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Research Article

Non-Toxic Buffer Layers in Flexible Cu(In,Ga)Se_2 Photovoltaic Cell Applications with Optimized Absorber Thickness

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Absorber layer thickness gradient in $Cu(In_{1-x}Ga_x)Se_2$ (CIGS) based solar cells and several substitutes for typical cadmium sulfide (CdS) buffer layers, such as ZnS, ZnO, ZnS(O,OH), $Zn_{1-x}Sn_xO_y$ (ZTO), ZnSe, and In_2S_3, have been analyzed by a device emulation program and tool (ADEPT 2.1) to determine optimum efficiency. As a reference type, the CIGS cell with CdS buffer provides a theoretical efficiency of 23.23% when the optimum absorber layer thickness was determined as 1.6 μm. It is also observed that this highly efficient CIGS cell would have an absorber layer thickness between 1 μm and 2 μm whereas the optimum buffer layer thickness would be within the range of 0.04–0.06 μm. Among all the cells with various buffer layers, the best energy conversion efficiency of 24.62% has been achieved for the ZnO buffer layer based cell. The simulation results with ZnS and ZnO based buffer layer materials instead of using CdS indicate that the cell performance would be better than that of the CdS buffer layer based cell. Although the cells with ZnS(O,OH), ZTO, ZnSe, and In_2S_3 buffer layers provide slightly lower efficiencies than that of the CdS buffer based cell, the use of these materials would not be deleterious for the environment because of their non-carcinogenic and non-toxic nature.

1. Introduction

Solar cells based on thin-film $CuInSe_2$ (CIS) and $Cu(In_{1-x}Ga_x)Se_2$ (CIGS) absorbers have major contributions in photovoltaic technology due to their lower cost, flexible modules, and high energy conversion efficiency of more than 21% [1–4]. The absorber works as a p-type doped area into a CIS and CIGS model with a typical thickness of 1-2 μm [5]. For the CIS absorber layer, the band gap is about 1 eV (0.98–1.04 eV) [6]. By introducing the gallium content, [Ga]/([Ga + In]), into the CIS absorber, the band gap of CIGS can be varied from 1.04 to 1.7 eV [4] although the optimal band gap of CIGS ranges from 1.16 eV to 1.38 eV due to the Ga grading in the CIS absorber [7–10]. To show the effects of absorber band gap on the properties of the CIGS solar cell, in this study, the CIGS band gap is optimized as 1.25 eV for [Ga]/([Ga + In]) = 0.45 [11]. While growing CdS buffer on the CIGS absorber, the critical thickness of the CdS buffer layer was found to be around 50 nm. Besides this, the chemical bath-deposited (CBD) ZnS buffer layer having a wider band gap (E_g = 3.68 eV) has shown the second highest efficiency in the thin-film technology for the replacement of CdS [12]. Atomic layer-deposited (ALD) $Zn_{1-x}Sn_xO_y$ (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% [11]. The wider band gap of ZTO is used as it permits transmitting the photons having lower wavelength into the absorber. 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 3.30 eV, which is 0.88 eV wider than that of CdS (E_g = 2.42 eV). But with the ZnO buffer layer, the cell does not show the light-soaking effect [13]. During the heteroepitaxial growth of the buffer layer using the atomic layer deposition (ALD) technique, the existence of the effect is realized. This effect is primarily associated with the surface properties of the CIGS absorber. To subside the light-soaking effect, the CIGS

Table 1: Material parameters for CIGS solar cell simulation.

Parameters	ZnO : Al	i-ZnO	CdS	CIGS
Thickness, τ (μm)	0.2	0.02	0.05	1
Dielectric constant, E_{ps}	7.8	7.8	12	13.6
Refractive index, N_{dx}	2	2	3.15	3.67
Band gap, E_g (eV)	3.30	3.30	2.42	1.25
Electron affinity, χ_e (eV)	4.6	4.6	3.74	4.19
Donor concentration, N_d (cm^{-3})	5×10^{16}	1×10^{17}	3×10^{16}	0
Acceptor concentration, N_a (cm^{-3})	0	0	0	2×10^{16}
Electron mobility, μ_n ($cm^2 V^{-1} s^{-1}$)	100	100	120	110
Hole mobility, μ_p ($cm^2 V^{-1} s^{-1}$)	25	25	40	35
Conduction band effective density of states, N_c (cm^{-3})	2.2×10^{18}	2.2×10^{18}	2.2×10^{18}	2.2×10^{18}
Valence band effective density of states, N_v (cm^{-3})	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}

Table 2: Base parameters of the substitute buffer layers.

