Investigation of the Current-Voltage Characteristics of CdS/CdTe-Based Solar Cells Using Model Calculations

[1]A.E. Nwogwugwu, [2]O.K. Echendu, [3]B.C. Anusionwu

[1, 2, 3]Physics Department, Federal University of Technology, P.M.B 1526 Owerri, Imo State, Nigeria

[1]adaeze.nwogwugwu@gmail.com, [2]oechendu@yahoo.com, [3]abedec@yahoo.com

Abstract

CdTe can be grown as n-type or p-type although the p-type can also be formed by converting n-CdTe to p-CdTe through the well known $CdCl_2$ treatment, which is an important step taken to improve the conversion efficiency of CdTe solar cells. However, the assumption by most researchers is that CdTe is always a p-type material and so can only form a p-n junction with its n-CdS counterpart. This is not always the case as n-n heterojunction + Schottky junction can be formed when an n-CdTe is involved, with group I metals such as Au and Cu as back metal contact. In this work, p-n junction model and Schottky junction model are presented. In order to verify the junction type formed by various CdS/CdTe-based solar cells reported in the literature, current-voltage data of these experimental results are simulated with the junction models using MATLAB programming platform and compared so as to find out the junction model that best describes each experimental result. Diode parameters such as ideality factor, barrier height, and series resistance were adjusted during the simulation. The junction models are found to be in good agreement with some of the experimental results.

Keywords: CdS/CdTe-based solar cell, J-V characteristics, p-n junction, Schottky junction, MATLAB, junction model.

1. Introduction

In the photovoltaic industry, there has been constant research to produce low cost and high conversion efficiency solar cells. A promising device in this field is thin-film CdS/CdTe heterojunction solar cell. CdS and CdTe form a good combination for solar cell application. CdS has a wide band gap of 2.42 eV and serves as the transparent window layer that allows a wide portion of the solar spectrum to reach the absorber layer [1]. CdTe on the other hand has a narrow band gap of 1.45 eV with high absorption coefficient, which makes it very suitable for the absorption of light from the major parts of the solar spectrum for photovoltaic conversion. Therefore, the CdTe absorber layer requires only a few micrometers thickness to absorb more than 90% of solar radiation with photon energy above the band gap [2]. CdTe also has high chemical stability. All of these make it a very interesting material for the production of thin-film solar cells. Although there is a lattice mismatch of about 10% between CdS and CdTe, the heterojunction formed between them has an extremely good electrical property which results in high fill factor in excess of 0.77 in produced solar cells [3].

CdS is usually the n-type counterpart while CdTe can be p-type or n-type depending on the stoichiometry of the material and external dopants added. P-type conductivity is exhibited by Te-rich layers of CdTe, while n-type conductivity is exhibited by Cd-rich layers of CdTe [4]. Also, during $CdCl_2$ treatment which is an important process taken to improve the conversion efficiency of CdTe solar cells, n-CdTe can be converted to p-CdTe [5]. This type of conversion has also been shown to go the other way round or even not to take place at all depending on the defect distribution in the CdTe starting material [4, 6-9]. However, the assumption by some researchers is that CdTe exists only as a p-type semiconductor and so always forms a p-n junction with CdS. Therefore, they described CdS/CdTe solar cells as p-n junction devices while other researchers described them as n-n heterojunction + Schottky junction devices based on the n-type CdTe. The aim of this paper, therefore, is to model and verify the type of junction formed by various experimentally reported CdS/CdTe-based solar cells in the literature.

2. Modeling and simulation

In this work, MATLAB, which stands for Matrix Laboratory, is used for all modeling and simulations. In general, the dark current-voltage characteristics of a diode such as a solar cell are described by the Shockley diode equation below [10]

$$J = J_0 \left[\exp\left(\frac{qV}{nkT}\right) - 1\right] \quad (1)$$

where J is current density ($J = I/A$, where I is current, and A is device active area), J_0 is reverse saturation current density, q is electron charge, V is bias voltage, n is diode ideality factor, k is Boltzmann constant, and T is absolute temperature.

