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Deposition duration effects on electrodeposited ZnTe thin films: material properties and device application potential

O.I. Olusola [a,*], N.E. Adesiji [a], O.O. Olusola [b], A.F. Afolabi [a], A.A. Faremi [c], Edson L. Meyer [d], Mojeed A. Agoro [d,e,**], T.M.W.J. Bandara [f], Nandu B. Chaure [g], M. Furlani [h], B.-E. Mellander [h], M.A.K.L. Dissanayake [i], S.S. Oluyamo [a], I. Albinsson [j]

[a] Department of Physics, The Federal University of Technology Akure, Akure, Nigeria
[b] Department of Physics, Bamidele Olumilua University of Education, Science and Technology Ikere, Ikere-Ekiti, Nigeria
[c] Department of Physics, Federal University Oye-Ekiti, Nigeria
[d] Fort Hare Institute of Technology, University of Fort Hare, Private Bag X1314, Alice 5700, Eastern Cape, South Africa
[e] Department of Chemistry, University of Fort Hare, Private Bag X1314, Alice 5700, Eastern Cape, South Africa
[f] Department of Physics and Postgraduate Institute of Science, University of Peradeniya, Peradeniya, Sri Lanka
[g] Department of Physics, Savitribai Phule Pune University, Pune, 411007, India
[h] Department of Physics, Chalmers University of Technology, Gothenburg, Sweden
[i] National Institute of Fundamental Studies, Hantana Road, Kandy, Sri Lanka
[j] Department of Physics, University of Gothenburg, Gothenburg, Sweden

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ABSTRACT

The effect of deposition duration on the material properties of ZnTe thin films synthesized using the potentiostatic electrodeposition technique and their potential for electronic device applications was investigated in this study. ZnTe films with thicknesses of approximately 100 nm, 220 nm, and 400 nm were successfully deposited at durations of 15, 30, and 60 min, respectively, using an aqueous electrolyte of zinc sulphate heptahydrate ($ZnSO_4{\cdot}7H_2O$) and tellurium dioxide (TeO_2) as sources of Zn^{2+} and Te^{4+} ions. Structural, morphological, optical, compositional, and electrical properties were characterized using X-ray diffraction (XRD), scanning electron microscopy (SEM), ultraviolet–visible (UV–Vis) spectroscopy, energy dispersive X-ray spectroscopy (EDX), capacitance–voltage (C–V), and current–voltage (I–V) measurements. The XRD results showed that crystallinity improved with longer deposition duration, while the SEM revealed that grain size increased from ~90 nm to ~380 nm. UV–Vis measurements revealed a decrease in optical band gap from 2.60 eV to 2.00 eV as deposition time increased from 0.25 to 1.00 h. The electrical measurements of the ZnTe thin films indicated a moderate doping density and resistivity value in the order of 10^4 Ωcm. The findings suggest that ZnTe forms a promising hetero-junction partner with CdS for solar cell fabrication. The solar cell parameters obtained were an open-circuit voltage (V_{oc}) of 0.48 V, a short-circuit current density (J_{sc}) of 19.7 mA cm^{-2}, a fill factor (FF) of 0.46 and device efficiency of 4.35%. These parameters were obtained for ZnTe thin films deposited at 60 min and treated with $CdCl_2$ in the cell structure, highlighting the device application potential of ZnTe films deposited under optimised duration.

1. Introduction

Among the group II-VI semiconductor materials, zinc telluride (ZnTe) has emerged as a highly promising material in the field of optoelectronics and semiconductor technology due to its unique properties and versatile applications [1–3]. It has found application in devices like light-emitting diodes, switching devices, X-ray detectors, and homojunction diodes [4,5]. At room temperature, ZnTe single crystal has a direct bandgap energy of 2.26 eV and is often polycrystalline with a cubic and hexagonal crystal structure [4,6–8]. Most research works revealed that ZnTe thin films are majorly of p-type electrical conductivity and that the n-type ZnTe thin film can only be obtained through

* Corresponding author.
** Corresponding author at: Fort Hare Institute of Technology, University of Fort Hare, Private Bag X1314, Alice 5700, Eastern Cape, South Africa.
E-mail addresses: oiolusola@futa.edu.ng (O.I. Olusola), magoro@ufh.ac.za (M.A. Agoro).

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extrinsic doping [9]. However, Olusola et al., (2016) reported that n-type ZnTe thin film can be obtained by intrinsic doping by altering the deposition potential [10]. ZnTe thin films have been grown using variety of methods like electrodeposition [11], vacuum evaporation [12], rf sputtering [13], chemical bath deposition [3], successive ionic layer absorption and reaction (SILAR) [8], closed spaced sublimation and other techniques as reported by [14] as well as different types of vapour deposition [3].

The effect of thickness on different properties of ZnTe thin films has been reported; for instance, Ibrahim et al., (2004) studied the structural and electrical properties of vacuum evaporated ZnTe thin films at various thicknesses [12]. The obtained results showed that the structural properties of the studied ZnTe thin film exhibited three diffraction peaks of which the (111) orientation was most predominant, this was also reported by Mahalingam et al. [4]. The intensities of the diffraction peaks were reported to have improved with increasing thickness of the films while the width of the peaks decreased with increasing thickness. These observations were attributed to the increase in the crystallinity and decrease in the internal microstrains of the ZnTe films as the thickness increased. The thin film electrical resistivity was also found to decline with thickness enhancement. Shaaban et al., (2009) in studying thickness effect on the microstructural parameters and optical constants of vacuum-evaporated ZnTe films also confirmed the increase in crystallinity and decrease in microstrains of the films with increasing thickness [7]. The work further showed that the extinction coefficient decreases with increasing film thickness. Also, the authors observed an increase in refractive index as the thickness of the film increases from 331 to 508 nm. The authors further reported that the energy band gap obtained for the different film thicknesses had the value 2.21 ± 0.01 eV, showing the independency of the energy band gap with film thickness. The energy gap independency on thickness was ascribed to uniform films stoichiometry within the explored thickness range. Since it has been established that varying thickness of the ZnTe film could have effect on its properties, the present study therefore investigates the effect of varying deposition duration as the primary processing parameter, which simultaneously governs film thickness, growth kinetics, elemental incorporation, crystallinity, morphology and thin film conductivity during electrodeposition of ZnTe semiconductors. The work further explores the possible applications of the electroplated materials in electronic device fabrication. Therefore, this work provides a comprehensive understanding of how electrodeposition duration kinetics control the properties of ZnTe thin films.