Parameters	ZnO	ZnS	ZnS(O,OH)	$Zn_{1-x}Sn_xO_y$	ZnSe	In_2S_3
τ (μm)	0.03	0.04	0.05	0.05	0.04	0.05
E_g (eV)	3.30	3.68	3.80	3.74	2.71	2.90
χ_e (eV)	4.60	4.13	4.24	4.06	4.09	3.85
N_d (cm^{-3})	1×10^{17}	5×10^{16}	1×10^{17}	1×10^{17}	2×10^{17}	1×10^{17}
μ_n ($cm^2 V^{-1} s^{-1}$)	100	250	200	160	60	400
μ_p ($cm^2 V^{-1} s^{-1}$)	30	70	60	40	20	120

surface is doped or etched with Zn, and hence, the solar cell with the ALD technique yielded an efficiency of 13.9% [14]. Besides the CdS, ZnS, and ZnO based buffer layers, we also investigate the properties of ZnSe, In_2S_3, and ZnS(O,OH) buffer layers and their effects on the CIGS solar cell performance.

2. Experimental

ADEPT 2.1 (a device emulation program and tool: version 2.1) is a one-dimensional online simulator to analyze the electrical and optical characteristics of silicon based solar cells, CIGS and CdTe based thin films, GaAs solar cells, and so on [15]. In this paper, ADEPT 2.1 was used to simulate and investigate CIGS solar cell properties with different buffer layers. Current-voltage characteristics in light and dark conditions can be achieved from the simulation carried out by ADEPT 2.1 simulation. For all the solar cell structures, quantum efficiency, *J-V* characteristics, electric field, current generation, saturation current, energy band gap profile, and so on are measured as a function of light bias, voltage, or temperature. Moreover, from the ADEPT 2.1 simulation, recombination profiles, carrier concentration, electric field distributions, and carrier current densities can be obtained as a function of thickness. However, the properties of the conventional CdS and its alternative materials such as ZnO, ZnS, ZnS(O,OH), ZTO, ZnSe, and In_2S_3 and their effects on the performance of the n-ZnO/i-ZnO/buffer/CIGS solar cell are emphasized in this study. The analytical aspects are observed due to the changes in efficiency (η), open-circuit voltage (V_{oc}), short-circuit current (J_{sc}), and fill factor (FF). The effects of CdS buffer layer thickness, the various buffer layer material parameters, and the CIGS absorber thickness are also taken into account during the simulation. The base parameters for the CIGS cell structure with CdS buffer used for the simulation are shown in Table 1 [1, 3, 4, 11, 16, 17]. The most important parameters of different buffer layer materials needed for the simulations are depicted in Table 2 [4, 17–31].

3. Results and Discussions

3.1. Effects of Absorber Thickness on CIGS Cell Performance. To make the simulation reasonable, the conventional CIGS thin-film structure has been ascertained in terms of $Cu(In,Ga)Se_2$ absorber. Firstly, to determine the optimum thickness of the CIGS cell structure with the most commonly used CdS buffer, the thickness of the CIGS absorber ($\tau_{absorber}$) was varied. In Figure 1(a), it is shown that the open-circuit voltage (V_{oc}) is increasing with varying $\tau_{absorber}$. Figure 1(b) shows that the short-circuit current density (J_{sc}) of the solar cell is also increasing with the increase of $\tau_{absorber}$. Because of being in the p-type area in the cell, V_{oc} and J_{sc} are increased with enhancement of the CIGS absorber layer thickness, $\tau_{absorber}$. This phenomenon permits the photons with longer wavelengths to be accumulated, which in turn leads to generation of electron-hole pair (EHP). It is also easily realized that if $\tau_{absorber}$ is decreased, the value of