For an n-type semiconductor-based Schottky barrier junction, assuming thermionic emission theory, the reverse saturation current density, J_0, is given by equation 2 [10].

$$J_0 = A^* T^2 \exp\left(-\frac{q\phi_B}{kT}\right) \quad (2)$$

where A^* is effective Richardson constant, T is absolute temperature, q is electron charge, ϕ_B is Schottky barrier height, and k is Boltzmann constant.

In the case of p-n junction model, assuming diffusion theory, the reverse saturation current density, J_0, is given by equation 3 [11].

$$J_0 = q\, N_V N_C \left[\frac{1}{N_A}\sqrt{\frac{D_n}{\tau_n}} + \frac{1}{N_D}\sqrt{\frac{D_p}{\tau_p}}\right] \mathrm{e}^{-\mathrm{E_g}/\mathrm{kT}} \quad (3)$$

where N_v is effective density of states of holes in the valence band, N_c is effective density of states of electrons in the conduction band, N_A is acceptor concentration, D_n is diffusion coefficient of electron, τ_n is electron carrier lifetime, N_D is donor concentration, D_p is diffusion coefficient of hole, τ_p is hole carrier lifetime, and E_g is band gap of the semiconductor involved. However, this equation is based on a p-n homojunction whereby the p-type and the n-type semiconductors are of the same material.

Under illumination condition, the current-voltage characteristics of both the Schottky junction and p-n junction models are in the simplest form described by the Shockley diode equation under illumination, according to equation 4 below [10].

$$J = J_0 \left[\exp\left(\frac{qV}{nkT}\right) - 1\right] - J_{SC} \quad (4)$$

where J is photocurrent density, J_0 is reverse saturation current density, and J_{sc} is short-circuit current density. The reverse saturation current density, J_0, for each junction type remains the same as in the dark condition.

Considering the effect of series resistance R_S, the voltage V in the diode equations is replaced with $V\text{-}JR_S$ [10]. Thus equation 1 can be rewritten as

$$J = J_0 \left[\exp\left(\frac{q(V - JR_S)}{nkT}\right) - 1\right] \quad (5)$$

while equation 4 can be rewritten as

$$J = J_0 \left[\exp\left(\frac{q(V - JR_S)}{nkT}\right) - 1\right] - J_{SC} \quad (6)$$

Equations 5 and 6 are then simulated and used to verify the junction types formed in some CdS/CdTe-based solar cells reported in the literature.

3. Results and discussion

In order to get the junction model that best describes each of the experiments, diode parameters like barrier height (ϕ_B), ideality factor (n), and series resistance (R_S) were varied during simulation. The simulated results of the dark and illuminated J-V characteristics are presented in Figures 1-5.

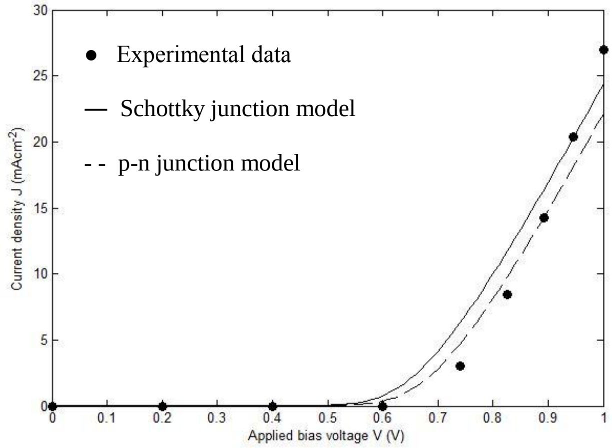

Figure1a: Dark J-V plot of n-CdS/p-CdTe solar cell with Cu/HgTe/graphite back contact [12] simulated with the p-n junction model and the Schottky junction model.