2. Experimental

2.1. Thin films deposition

The cathodic electrodeposition of ZnTe binary compound semiconductors was carried out in a potentiostatic mode using a two – electrode system which consists of the working electrode or cathode (this is the conducting glass substrate attached to the graphite plate) and the anode, which is the graphite rod. The electrolytic bath used for the deposition comprised of: 0.1 M of zinc sulphate heptahydrate ($ZnSO_4.7H_2O$) and 5 ml of dissolved tellurium dioxide (TeO_2) solution in a glass beaker containing 400 ml of deionised water. Details of the preparation of the dissolved TeO_2 solution can be found in [11]. The 0.1 M of $ZnSO_4.7H_2O$ corresponds to approximately 11.50 g.

The use of diluted ammonia solution and sulphuric was employed in adjusting the bath pH to 3.50 ± 0.02. Cathodic voltage of 1600 mV and bath temperature of 80 °C was used for the thin film electrodeposition. These bath parameters were selected based on the previous optimisation work carried out on electrodeposition of ZnTe thin films by Olusola et al., (2016) in [10]. The bath was moderately stirred on a magnetic heater with an embedded magnetic stirring unit. Fluorine-doped tin oxide conducting glass substrates (glass/FTO) which belongs to the transparent conducting oxide (TCO) family served as the cathode for the films growth, while a carbon rod was used as the anode. The conducting glass/FTO substrates were properly cleaned using soap solution. Substrates rinsing was done using organic solvents and deionised water. FTO substrates with a sheet resistance of 7 Ω/sq. and an active area of 2 cm × 2.5 cm were used for the thin films electrodeposition. The electrolytic bath containing the deposition ions was stirred at 300 RPM. The cathode and anode were positioned parallel to each other with a separation distance of 4 cm.

The optoelectronic properties of electrodeposited ZnTe layers were studied using appropriate characterisation techniques. Techniques such as x-ray diffraction (XRD), scanning electron microscopy (SEM), ultraviolet-visible spectroscopy, energy dispersive x-ray spectroscopy (EDX), capacitance-voltage (C-V) and current-voltage (I-V) were used in investigating the structural, morphological, optical, compositional and electrical properties of the materials respectively. Electrical conductivity type of the electroplated layers was investigated using photo-electrochemical (PEC) cell measurement technique. The details of the PEC cell measurement set-up can be found in [15].

3. Results and discussion

3.1. Structural study of electrodeposited ZnTe layers

The thickness of the electroplated films was theoretically determined using Faraday's law of electrolysis given in Eq. (1) [10].

$$T = \frac{Mjt}{nF\rho} \tag{1}$$

where M is the molar mass, J is the average deposition current density, t is the deposition time, n is the number of electrons involved in the deposition of 1 mol of the thin film, ρ is the density of thin film, and F is the Faraday's constant.

According to Faraday's law given in Eq. (1), the thickness is directly proportional to time. As expected, the film thickness was found to increase as deposition time increases. The thickness of the ZnTe layers grown at 0.25, 0.50 and 1.00 h was estimated to be ~100, 220 and 400 nm respectively.

The XRD spectra of ZnTe semiconductors electrodeposited at varying growth duration is shown in Fig. 1. As seen in Fig. 1, polycrystalline ZnTe thin films with hexagonal crystal structure was formed. The preferred plane of orientation occurred along the (100) hexagonal plane of the most pronounced peak at an approximate position of $2\theta = 24^o$. Aside this prominent peak, another peak with lesser intensity also occurred along the (110) plane. The observed peaks correspond with the peak values from JCPDS reference data with code number, 01–080-0009 and the thin film growth duration has effect on the material crystallinity. The preferred orientation peak intensity increases with thickness as illustrated in Fig. 2. This present result agrees with the results reported by Ibrahim et al., in [12].

3.2. Morphological study of electrodeposited ZnTe binary compound semiconductors

Morphological properties of the chalcogenide ZnTe semiconductors electroplated at three different growth durations of 0.25, 0.50 and 1.00 h are given in Fig. 3. The average grain sizes determined from SEM were ~90 nm, 207 nm and 380 nm for deposition times of 0.25, 0.50 and 1.00 h, respectively. This result thus showed that the grains increase with increase in growth duration. Our experimental investigation agreed with the previous reports by [7]. These grain sizes are slightly lower than the theoretical thicknesses of 100 nm, 220 nm and 400 nm estimated using Faraday's law. The close correlation between grain size and film thickness suggests a columnar growth mode, where grains extend through the film thickness. The small difference is attributed to less than 100% current efficiency during deposition. Faraday's law assumes all charge

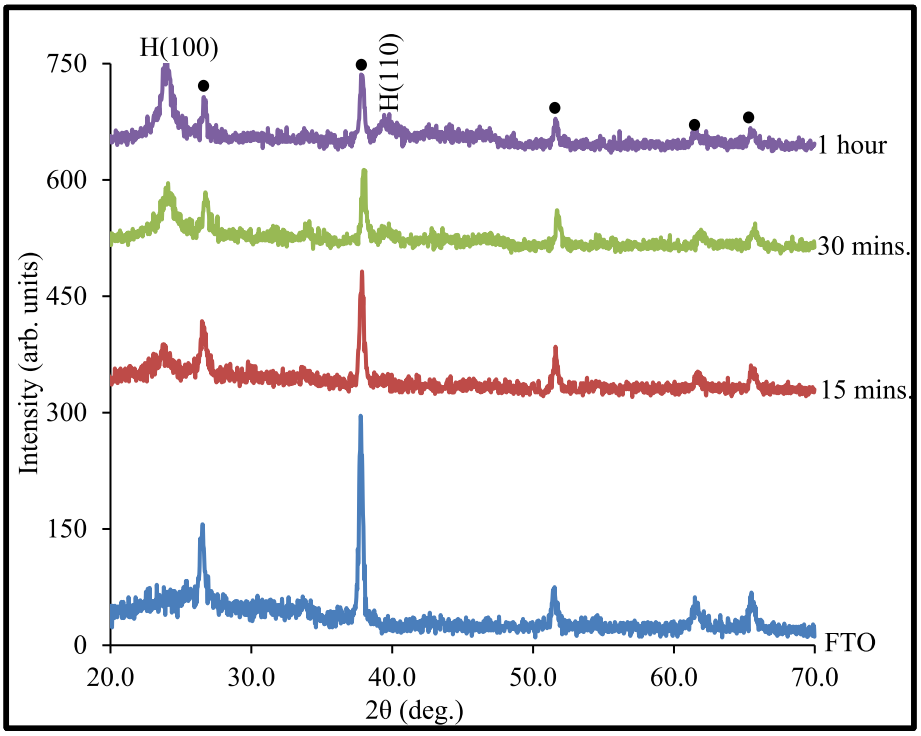

Fig. 1. XRD spectra of ZnTe layers electrodeposited at different durations of 15, 30 and 60 min (Note: The FTO peaks are indicated with black dots in the figure).