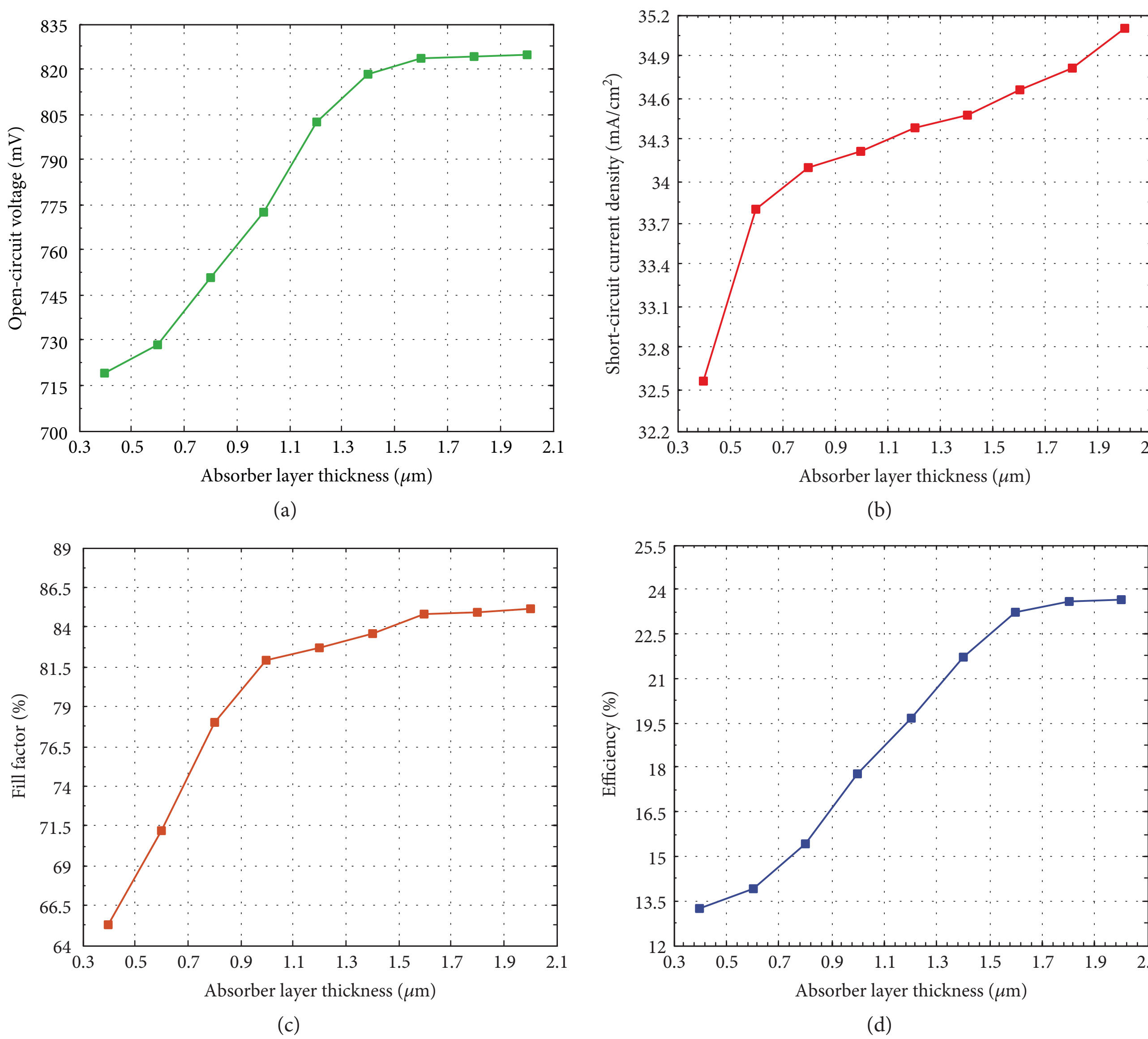

FIGURE 1: Performance variation due to variable thickness of the CIGS absorber layer: (a) open-circuit voltage (V_{oc}); (b) short-circuit current density (J_{sc}); (c) fill factor; (d) efficiency.

both V_{oc} and J_{sc} will be decreased. It is seen from Figure 1(c) that, after 1 μm, the fill factor (FF) of this simulated CIGS solar cell is almost constant with the $\tau_{absorber}$ variation. From Figure 1(d), it is clearly observed that the solar cell efficiency (η) increases with the increase of the CIGS absorber thickness, but over 1.6 μm, the efficiency variation seems to be very slow. $\tau_{absorber}$ would be optimum around 1.6–2 μm. The efficiencies were recorded as 17.76% and 23.67% for the thicknesses of 1 μm and 2 μm, respectively. By comparing these results, it is observed that a 5.47% increase in efficiency was found due to the increase of 0.6 μm (from 1 μm) in $\tau_{absorber}$. And an enhancement of 0.4 μm from 1.6 μm in $\tau_{absorber}$ results in only 0.44% increase in efficiency.

The recombination process at the back contact of the cell may cause the enhancement in the values of J_{sc} and V_{oc}. The back contact will go very close to the depletion area while reducing the absorber layer thickness. Therefore, the back contact captures the electrons for the recombination in an easy way. Hence, a smaller number of electrons contribute to the collection efficiency, and thus, the values of J_{sc} and V_{oc} decrease. Figure 2 shows the J-V characteristic curve with the performance parameters such as V_{oc}, J_{sc}, FF, and efficiency computed after conducting the simulation.

Figure 3 shows the variation in quantum efficiency with respect to photons' wavelengths according to the variation in absorber layer thickness, $\tau_{absorber}$. It is observed that if the thickness of the absorber layer increases, then the quantum efficiency of the solar cell is increased. While increasing the thickness of the absorber layer, a large number of photons are absorbed, including photons