From Figure 1a, it can be seen that at a voltage of 0.6 V the current density for both models increased a little. Subsequently, the current density of the experiment started increasing with the experiment being closer to the p-n junction model up to a voltage of 0.89 V when it then goes closer to the Schottky junction model. The experiment was reported by Cahen *et al* [12] to be a typical dark J-V curve of a p-n junction. From the simulation result, it is evident that the experiment is best described by the p-n junction model. Thus, the junction type formed in the experiment agrees with the p-n junction model. The values of the adjustable parameters used in the simulation are ϕ_B = 0.97 eV, n = 1.39, R_S = 11.7 Ωcm^2.

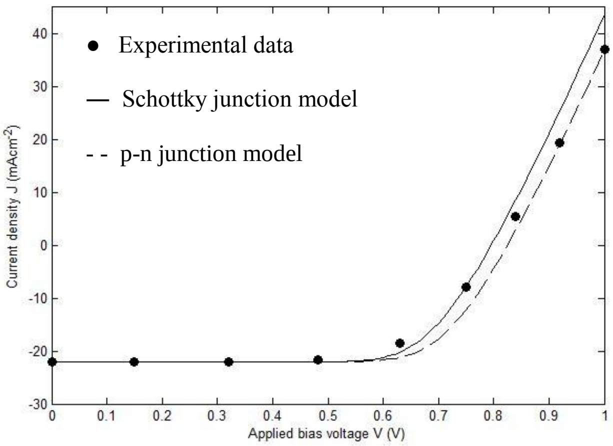

Figure 1b: Illuminated J-V plot of n-CdS/p-CdTe solar cell with Cu/HgTe/graphite back contact [12] simulated with the p-n junction model and the Schottky junction model.

Figure 1b is the illuminated J-V plot of Figure 1a. From this illuminated J-V plot, it is observed that at a voltage of 0.48 V, the current densities of the experiment and the junction models increase slightly with the increase being more noticeable in the experiment. The experiment can be seen to be closer to the Schottky junction model up to a voltage of 0.75 V, and then moves very closely towards the p-n junction model as the current further increases. Therefore, the experiment agrees partly with the Schottky junction model and partly with the p-n junction model. This is unlike its dark J-V plot (Figure 1a) that is in good agreement with the p-n junction model. The simulation was done with values of the adjustable parameters given as ϕ_B = 0.97 eV, n = 1.39, R_S = 3.8 Ωcm^2.

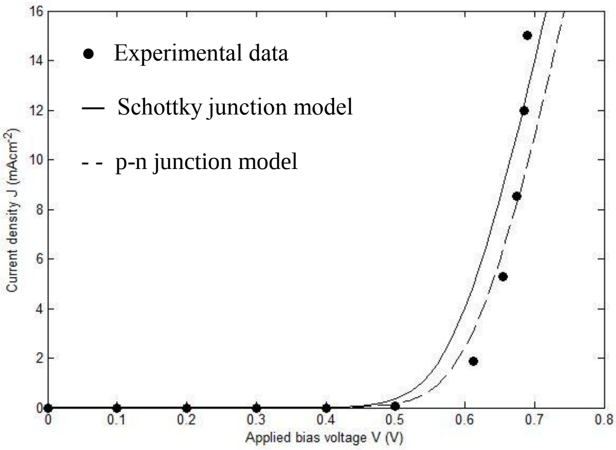

Figure 2a: p-n junction model and Schottky junction model simulated with dark J-V curve of n-CdS/p-CdTe/ZnTe/ZnTe:Cu structure [13].

In Figure 2a, the experiment as reported by Wu *et al* [13] involved the use of n-CdS and and p-CdTe, which indicates the presence of a p-n junction. Taking a look at the figure, it is noticeable that at 0.5 V there is a little increase in current density for the experiment and also for the junction models. At that same voltage, the experiment can be seen to be nearer to the p-n junction model than it is to the Schottky junction model. However, from 0.67 V it begins to go close to the Schottky junction model. Based on these observations, the experiment is said to agree with the p-n junction model since it maintains a longer closeness with it than with the Schottky junction model. The values of the adjustable parameters used in the simulation are ϕ_B = 0.97 eV, n = 1.23, R_S = 6.1 Ωcm^2.