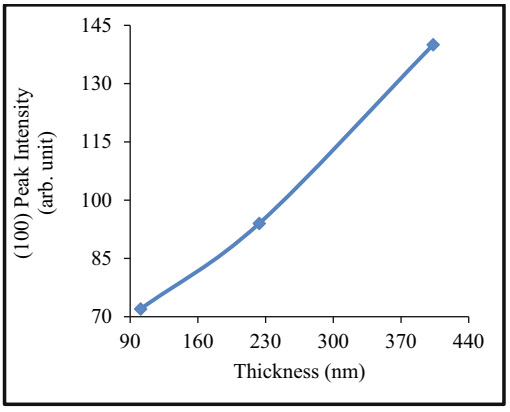

Fig. 2. Preferred orientation peak intensity along (100) plane versus ZnTe film thickness.

contributes to deposition, but in practice some current is lost to side reactions such as water electrolysis, H_2 evolution at higher cathodic potential, film porosity and grain boundaries (Madugu et al., 2016). Therefore, experimental grain sizes are typically less than the theoretical thickness values.

3.3. Compositional study of electrodeposited ZnTe layers

In this section, EDX technique was used in studying the effect of growth duration on the atomic composition of *Zn* and *Te* atoms existing in the ZnTe layers. Three samples deposited at same cathodic voltage (V_g) of 1.60 V and different durations ranging from 0.25 to 1.00 h were used for the compositional analysis. The EDX spectra of ZnTe films deposited for 15, 30 and 60 min are shown in Fig. 4a, b and c respectively. It was observed that as the deposition time increases, the percentage of zinc atom deposited to form the ZnTe film increases while the atomic percentage of tellurium inside the ZnTe layers reduces. Te has a more positive standard reduction potential than Zn^{2+} and thus deposits preferentially during the initial stage of electrodeposition, yielding Te-rich films [16]. As deposition proceeds, the low-concentration Te species become diffusion-limited and depleted at the cathode surface, while the high-concentration Zn^{2+} supply remains sufficient. This causes the Zn deposition rate to increase relative to Te, leading to an increase in Zn atomic percentage and a decrease in Te atomic percentage with increasing deposition time. Consequently, ZnTe layers grown for a shorter duration are Te-rich, whereas longer growth times yield films with reduced Te content.

Fig. 5 gives a summary of the atomic composition of zinc and tellurium atoms present in the ZnTe semiconductor and their variation with the growth time. The zinc:tellurium atoms ratio in the electrodeposited materials equally changes as the deposition time is increased from 0.25 to 1.00 h. This experiment clearly shows that the prediction of percentage of atoms available in a certain semiconductor material does not solely depend on deposition potential as reported by [10] but can also vary based on the growth duration. By changing the deposition time; the optoelectronic properties of the material can likewise change. The result obtained from this experiment can be a good explanation as to why a decrease was noticed in the band gap of ZnTe films as the deposition time increases (See Fig. 7). At longer duration (for example, 1.00 h), more *Zn* was electroplated than *Te* thereby resulting to a steady decrease in the energy band gap of ZnTe semiconductors as a result of the metallic nature of *Zn*.

3.4. Optical study of electrodeposited ZnTe compound semiconductors

The optical transmittance spectra of electroplated ZnTe layers grown within the explored deposition duration is shown in Fig. 6. As seen in the figure, it was noticed that the % transmittance of the deposited materials increases as the incident photon wavelength increases. Also, a reduction in the transmittance spectra was observed as the thin film thicknesses increases. ZnTe layer with ~100 nm thickness has the highest transmittance starting from ultraviolet region to visible and near infrared region while the layer with ~400 nm thickness has the least