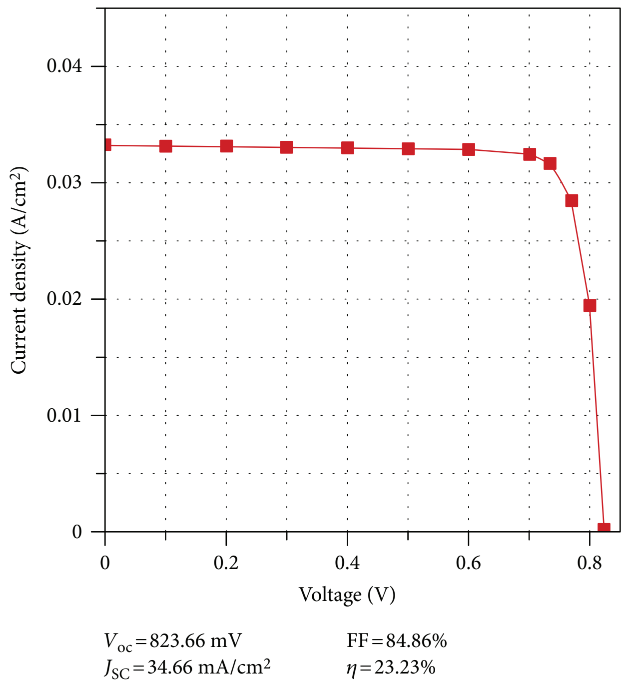

FIGURE 2: *J-V* characteristic curve with photovoltaic parameters.

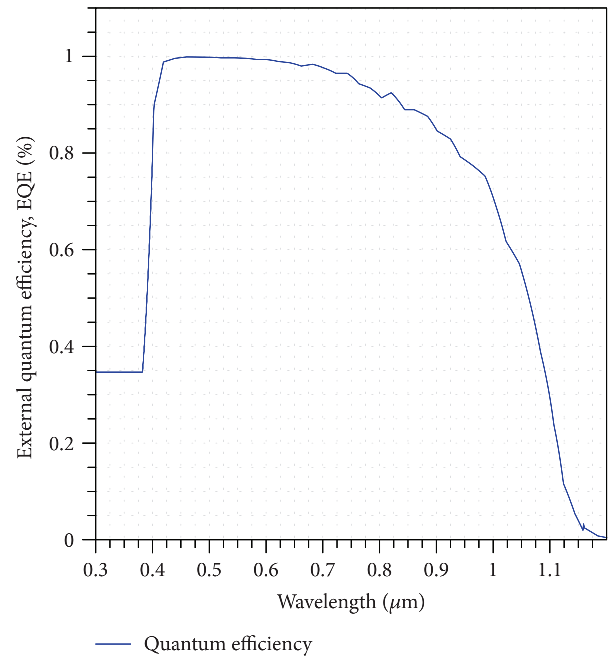

FIGURE 3: Spectral response of CIGS photovoltaic cell.

having longer wavelengths. The absorbed photons produce a larger number of electron-hole pairs (EHP) in this way. Thus, the increased $\tau_{absorber}$ substantiates the increase in external quantum efficiency (EQE).

3.2. Effects of Various Buffer Layers on Cell Efficiency. The six potential buffer layers which have been investigated besides the conventional CdS are ZnS, ZnS(O,OH), ZnSe, ZnO, $Zn_{1-x}Sn_xO_y$, and In_2S_3. For all cases, the thickness has been varied from 0.01 μm to 0.1 μm. More photons are absorbed by the CdS buffer layer while increasing the thickness of the layer. The optimum thickness of CdS buffer is determined as 0.05 μm since J_{sc} decreased dramatically after 0.05 μm [32]. However, the ZnS(O,OH) based CIGS solar cell is typically not affected by the thickness of the buffer layer because of the wider band gap of ZnS. It is seen that the efficiencies of the ZnO, ZnSe, and In_2S_3 based solar cells have been decreased when the thicknesses of these layers cross beyond 0.05 μm. Hence, the optimum thickness of the mentioned buffer layers would be suggested as 0.05 μm. On the other hand, after the buffer layer thickness of 0.06 μm, the efficiency of the $Zn_{1-x}Sn_xO_y$ (ZTO) based CIGS cell increases. Figure 4 gives a summary of the simulated *J-V* characteristic curves with different performance parameters for the CIGS cell based on various buffer layers.

From the simulated results, it is suggested that the ZnO buffer would be a promising alternative to the CdS buffer layer in the CIGS cell as the ZnO and ZnS based cells have reached efficiency levels of 23.67% and 24.62%, respectively. Consequently, ZnO and ZnS are proposed to be very potential materials for conventional CdS replacement because of having wider band gap than that of CdS and higher efficiency than that of the CdS based cell. Although ZTO, ZnS(O,OH), ZnSe, and In_2S_3 based cells provide slightly lower efficiencies than CdS based CIGS solar cells, these materials are nontoxic in nature while the CdS is categorized as carcinogenic and toxic [33]. As a result, these materials can be used as substitute buffer layers for CIGS absorber-based chalcopyrite thin-film photovoltaic devices and will be environmentally friendly enough compared to that of the CdS based cell. The comparisons among different performance parameters of CIGS cells with different substitute buffer layers are shown in Figure 5.

Finally, the comparisons of the improved cell efficiencies for different buffer layers with the relevant experimental results in the literature [1, 11, 12, 17, 34–36] are shown in Table 3.