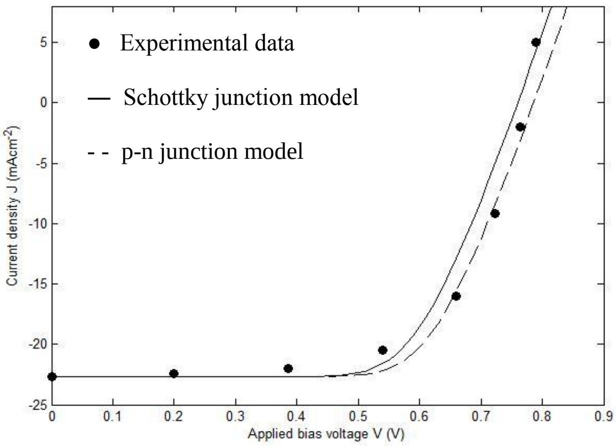

Figure 2b: The p-n junction model and the Schottky junction model simulated with illuminated J-V curve of n-CdS/p-CdTe/ZnTe/ZnTe:Cu structure [13].

In Figure 2b, which is the illuminated J-V curve of Figure 2a, the current density of the experiment starts to increase early at 0.2 V thereby shifting away from the models. As it increases further, it cuts across the Schottky junction model and goes very close to the p-n junction model, almost aligning with it until around 0.76 V when it deviates significantly from it and moves towards the Schottky junction model. Thus, it can be said that the p-n junction model best describes the experiment and is in agreement with the experimental result. The values of the adjustable parameters used in the simulation are ϕ_B = 0.97 eV, n = 1.23, R_S = 5.7 Ωcm^2.

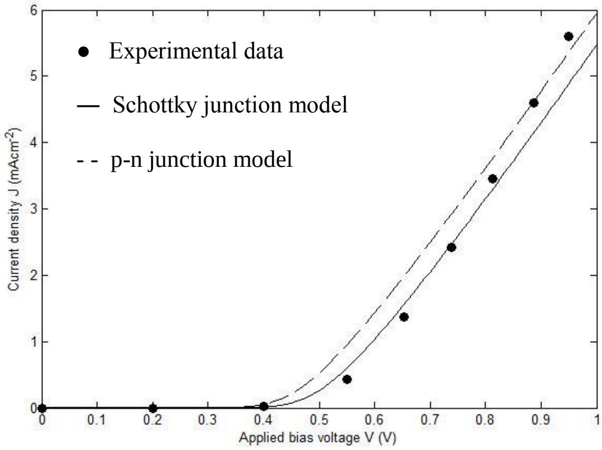

Figure 3a: Simulation of the p-n junction model and the Schottky junction model with room temperature dark J-V characteristics of glass/FTO/n-CdS/n-CdTe/Au device [5].

The experiment corresponding to Figure 3a resulted in the formation of an n-n heterojunction and Schottky junction, as reported by Echendu *et al* [5]. This was achieved by fabricating n-CdS/n-CdTe solar cell with Au metal contact. Looking at the figure, the experiment is seen to follow the Schottky junction model closely from a voltage of 0.4 V up to 0.81 V when it eventually shifts away from it and goes towards the p-n junction model. This indicates the presence of a Schottky junction in the experiment thereby verifying the junction type formed in the experiment as explained by the authors. For this simulation, the values of the adjustable parameters are ϕ_B = 1.03 eV, n = 1.05, R_S = 80 Ωcm^2.

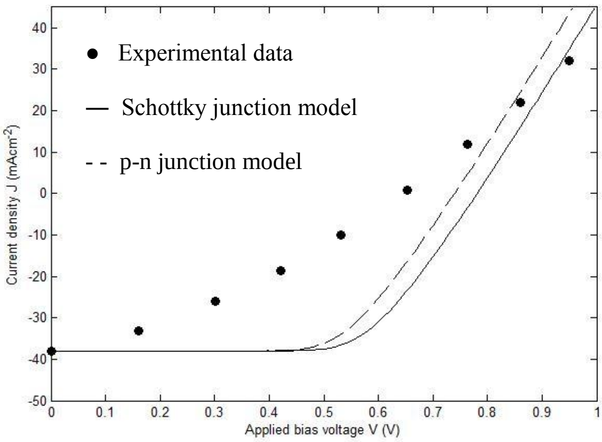

Figure 3b: Simulation of the p-n junction model and the Schottky junction model with room temperature illuminated J-V characteristics of glass/FTO/n-CdS/n-CdTe/Au device [5].