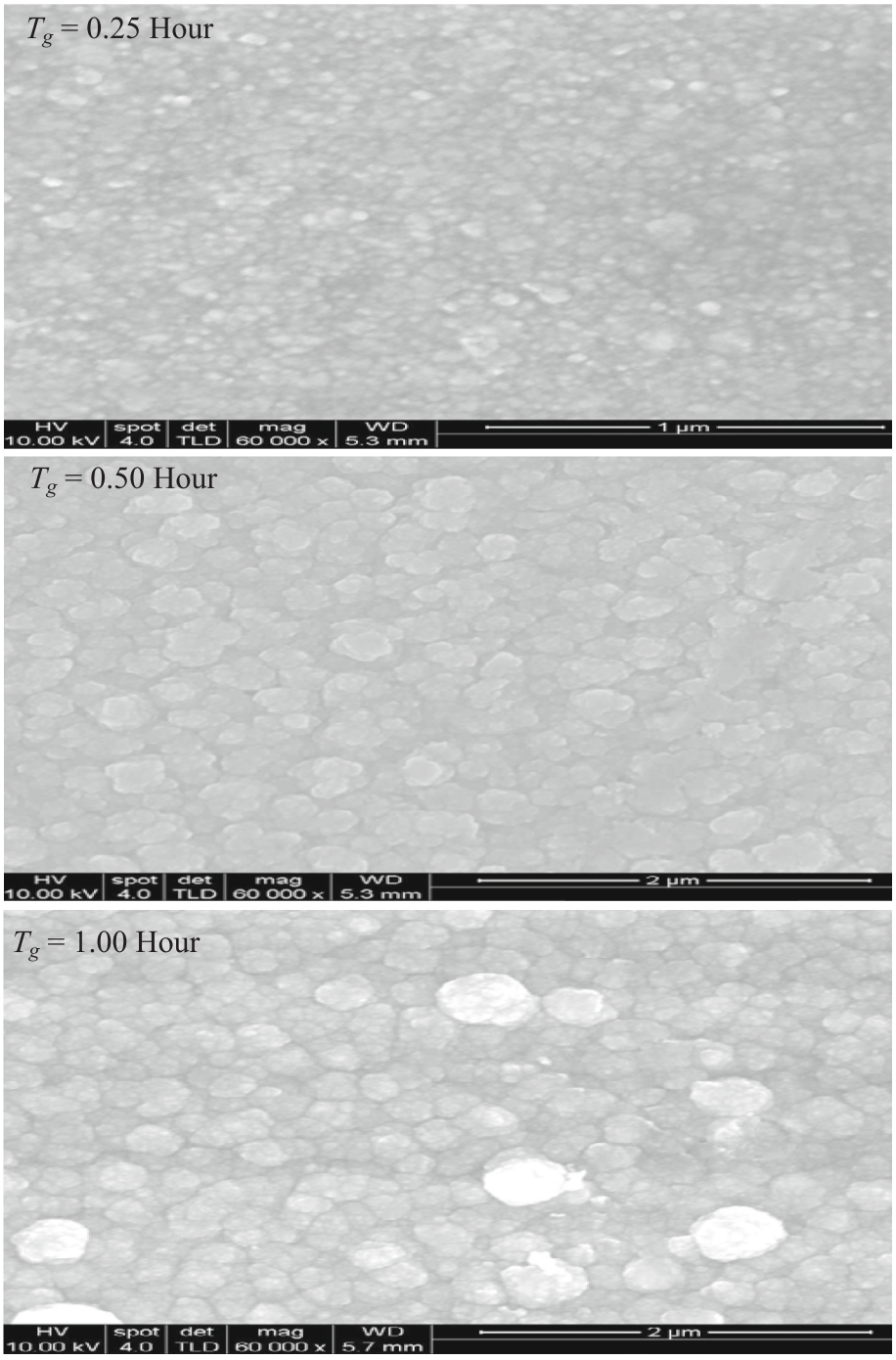

Fig. 3. SEM micrographs of ZnTe semiconductors electroplated between 0.25 and 1.00 h.

transmittance. At the infrared region, the highest transmittance was observed for all the thin films. Similar result was also reported in [11]. ZnTe has been reported to find useful application as an infrared detector possibly due to its ability to possess high transmittance at the near infrared region [17]. ZnTe layers of ~100 nm can be applied as window layer in solar cells application due to its high transmittance feature.

ZnTe layer with ~100 nm thickness exhibits the highest transmittance across the UV to near-infrared region, while the ~400 nm thick layer shows the lowest transmittance. This is due to increased absorption and scattering with increasing thickness. In the infrared region, all ZnTe films show increased transmittance relative to the visible region because photon energies are below the bandgap; this is similar to the result obtained in [11]. Due to the wide infrared transparency window, ZnTe and other II – VI binary compound semiconductors such as ZnSe can be used in infrared optical window applications and as substrates for infrared detectors [18]. High transmittance in the near-infrared (NIR) region is important for applications such as infrared optical window because it allows infrared radiation to pass through the material with minimal optical loss. This property is important as transmission window in IR spectroscopy, optoelectronic windows, and photonic devices. ZnTe thin films possess semiconductor band structures and actively interact with electromagnetic radiation while polymer-based lightweight composites mainly provide structural, thermal, or electrical-insulation functions [19]. The lightweight composites are primarily designed for mechanical reinforcement and insulation unlike ZnTe that is suitable for optoelectronic and photodetection applications.