4. Conclusions

At first, the performance measurements due to the variation in absorber layer thickness in the CIGS solar cell with a CdS buffer layer have been investigated, and thus, the optimum thickness has been figured out from the analysis. Afterwards, various buffer layer materials such as ZnO, ZnS, ZnS(O,OH), ZnSe, ZTO, and In_2S_3 have been used into the CIGS cells. The optimum thicknesses of all the buffer layer materials studied are in the range of 0.04–0.06 μm whereas the absorber layer thickness was optimized as 1.6 μm. While comparing the performances of the cells with different buffer layers, it has been observed that the cell with a ZnS buffer layer reveals the highest efficiency of 24.62% among all the cells studied. The second highest efficiency of 23.67% was found from the simulation result of the cell having a ZnO buffer layer. Besides, the comparative analysis of the cells with ZnS(O,OH), ZnSe, ZTO, and In_2S_3 buffer layers also shows a higher efficiency of more than 18%, which asserts the possible replacement of the conventional CdS buffer layer material in CIGS thin-film device structures.

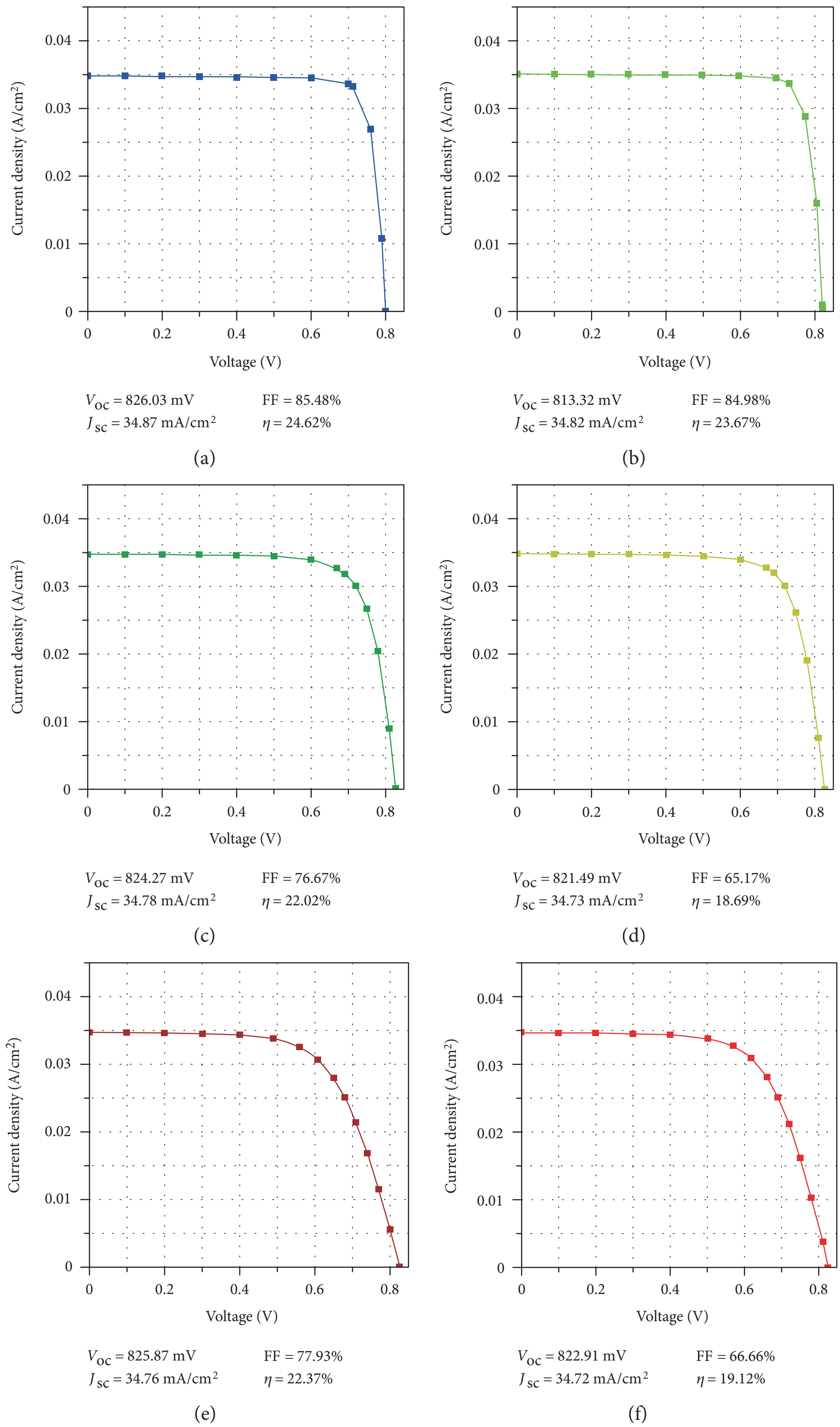

FIGURE 4: *J-V* characteristic curves for CIGS cell with different buffer layers: (a) ZnS; (b) ZnO; (c) ZnS(O,OH); (d) ZnSe; (e) ZTO; (f) In_2S_3.

