quantitatively estimate these optical losses. Recombination losses are determined by using the continuity equation, which considers both the diffusion and drift components of the photocurrent. These losses depend on the physical properties of the absorber layer, such as the absorption coefficient, and are used to quantitatively determine the recombination losses [3, 11, 12].

Recently, our analytical model was employed to investigate the impact of optical and recombination losses on these cells' performance [11]. In this model, a multilayer thin film solar cell structure consisting of an absorber layer (CZTSe), a window layer (CdS), and charge-collecting contacts (ITO and/or ZnO), is studied. Before the light reaches to absorber layer, where pairs of electrons and holes are generated, light passes through the TCO and window layers of the solar cell [12].

In addition, two resistors contribute significantly to the performance of CZTSe cells. The first type of resistance is known as series resistance (Rs) which can arise from several factors within the solar cell. The current flowing through the semiconductor materials of the p-n junction encounters resistance, and the interface between the semiconductor material and the metal contact can also behave as a resistor. Additionally, the metal contacts themselves have resistance. When the solar cell generates current, it loses voltage across this series resistance. Shunt resistance (Rsh) is the second type of resistance and results from macroscopic defects within the solar cell that create an alternative route for the generated photocurrent. This can be due to issues such as cracks in the semiconductor layers or unintended current pathways along the cell edges. A lower shunt resistance allows a greater portion of the photocurrent to flow through these unintended paths, whereas a higher shunt resistance reduces this loss. Achieving an ideal p-n junction requires minimizing series resistance while maximizing shunt resistance [13-17].

We study in this work, theoretically the impact of electrical losses resulting from series and shunt resistance on the CdS/CZTSe solar cell performance. Moreover, the optical and recombination losses will be considered in the computations based on our earlier studies [11]. Calculations have been determined for the cell efficiency, fill factor, open circuit voltage, and short circuit current density. These parameters' calculations are done using the optical, and recombination losses that can occur in this cell.

2. Theoretical Model

In order to create a heterojunction with absorber layer CZTSe with a thin window layer of 60 nm CdS n-type. It uses a transparent conducting oxide (TCO) with an energy gap of 3.3 eV, such as ITO or ZnO: AL. Furthermore, the working temperature was kept at 300 K, and the spectrum was adjusted to the global Am 1.5 standard. The CZTSe solar cell's schematic structure is displayed in Figure (**1-a**). The equations described the optical and recombination losses and their effect on the cell parameters have been studied in our earlier studies [3, 11, 12, 18, 19].

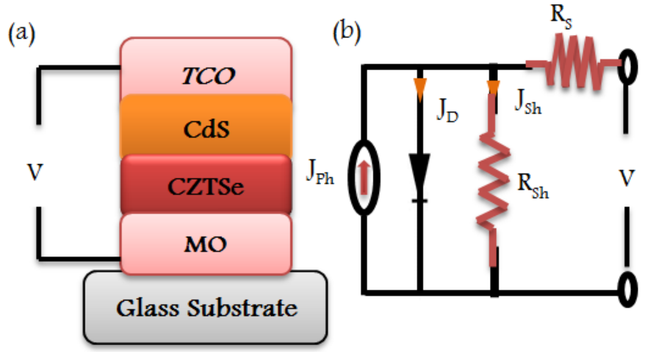

Fig. 1: (a) Schematic diagrams for CZTSe thin film solar cells, (b) the corresponding circuit used to model the cell.

The corresponding electrical circuit used to model the J(V) characteristics of the cell is illustrated in Fig. (**1-b**). When the solar cell is illuminated, its J(V) characteristic can be expressed as the linear superposition of its dark characteristics and the photocurrent generated, based on the standard diode equation if we ignore the effect of electrical losses [18]:

$$J(V) = J_0\left[exp\left(\frac{qV}{AkT}\right) - 1\right] - J_{Ph} \qquad (1)$$

where T is the absolute temperature, k is the Boltzmann constant, and q is the elementary charge. The reverse saturation current is denoted by J_0, the ideality factor by A, and the produced photocurrent by J_{Ph}. The values of J_0 and A are taken from [20].

A more complex expression is produced by the series and shunt resistance expression as the following equation will demonstrate [13]:

$$J(V) = J_0\left[exp\left(\frac{qV-JR_S}{AkT}\right) - 1\right] + \frac{V-JR_S}{R_{Sh}} - J_{ph} \qquad (2)$$

This equation cannot be solved analytically. It was solved by using mathematical modeling in the MATLAB program. There are two interesting limiting instances. V=0 when R=0, resulting in the short circuit condition density (J_{SC}). The current refers to the short circuit current density in this instance.

$$J = J_{SC} = J_{ph} \qquad (3)$$

The second limiting case is the open circuit condition, which occurs when R→∞. In this state, the net current density is zero, and the voltage generated is the open circuit voltage (V_{OC}).