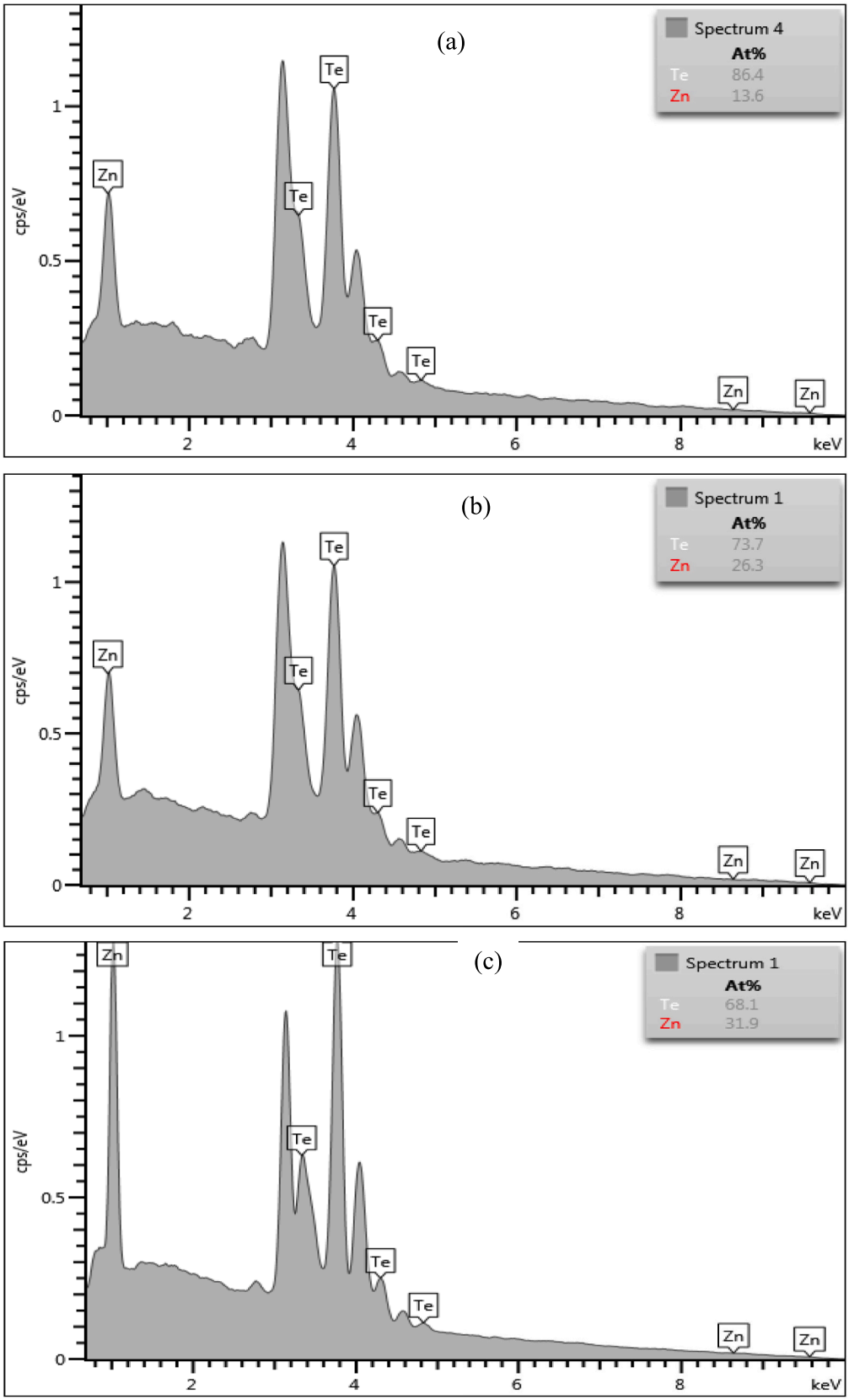

Fig. 4. The EDX spectra of ZnTe thin films electrodeposited on FTO conducting glass substrates at 1600 mV for: (a) $t_g = 0.25$ h, (b) $t_g = 0.50$ h and (c) $t_g = 1.00$ h.

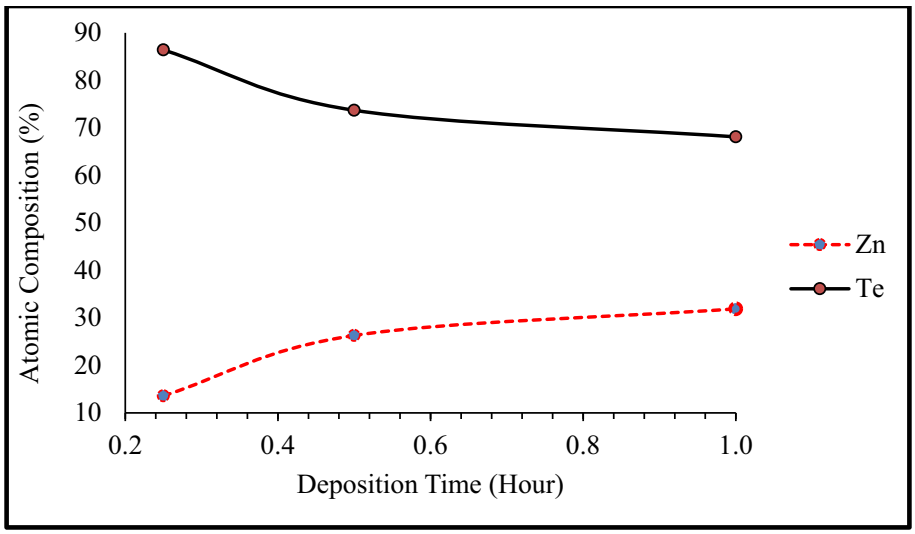

Fig. 5. Atomic compositional analysis of ED – ZnTe layers grown at durations ranging between 0.25 and 1.00 h.

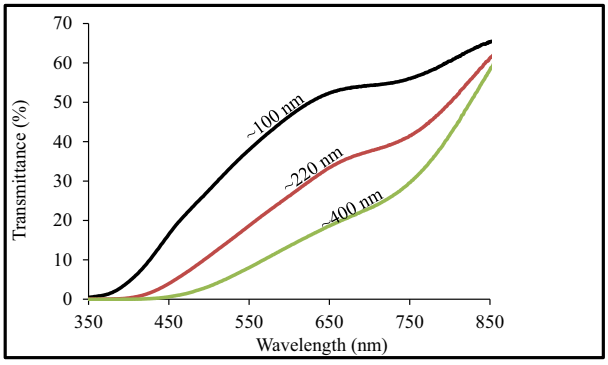

Fig. 6. Optical transmittance spectra of electrodeposited ZnTe layers of varying thicknesses.

The band gap energy of ED – ZnTe was evaluated using Tauc plot shown in Fig. 7. In this plot, a graph of $(\alpha h\nu)^2$ was plotted against the photon energy ($h\nu$). By extrapolating the line of best tangent of the plot to the ($h\nu$) axis at the point where $(\alpha h\nu)^2 = 0$, band gap values of ~2.60 eV, ~2.20 eV, and ~2.00 eV were obtained at growth duration of 15, 30 and 60 min respectively. The obtained results showed that the optical properties of electrodeposited ZnTe layers most especially the energy band gaps are dependent on the thin film thickness. This result contradicts the report given by Shaaban et al., that ZnTe layers have same energy band gaps within the author's explored thickness range [7]. The different energy gaps obtained in this work may be due to the different atomic compositions of zinc and tellurium atoms present in the ZnTe layer as discussed in section 3.3. This different composition causes the ZnTe stoichiometry to differ from one other. Also, the different grain sizes possessed by the materials at different thicknesses of 100, 220 and 400 nm can lead to this variation.

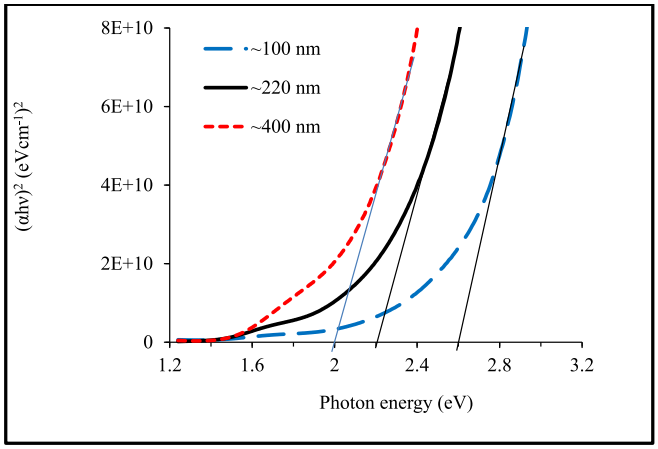

Fig. 7. The Tauc plot of electrodeposited ZnTe layers of varying thicknesses.