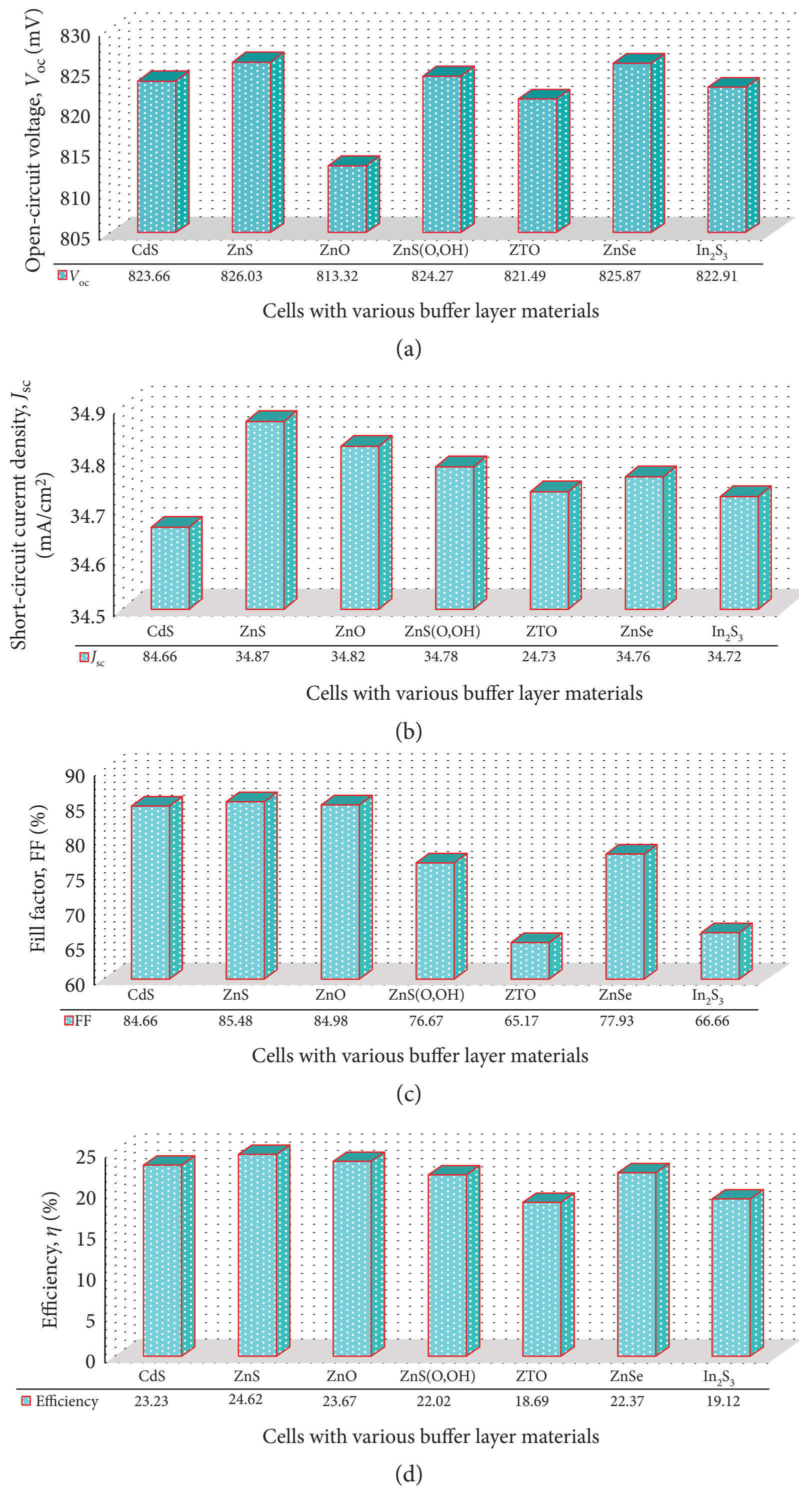

Figure 5: Performance comparison among CIGS cells with different buffer layers: (a) open-circuit voltage, V_{oc}; (b) short-circuit current density, J_{sc}; (c) fill factor, FF; (d) efficiency, η.

Table 3: Comparisons of the improved efficiencies with the relevant experimental results.

Cells	CdS	ZnS	ZnO	ZnS(O,OH)	ZTO	ZnSe	In_2S_3
Proposed cells	23.23	24.62	23.67	22.02	18.69	22.37	19.12
Reference cells	22.60 [1]	18.10 [12]	20.80 [34]	18.40 [35]	18.20 [11]	19.15 [17]	16.40 [36]

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Authors' Contributions

Md. Asaduzzaman conducted the simulation, analyzed the simulation results, and prepared and submitted the manuscript. Md. Billal Hosen and Md. Karamot Ali assisted in conducting the simulation, analyzing the results, and preparing the manuscript. Ali Newaz Bahar supervised the study. All authors finally approved the manuscript for submission.