A solar cell's conservation efficiency is calculated by dividing its output electrical power by its incident optical power and it is given by:

$$\eta = \frac{P_m}{P_{in}} \times 100\% = \frac{FF \times J_{SC} \times V_{OC}}{P_{in}} \qquad (4)$$

where P_{in} is the total Am 1.5 solar spectrum power and FF is the fill factor, which determines the power that can be achieved from a solar cell. The fill factor can be expressed as the following equation:

$$FF = \frac{V_m \times J_m}{V_{OC} \times J_{SC}} \qquad (5)$$

where the maximum voltage and current density are denoted by V_m and J_m, respectively.

3. Results and Discussion

According to our previous work [11], the cell efficiency, fill factor, open circuit voltage, and short circuit current density were all estimated. Based on the optical and recombination losses that may happen in this cell, these characteristics were calculated. It was found that the maximum conservation efficiency (η) is 16% when the thickness of TCO is 80 nm, and the thickness of CdS is 60 nm, where the effect of electrical losses has been neglected by considering that series resistance equals zero and shunt resistance is infinity. To investigate the effect of R_S and R_{Sh} on the CdS/CZTSe solar cell performance, we individually varied the resistances while all other factors remained constant. Firstly, we study the variance in the J(V) characteristics curve and cell parameters with series resistance, keeping $R_{sh} = \infty$. **Fig. 2a** shows that with increasing the series resistance the curves are shifted upward, with all showing similar open circuit voltage values around 860 mV. A comparable behavior was observed in Ref. [13].

The power-voltage P(V) curve corresponding to the J(V) curves is shown in **Fig. 2b**. The peak refers to the maximum power points (P_{max}) and gives the maximum power that can be extracted from solar cell. This P_{max} divided by the incident power gives the efficiency of the solar cell. It is clear that the value of P_{max} decreases with increasing the series resistance.

The dependence of conservation efficiency (η), fill factor (FF), and the open circuit voltage (V_{OC}) on the series resistance (R_S) has been plotted in Fig.**3**. It can be seen that as the series resistance increases from zero Ω to 25 Ω, FF decreases from 80.3%to 36% with a ratio of about 44%. Besides, the cell efficiency decreases from 16% to 7%. The open-circuit voltage decreases from 0.880V to 0.860V as the series resistance increases. An increase in R_S corresponds to higher bulk and contact resistance, which results in reduced charge collection efficiency of the device. Consequently, this leads to a decrease in the overall efficiency, as illustrated in **Fig. 3.**

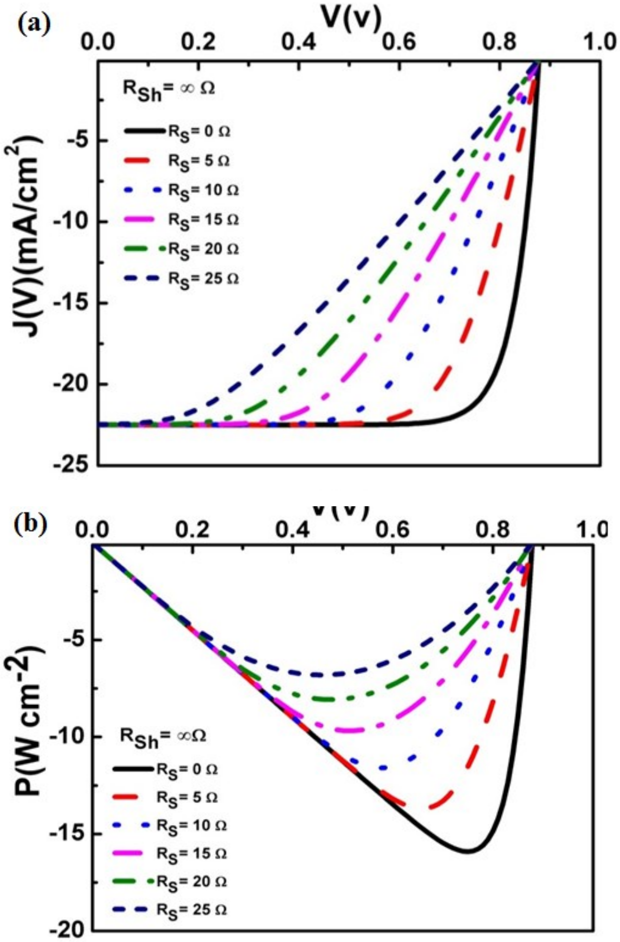

Fig. 2: The impact of series resistance R_s on the J(V) characteristics of (a) CdS/CZTSe, (b) Power voltage characteristics (b).