The observed reduction in the optical band gap from 2.60 eV to 2.00 eV as the thickness increases can thus be attributed to underlying mechanisms such as improved crystallinity, grain growth, and compositional changes in the ZnTe thin films. Enhanced crystallinity, evidenced by increased diffraction peak intensity, reduces the density of grain boundaries and defect states while promoting the growth of larger grains. In addition, the increased Zn incorporation with increasing deposition time, as confirmed by the EDX analysis, altered the film stoichiometry, which also contributed to the observed decrease in the band gap. These structural and compositional changes collectively contribute to the reduction in optical band gap. Researchers have reported that semiconductor materials with higher bandgaps have lesser grains while bigger grains are characteristic feature of materials with lesser energy band gaps; this shows that the particle sizes influences the material optical properties [20].

3.5. Electrical study of electrodeposited ZnTe layers at different thicknesses

PEC cell, current – voltage and capacitance – voltage measurement techniques were employed in determining the electronic properties of the deposited ZnTe layers. Measurements from the PEC cell revealed the p – type electrical conduction behaviour of electrodeposited ZnTe layers at varying magnitudes; this is diagrammatically represented in Fig. 8.

Device architecture comprising of p-ZnTe layers and appropriate metal contacts were fabricated to study the material resistivity and acceptor doping density. Current – voltage (I – V) technique was used in determining the material resistivity while capacitance – voltage (C – V) technique was utilised in investigating the doping density of the material. As seen in Fig. 9, the resistivity of ZnTe layers decreases with increase in thickness. Ibrahim et al., (2004) similarly reported a decrease in the resistivity of ZnTe thin films produced by thermal evaporation as the thickness increases. The authors attributed this decrease to improved crystallinity and larger grains produced at higher thickness [12]. As seen in this work, ZnTe layer with higher thickness which was grown for one

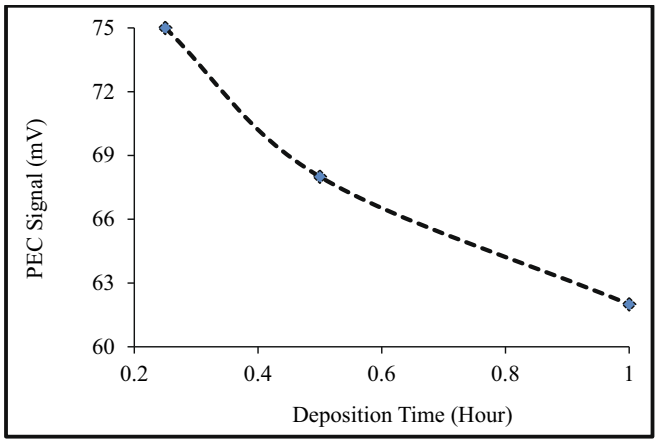

Fig. 8. PEC signals of electrodeposited ZnTe layers at varying growth duration.

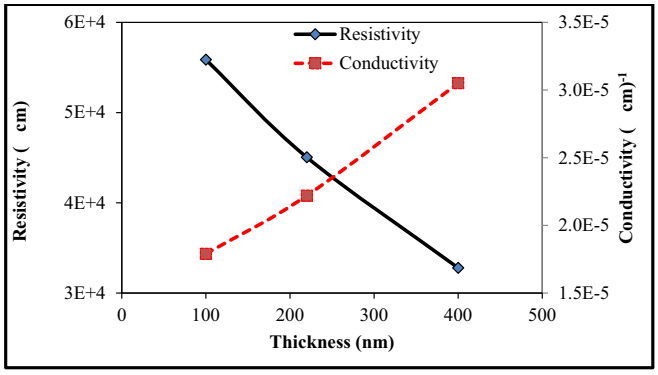

Fig. 9. Resistivity and conductivity of ZnTe layers at varying thicknesses.

hour has better crystallinity and bigger grains when compared to the ZnTe films deposited for lesser duration. Increased thickness means more films are coated on the substrate and this makes the semiconducting atoms to have more valence electrons, bigger grains as reported by [12] and as seen in Fig. 3 in this work. Thus, there will be creation of more charge carriers if the material defects are kept at a minimal level. Since more mobile charge carriers are created at higher thin film thickness, there will be more conduction electrons at the conduction band and this will further improve the material conductivity and decrease the resistivity. This explains why the conductivity of the electroplated ZnTe layers in Fig. 9 increases with the thin film thickness while the resistivity decreases as the thickness of the ZnTe layers increases.

The capacitance-voltage and Mott-Schottky plots of the devices fabricated from ZnTe layer grown for 1.00 h are shown in Fig. 10(a) and (b) respectively. ZnTe thin film layer has a depletion capacitance (C_o) of ~0.86 nF as seen in Fig. 10(a). This was used in estimating the depletion width (W) of the fabricated device to be ~337 nm. By comparing the depletion width value with the material thickness of ZnTe layers grown for 1.00 h, it can be ascertained that the material is almost fully depleted. From Fig. 10(b), acceptor doping density (N_A) of the p – ZnTe was estimated to be $\sim 8.1 \times 10^{16}$ cm^{-3}. The effective density of states of ZnTe thin films in the valence band edge (N_V) was also estimated as $\sim 2.24 \times 10^{18}$ cm^{-3}. The ZnTe layer was found to be moderately doped since the N_A is lesser than the N_V.

The fabrication of solar cell with 3 mm diameter and structure, glass \FTO\n-CdS\p-ZnTe\Au was executed with the goal of studying the electronic behaviour of the electroplated ZnTe layers. Details of preparation of the n-CdS layers can be found in [21]. The choice of using $CdCl_2$ as surface treatment to enhance the ZnTe layer crystallinity was reported by [22]. Therefore, in order to improve the material property, the heterostructure top surface was annealed ordinarily in air with and without $CdCl_2$ treatment for 10 min at temperature of 300 °C. The solar cell parameters obtained are stated in Table 1.

As seen in Table 1, the ZnTe – based solar cell device structure annealed ordinarily in air without surface treatment has the highest series resistance (R_s) and least shunt resistance (R_{sh}). The implication of this is that the cells produced from such materials will have low

Table 1
Obtained solar cell parameters of glass\FTO\n-CdS\p-ZnTe structures annealed in air with and without $CdCl_2$ surface treatment.