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References

[1] P. Jackson, R. Wuerz, D. Hariskos, E. Lotter, W. Witte, and M. Powalla, "Effects of heavy alkali elements in Cu(In,Ga)Se_2 solar cells with efficiencies up to 22.6%," *Physica Status Solidi (RRL)*, vol. 10, no. 8, pp. 583–586, 2016.

[2] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, "Solar cell efficiency tables (version 48)," *Progress in Photovoltaics: Research and Applications*, vol. 24, no. 7, pp. 905–913, 2016.

[3] T. M. Friedlmeier, P. Jackson, A. Bauer et al., "Improved photocurrent in Cu(In,Ga)Se_2 solar cells: from 20.8% to 21.7% efficiency with CdS buffer and 21.0% Cd-free," *IEEE Journal of Photovoltaics*, vol. 5, no. 5, pp. 1487–1491, 2015.

[4] M. Asaduzzaman, M. Hasan, and A. N. Bahar, "An investigation into the effects of band gap and doping concentration on Cu(In,Ga)Se_2 solar cell efficiency," *SpringerPlus*, vol. 5, no. 1, 578 pages, 2016.

[5] A. O. Pudov, A. Kanevce, H. A. Al-Thani, J. R. Sites, and F. S. Hasoon, "Secondary barriers in CdS–$CuIn_{1-x}Ga_xSe_2$ solar cells," *Journal of Applied Physics*, vol. 97, no. 6, 064901 pages, 2005.

[6] K. Ramanathan, M. A. Contreras, C. L. Perkins et al., "Properties of 19.2% efficiency ZnO/CdS/$CuInGaSe_2$ thin-film solar cells," *Progress in Photovoltaics: Research and Applications*, vol. 11, no. 4, pp. 225–230, 2003.

[7] A. Han, Y. Sun, Y. Zhang, X. Liu, F. Meng, and Z. Liu, "Comparative study of the role of Ga in CIGS solar cells with different thickness," *Thin Solid Films*, vol. 598, pp. 189–194, 2016.

[8] O. Lundberg, M. Edoff, and L. Stolt, "The effect of Ga-grading in CIGS thin film solar cells," *Thin Solid Films*, vol. 480–481, pp. 520–525, 2005.

[9] S. H. Song and S. A. Campbell, "Heteroepitaxy and the performance of CIGS solar cells," *IEEE 39th Photovoltaic Specialists Conference (PVSC)*, pp. 2534–2539, 2013.

[10] O. Lundberg, M. Bodegård, J. Malmström, and L. Stolt, "Influence of the Cu(In,Ga)Se_2 thickness and Ga grading on solar cell performance," *Progress in Photovoltaics: Research and Applications*, vol. 11, no. 2, pp. 77–88, 2003.

[11] J. Lindahl, U. Zimmermann, P. Szaniawski et al., "Inline Cu(In,Ga)Se Co-evaporation for high-efficiency solar cells and modules," *IEEE Journal of Photovoltaics*, vol. 3, no. 3, pp. 1100–1105, 2013.

[12] T. Nakada and M. Mizutani, "18% efficiency Cd-free Cu(In, Ga)Se_2 thin-film solar cells fabricated using chemical bath deposition (CBD)-ZnS buffer layers," *Japanese Journal of Applied Physics*, vol. 41, no. 2B, pp. L165–L167, 2002, no. Part 2.

[13] R. Mikami, H. Miyazaki, T. Abe, A. Yamada, and M. Konagai, "Chemical bath deposited (CBD)-ZnO buffer layer for CIGS solar cells," *Proceedings of 3rd World Conference on Photovoltaic Energy Conversion, 2003*, vol 1, pp. 519–522, 2003.

[14] S. Chaisitsak, A. Yamada, and M. Konagai, "Comprehensive study of light-soaking effect in ZnO/Cu(InGa)Se_2 solar cells with Zn-based buffer layers," *MRS Online Proceedings Library Archive*, vol. 668 H9–H10, 2001.

[15] J. Gray, X. Wang, R. V. K. Chavali, X. Sun, A. Kanti, and J. R. Wilcox, "Adept 2.1," 2015.

[16] M. Gloeckler, A. L. Fahrenbruch, and J. R. Sites, "Numerical modeling of CIGS and CdTe solar cells: setting the baseline," *Proceedings of 3rd World Conference on Photovoltaic Energy Conversion, 2003*, vol 1, pp. 491–494, 2003.

[17] P. Chelvanathan, M. I. Hossain, and N. Amin, "Performance analysis of copper–indium–gallium–diselenide (CIGS) solar cells with various buffer layers by SCAPS," *Current Applied Physics*, vol. 10, no. 3, Supplement, pp. S387–S391, 2010.

[18] T. Nakada, K. Furumi, and A. Kunioka, "High-efficiency cadmium-free Cu(In,Ga)Se_2 thin-film solar cells with chemically deposited ZnS buffer layers," *IEEE Transactions on Electron Devices*, vol. 46, no. 10, pp. 2093–2097, 1999.