Figure 3b, which is the illuminated J-V curve of Figure 3a, is for an experiment with a very low fill factor and therefore, cannot be described by any of the models. The low fill factor is possibly due to high series resistance and formation of recombination centers during the device processing as reported in the experiment by the authors of the work [5]. The values of the adjustable parameters for this simulation are ϕ_B = 1.03 eV, n = 1.05, R_S = 4.35 Ωcm^2.

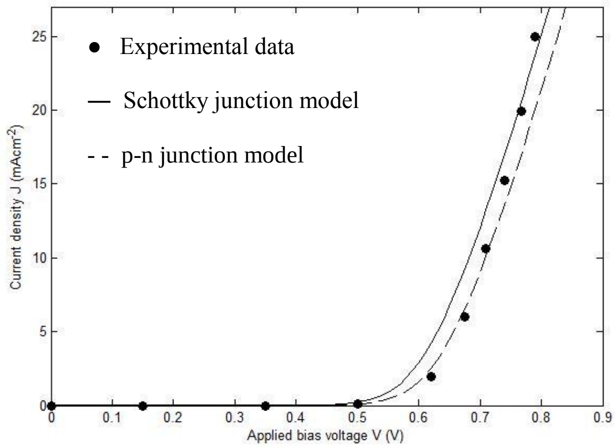

Figure 4a: Dark J-V curve of n-CdS/p-CdTe/$Cu_{1.4}Te$ solar cell [14] simulated with the Schottky junction model and the p-n junction model.

Figure 4a shows how the experiment fits the p-n junction model very closely until around 0.71 V when it starts deviating from it, moving towards the Schottky junction model as the current density further increases. Luo *et al* [14] reported that the experiment was done using an n-CdS and a p-CdTe and this implies that a p-n junction was formed. The result shows that the experiment is in good agreement with the p-n junction model. The values of the adjustable parameters for this simulation are ϕ_B = 0.97 eV, n = 1.27, R_S = 5.8 Ωcm^2.

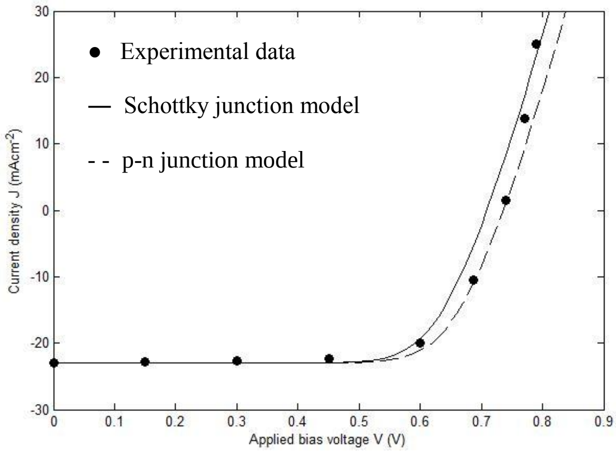

Figure 4b: Illuminated J-V curve of n-CdS/p-CdTe/$Cu_{1.4}Te$ solar cell [14] simulated with the Schottky junction model and the p-n junction model.

Figure 4b is the illuminated J-V curve of Figure 4a. It is noticeable in this figure that as the current density increases, the experiment maintains a closer proximity to the Schottky junction model. At 0.69 V, the experiment is seen to be very close to the p-n junction model up to 0.74 V when it starts deviating from it and moves back to the Schottky junction model. This shows the presence of both models in the experiment with the Schottky junction model being prevalent. The values of the adjustable parameters used in this simulation are ϕ_B= 0.97 eV, n = 1.27, R_S = 2.5 Ωcm^2.