Samples condition	The measured parameters of fabricated solar cell device obtained under AM1.5 illumination					
	R_s (Ω)	R_{sh} (Ω)	V_{oc} (V)	J_{sc} (mAcm^{-2})	FF	η (%)
Annealed without $CdCl_2$	1667	4493	0.42	4.84	0.32	0.65
Annealed with $CdCl_2$	311	6086	0.48	19.7	0.46	4.35

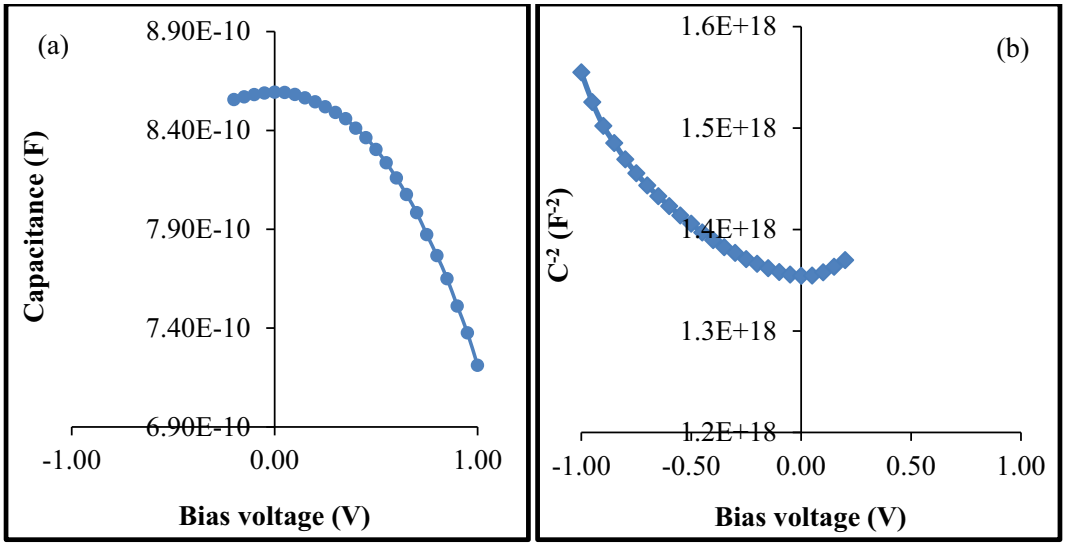

Fig. 10. (a) Capacitance-voltage and (b) Mott-Schottky plots of Schottky diode fabricated from ZnTe grown for 1.00 h.

efficiency. For solar cells to perform optimally, the R_s must be reduced to the smallest possible value while the R_{sh} should be enhanced, at least in the MΩ range. High R_s values do lead to reduction in solar cell parameters most especially the fill factor (*FF*) and they are mostly caused by the resistances from bulk materials, back – metal electrical contacts and resistance contribution from the oxide layer formed in – between the metal and semiconductor used in fabricating the electronic device [23], [24,25]. In a similar manner, low R_{sh} also lead to a significant reduction in solar cell parameters. The presence of low shunt resistance indicates there is an existence of alternative current leakage paths produced at the semiconductor interface. The lesser R_{sh} value seen in devices annealed without $CdCl_2$ treatment showed that some of the photogenerated charge carriers are lost through the leakage paths and this effect is seen in the reduced short circuit current density (J_{sc}) value. This implies that the net current flowing through the external circuit decreases and this can ultimately lower the cell performance. The leaked currents give rise to what is known as reverse saturation current and this is a possible cause for diodes (or basically solar cells measured under dark condition) with low R_{sh} values to possess high leakage current due to the alternative path provided by the low R_{sh}.

As seen in Table 1, the application of $CdCl_2$ lowers the R_s value and enhanced the R_{sh} value; this aided the reduction of leakage paths through which the photogenerated charge carriers can flow through. $CdCl_2$ treatment has the ability to improve device performance by: promoting grain growth and improving crystallinity as reported by [26], reducing recombination centres, increasing shunt resistance, and lowering series resistance as seen in this work. The effect of the surface treatment can be seen in the improvement of solar cell parameters and in the overall, an efficiency enhancement of ZnTe – based solar cells from 0.65% to 4.35% after $CdCl_2$ treatment. Elimination of tellurium – related defects is also made possible with the $CdCl_2$ treatment [27]. The I – V characteristics of the cells developed from glass\FTO\n-CdS\p-ZnTe heterostructure treated in the absence and presence of $CdCl_2$ aqueous solution are illustrated in Figs. 11 and 12 respectively. Several solar cells with the $CdCl_2$ heat-treated device configuration were fabricated and characterized. Fig. 13 shows the statistical distribution of photovoltaic parameters obtained from 5 devices. The efficiencies measured were 3.10%, 3.18%, 3.88%, 4.20%, and 4.35% with an average of 3.74 ± 0.54%. The observed variation in efficiency is attributed to small differences in film thickness uniformity, back contact reproducibility, and pinhole density across the measured devices. For the purpose of this work, the cell with the highest efficiency of 4.35% is reported.

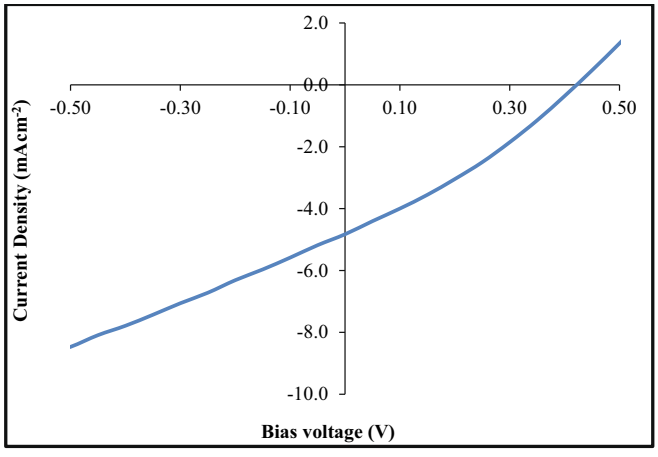

Fig. 11. A.M 1.5 illuminated I-V characteristics of solar cell developed from glass\FTO\n-CdS\p-ZnTe device architecture annealed without $CdCl_2$ treatment.