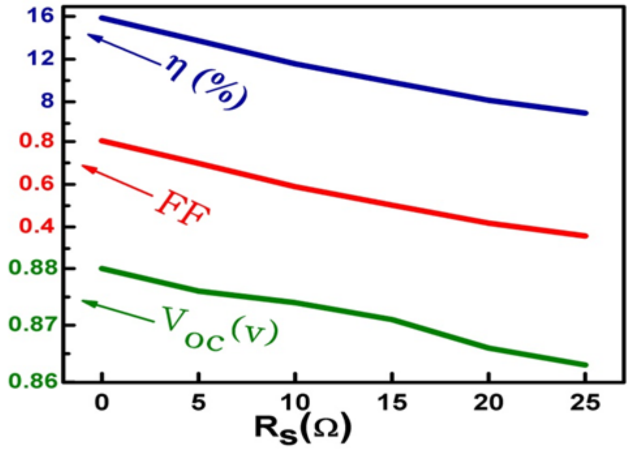

Fig. 3: The dependence of conservation efficiency, fill factor, and the open circuit voltage on the series resistance.

Secondly, the variation of J(V) characteristics curve and cell parameters with shunt resistance R_{Sh} has been studied, keeping Rs = zero Ω as shown in **Fig.4**. **Fig. 4a** shows that with increasing the shunt resistance the open-circuit voltage increased where the curves are shifted downward. Moreover, all curves have close values of the short circuit current density of about 22.5 mA/cm^2. The P(V) curve corresponding to the J(V) curves is displayed in **Fig. 4b**. The value of P_{max} increases with increasing the shunt resistance.

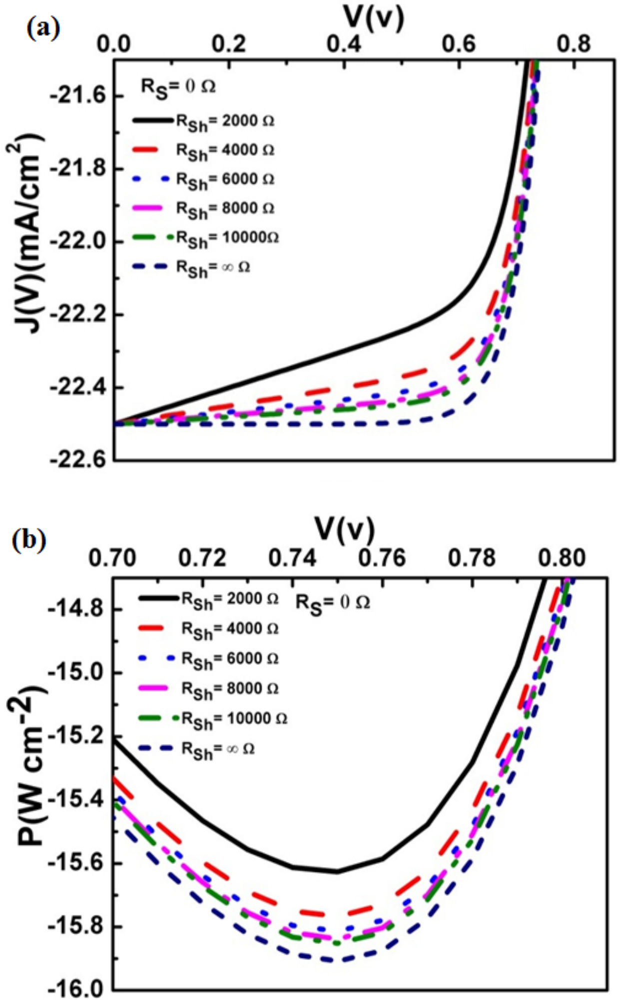

Fig. 4: The impact of shunt resistance R_{Sh} on the J(V) characteristics of (a) CdS/ CZTSe (a), (b) Power voltage characteristics.

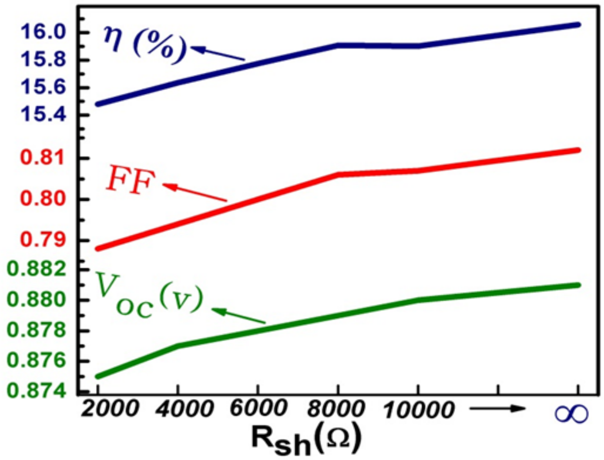

Fig. 5: The dependence of conservation efficiency, fill factor, and the open circuit voltage on the series resistance.