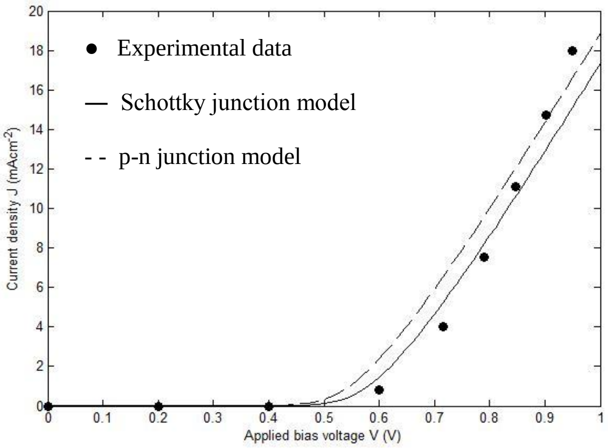

Figure 5a: Simulation of dark J-V graph for glass/FTO/n-ZnS/n-CdS/n-CdTe/Au 3-layer solar cell [15] with the Schottky junction model and the p-n junction model.

The experiment in Figure 5a is similar to the one in Figure 3a except that in the case of Figure 5a, two n-n heterojuctions and a Schottky junction were formed as reported by Echendu and Dharmadasa [15]. Figure 5a shows that the experiment is closer to the Schottky junction model than it is to the p-n junction model and so it is best described by the Schottky junction model. Therefore, the junction type formed in the experiment is in agreement with the Schottky junction model. For this simulation, the values of the adjustable parameters are ϕ_B = 1.02 eV, n = 1.16, R_S = 20.5 Ωcm^2.

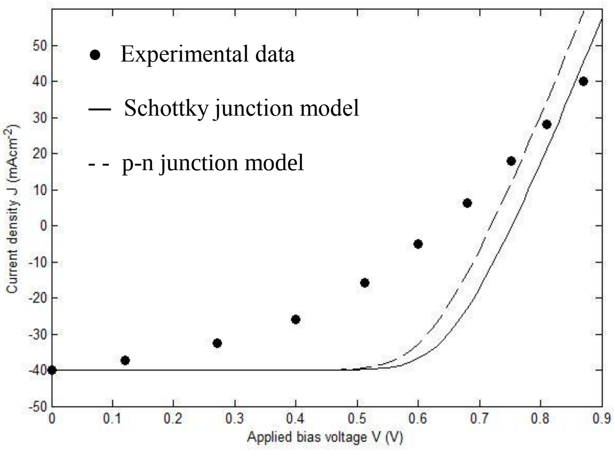

Figure 5b: Simulation of illuminated J-V graph for glass/FTO/n-ZnS/n-CdS/n-CdTe/Au 3-layer solar cell [15] with Schottky junction model and p-n junction model.

Figure 5b, being the J-V curve for Figure 5a under illumination condition, has a low fill factor for the experiment just like the experiment corresponding to Figure 3b and also cannot be described by any of the models. It was reported in the experiment that the low fill factor is due to high series resistance as a result of recombination and generation centers having high concentration in the device structures. The values of the adjustable parameters used in this simulation are ϕ_B = 1.02 eV, n = 1.16, R_S = 2.08 Ωcm^2.

4. Conclusion

In summary, the junction types of some CdS/CdTe-based experiments obtained from the literature were verified. This was achieved through modeling and simulation and by adjusting some of the diode parameters. The dark and illuminated J-V curves of the experiments showed good agreement with some of the theoretical models. The results show that CdTe does not only exist as a p-type material but also as an n-type material and so can form a p-n junction or an n-n heterojunction + Schottky barrier junction with its n-CdS counterpart in devices such as solar cells.

References

1. S. Babkair, "Charge Transport Mechanisms and Device Parameters of CdS/CdTe Solar Cells Fabricated by Thermal Evaporation," *J. King Abdulaziz Univ.*, vol. 22, no. 1, pp. 21–33, 2010.