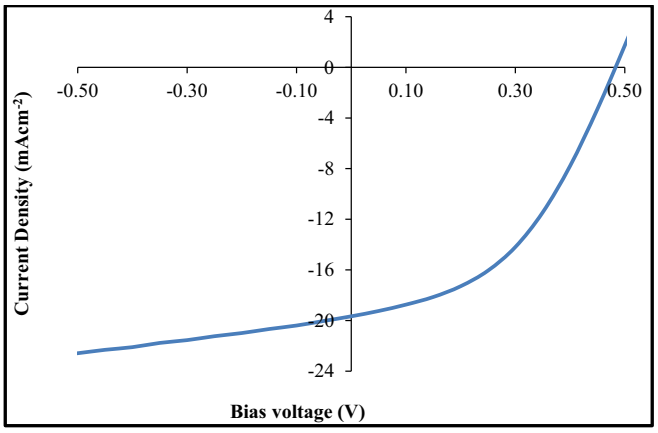

Fig. 12. A.M 1.5 illuminated I-V characteristics of solar cell developed from glass\FTO\n-CdS\p-ZnTe heterostructure annealed with $CdCl_2$ treatment.

4. Conclusion

The experimental investigations carried out revealed that deposition duration variation influenced the thickness and optoelectronic properties of electrodeposited ZnTe compound semiconductor. The optical investigation revealed that the energy gap decreases as thin film thickness increases. Thus, the band gap tunability from 2.60 eV to 2.00 eV is made possible by varying the deposition duration of the electrodeposited ZnTe layers from 15 min to 60 min. In a similar pattern, the higher optical transmittance observed at lesser growth duration will make the investigated material a suitable window candidate for solar cells fabrication. Improved crystallinity and larger grains were also observed as the thickness of ZnTe thin films increased. The experimental investigations revealed an increase of grain size from ~90 nm to ~380 nm as the deposition duration was increased from 15 min to 60 min. The EDX results demonstrate that increasing deposition duration alters the Zn/Te atomic ratio, indicating that growth time affects film stoichiometry in addition to thickness. These compositional variations contribute to the observed band-gap tuning and ultimately influence the electrical characteristics and photovoltaic performance of CdS/ZnTe heterojunction devices. The p – type electrical conductivity, moderate resistivities within the order of 10^4 Ωcm, tunable band gap and moderate doping of the material make the studied materials appropriate for optoelectronic applications such as solar cells. The solar cells fabrication using the structure, glass\FTO\n-CdS\p-ZnTe\Au established the suitability of ZnTe layers as hetero-partner to n-type CdS semiconductor. The application of $CdCl_2$ on the top layer of the device structure as means of surface treatment revealed that the cell efficiency can be enhanced. Though the current efficiency is low, future investigation is aimed at further improving the material properties, optimize interface quality, and carrier transport in other to achieve a more effective solar cell device.

CRediT authorship contribution statement

O.I. Olusola: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **N.E. Adesiji:** Writing – original draft, Visualization, Investigation. **O.O. Olusola:** Writing – original draft, Investigation. **A.F. Afolabi:** Writing – review & editing, Investigation. **A. A. Faremi:** Writing – review & editing, Investigation. **Edson L. Meyer:** Writing – review & editing, Resources, Funding acquisition. **Mojeed A. Agoro:** Writing – review & editing, Validation, Resources, Project administration, Funding acquisition, Formal analysis. **T.M.W.J. Bandara:** Writing – review & editing, Data curation. **Nandu B. Chaure:** Writing – review & editing, Validation, Data curation. **M. Furlani:**

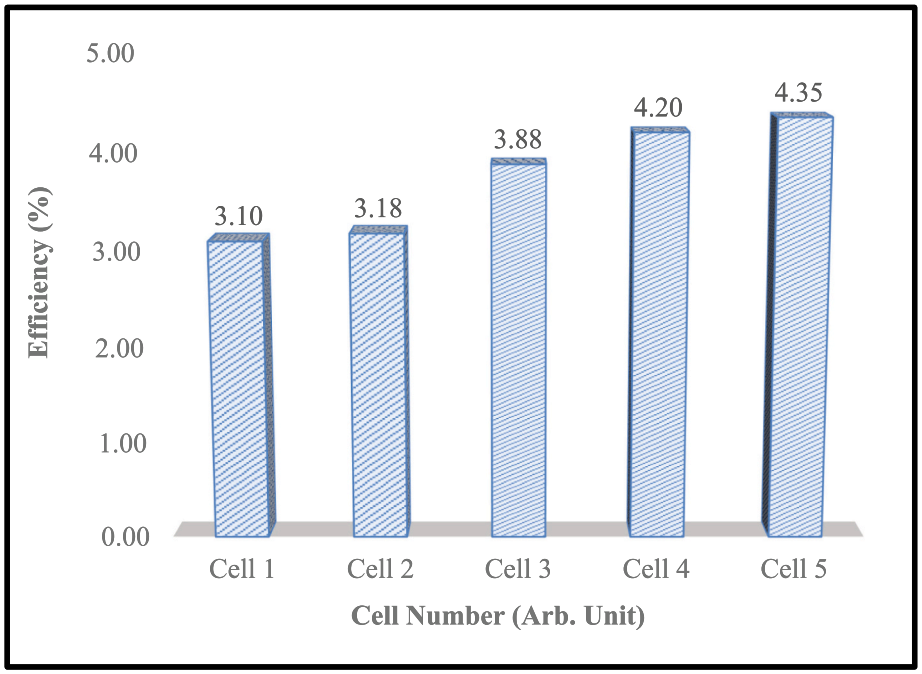

Fig. 13. Statistical distribution of power conversion efficiency for $CdCl_2$ heat-treated CdS/ZnTe solar cells (Note: Five devices were measured with efficiencies ranging from 3.10% to 4.35%, giving an average of 3.74 ± 0.54%).

Writing – review & editing, Validation, Resources. **B.-E. Mellander:** Writing – review & editing, Supervision, Resources. **M.A.K.L. Dissanayake:** Validation, Supervision, Methodology. **S.S. Oluyamo:** Writing – review & editing, Supervision, Methodology. **I. Albinsson:** Supervision, Resources, Project administration, Funding acquisition.

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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Data availability

Data will be made available on request.

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