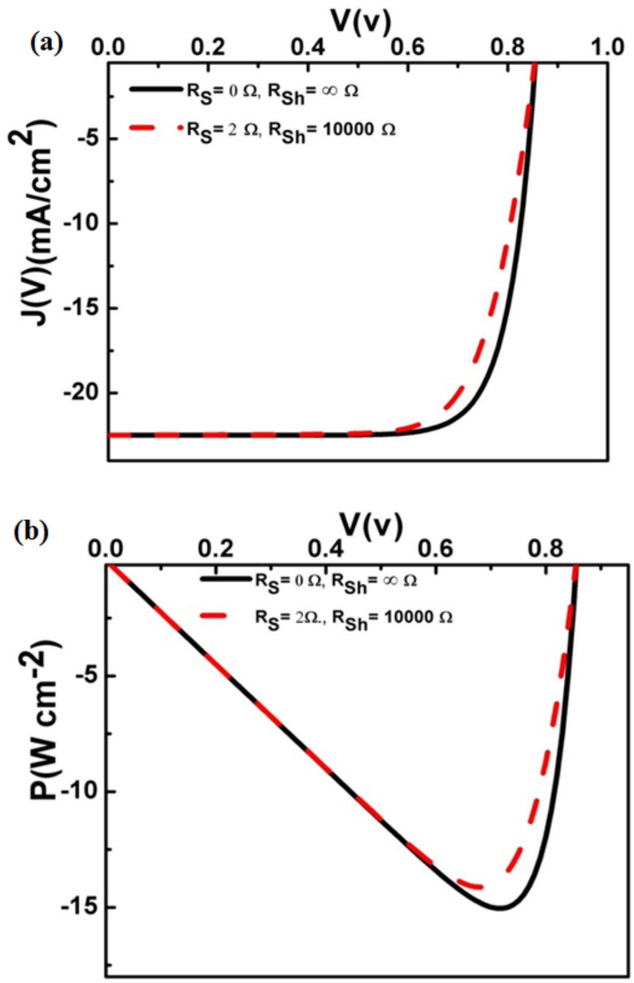

Fig. 6: The effect of series resistance R_S and shunt resistance R_{Sh} on the behavior of J–V characteristics of (a) CdS/ CZTSe, (b) Power-voltage characteristics.

In real solar cells, both series and shunt resistances have an effect on the performance of solar cells. Figure **6** compares the behavior of J(V) characteristics of CdS/ CZTSe, and Power voltage characteristics at fixed values of R_S =2 Ω and R_{Sh} =10000 Ω with the ideal case (R_S =0 Ω and R_{Sh} = ∞ Ω). It can be observed that the open-circuit voltage decreases from 0.880V to 0.870 V. FF decreases from 0.803 to 0.720. The cell efficiency decreases from 16% to 14.1%.

4. Conclusion

In this study, we studied the impact of series and shunt resistance on the performance of solar cells, particularly focusing on CdS/CZTSe cells. Initially, increasing series resistance indicated a decline in fill factor and efficiency, as series resistance increased from 0 Ω to 25 Ω, FF dropped from 0.803 to 0.360, and efficiency decreased from 16% to 7%, while the open circuit voltage slightly decreased from 0.880 V to 0.860 V. Conversely, when shunt resistance was varied, an increase in shunt, the open circuit voltage marginally increased from 0.875 V to 0.882 V, FF improved from 0.788 to 0.812, and efficiency rose from 15.5% to 16%. Finally, at R_s=2 Ω and R_{Sh}=10000 Ω, the cell shows decreases in V_{oc}(0.880V to 0.870V), FF (0.803 to 0.720), and efficiency (16% to 14.1%). These findings illustrate the role of resistance parameters in optimizing solar cell performance. In conclusion, minimizing R_s and maximizing R_{Sh} are essential to increase the efficiency and optimize the overall performance of CdS/CZTSe solar cells.

CRediT authorship contribution statement:

Sh. S. Ali; writing, formal analysis, validation, data curation, investigation and methodology. **W. S. Mohamed**; Wrieting-review and editing. **H. A. Mohamed**; supervision, Wrieting-review and editing. All authors have read and agreed to the published version of the manuscript.

Data availability statement

The data used to support the findings of this study are available from the corresponding author upon request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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