2. M. Wimbor, A. Romeo, and M. Igalson, "Electrical characterisation of CdTe/CdS photovoltaic devices," *Opto-Electronics Rev.*, vol. 8, no. 4, pp. 375–377, 2000.

3. X. Wu, "High-Efficiency Polycrystalline CdTe Thin-Film Solar Cells," *Solar Energy,* vol.77, no. 6, pp. 803-814, 2004.

4. I.M. Dharmadasa, "Review of the $CdCl_2$ Treatment Used in CdS/CdTe Thin Film Solar Cell Development and New Evidence towards Improved Understanding," *Coatings*, vol. 4, no. 2, pp. 282–307, 2014.

5. O.K. Echendu, F. Fauzi, A. R. Weerasinghe, and I. M. Dharmadasa, "High Short-Circuit Current Density CdTe Solar Cells Using All-Electrodeposited Semiconductors," *Thin Solid Films*, vol. 556, pp. 529–534, 2014.

6. T. Schulmeyer, J. Fritsche, A. Thißen, A. Klein, W. Jaegermann, M. Campo, J. Beier, "Effect of In Situ UHV $CdCl_2$-Activation on the Electronic Properties of CdTe Thin Film Solar Cells," *Thin Solid Films*, vol. 431-432, pp. 84-89, 2003.

7. I.M. Dharmadasa, P.A. Bingham, O.K. Echendu, H.I. Salim, T. Druffel, R. Dharmadasa, G.U. Sumanasekera, R.R. Dharmasena, M.B. Dergacheva, K.A. Mit, K.A. Urazov, L. Bowen, M. Walls, A. Abbas, "Fabrication of CdS/CdTe Based Thin Film Solar Cells Using an Electrochemical Technique," *Coatings*, vol. 4, pp. 380-415, 2014.

8. C. Li, Y. Wu, J. Poplawsky, T.J. Pennycook, N. Paudel, W. Yin, S.J. Haigh, M.P. Oxley, A.R. Lupini, M. Al-Jassim, S.J. Pennycook, Y. Yan, "Grain-boundary enhanced carrier collection in CdTe solar cells," *Phys. Rev. Lett.*, vol. 112, no. 15, 2014.

9. O.K. Echendu and I.M. Dharmadasa, "The Effect on CdS/CdTe Solar Cell Conversion Efficiency of the Presence of Fluorine in the Usual $CdCl_2$ Treatment of CdTe," *Materials Chemistry and Physics*, vol. 157, pp. 39-44, 2015.

10. S.M. Sze and K.K. Ng, "Physics of Semiconductor Devices," 3rd edition, *John Wiley & Sons, Inc., New Jersey, United States of America,* 2007.

11. T. Soga, "Nanostructured Materials for Solar Energy Conversion," Chapter1, Edited by Tetsu Soga and Published by *Elsevier,* 2006.

12. D. Cahen, K. Gartsman, G. Hodes, O. Rotlevy, I. Visoly-Fisher, & K. Dobson, "Overcoming Degradation Mechanisms in CdTe Solar Cells," 2000. Retrieved July 18, 2017 from https://digital.library.unt.edu/ark:/67531/metadc710520/m2/1/high_res_d/754634.pdf

13. L. Wu, L. Feng, W. Li, J. Zhang, B. Li, Z. Lei, ... J. Zheng, "Effect of ZnTe/ZnTe:Cu Complex Back-Contact on Device Characteristics of CdTe Solar Cells". *Science in China, Series E: Technological Sciences*, vol. 50, no. 2, pp. 199–205, 2007.

14. G. Luo, B. Lv, W. Li, L. Feng, J. Zhang, L. Wu, & G. Zeng, "Characterization of $Cu_{1.4}Te$ Thin Films for CdTe Solar Cells". *International Journal of Photoenergy*, vol. 2014, Article ID 762576, 5 pages, 2014.

15. O.K. Echendu & I.M. Dharmadasa, "Graded-Bandgap Solar Cells Using All-Electrodeposited ZnS, CdS and CdTe Thin-Films". *Energies*, vol. 8, no. 5, pp. 4416–4435, 2015.