[19] M. M. Islam et al., "CIGS solar cell with MBE-grown ZnS buffer layer," *Solar Energy Materials and Solar Cells*, vol. 93, no. 6–7, pp. 970–972, 2009.

[20] M. Nguyen, K. Ernits, K. F. Tai et al., "ZnS buffer layer for $Cu_2ZnSn(SSe)_4$ monograin layer solar cell," *Solar Energy*, vol. 111, pp. 344–349, 2015.

[21] C. Zhang, S. Pan, T. Heng et al., "Stable inverted low-bandgap polymer solar cells with aqueous solution processed low-temperature ZnO buffer layers," *International Journal of Photoenergy*, vol. 2016, no. 2016, Article ID 3675036, 7 pages, 2016.

[22] R. N. Bhattacharya and K. Ramanathan, "Cu(In,Ga)Se_2 thin film solar cells with buffer layer alternative to CdS," *Solar Energy*, vol. 77, no. 6, pp. 679–683, 2004.

[23] J. Lindahl, J. Keller, O. Donzel-Gargand, P. Szaniawski, M. Edoff, and T. Törndahl, "Deposition temperature induced conduction band changes in zinc tin oxide buffer layers for Cu(In,Ga)Se_2 solar cells," *Solar Energy Materials and Solar Cells*, vol. 144, pp. 684–690, 2016.

[24] M. Asaduzzaman, A. N. Bahar, M. M. Masum, and M. M. Hasan, "Cadmium free high efficiency $Cu_2ZnSn(S,Se)_4$ solar cell with $Zn_{1-x}Sn_xO_y$ buffer layer," *Alexandria Engineering Journal*, 2017, article in press.

[25] D. Hariskos, S. Spiering, and M. Powalla, "Buffer layers in Cu(In,Ga)Se_2 solar cells and modules," *Thin Solid Films*, vol. 480–481, pp. 99–109, 2005.

[26] N. Khoshsirat, N. A. M. Yunus, M. N. Hamidon, S. Shafie, and N. Amin, "Analysis of absorber and buffer layer band gap grading on CIGS thin film solar cell performance using

SCAPS," *Pertanika Journal of Science and Technology*, vol. 23, no. 2, pp. 241–250, 2015.

[27] L. Wang, X. Lin, A. Ennaoui, C. Wolf, M. C. Lux-Steiner, and R. Klenk, "Solution-processed In_2S_3 buffer layer for chalcopyrite thin film solar cells," *EPJ Photovoltaics*, vol. 7, 70303 pages, 2016.

[28] F. Engelhardt, L. Bornemann, M. Köntges et al., "Cu(In,Ga)Se_2 solar cells with a ZnSe buffer layer: interface characterization by quantum efficiency measurements," *Progress in Photovoltaics: Research and Applications*, vol. 7, no. 6, pp. 423–436, 1999.

[29] N. A. Okereke and A. J. Ekpunobi, "ZnSe buffer layer deposition for solar cell application," *Journal of Non-Oxide Glasses*, vol. 3, no. 1, pp. 31–36, 2011.

[30] J. Wang and M. Isshiki, "Wide-bandgap II–VI semiconductors: growth and properties," in *Springer Handbook of Electronic and Photonic Materials*, S. Kasap and P. Capper, Eds., pp. 325–342, Springer US, 2006.

[31] T.-H. Yeh, C.-H. Hsu, W.-H. Ho, S.-Y. Wei, C.-H. Cai, and C.-H. Lai, "An ammonia-free chemical-bath-deposited ZnS(O,OH) buffer layer for flexible Cu(In,Ga)Se_2 solar cell application: an eco-friendly approach to achieving improved stability," *Green Chemistry*, vol. 18, no. 19, pp. 5212–5218, 2016.

[32] Y. Yamamoto, K. Saito, K. Takahashi, and M. Konagai, "Preparation of boron-doped ZnO thin films by photo-atomic layer deposition," *Solar Energy Materials and Solar Cells*, vol. 65, no. 1–4, pp. 125–132, 2001.

[33] M. P. Waalkes, "Cadmium carcinogenesis in review," *Journal of Inorganic Biochemistry*, vol. 79, no. 1–4, pp. 241–244, 2000.

[34] P. Jackson, D. Hariskos, R. Wuerz, W. Wischmann, and M. Powalla, "Compositional investigation of potassium doped Cu(In,Ga)Se_2 solar cells with efficiencies up to 20.8%," *Physica Status Solidi (RRL)*, vol. 8, no. 3, pp. 219–222, 2014.

[35] T. Kobayashi, K. Yamauchi, and T. Nakada, "Comparison of cell performance of ZnS(O,OH)/CIGS solar cells with UV-assisted MOCVD-ZnO:B and sputter-deposited ZnO : Al window layers," *IEEE Journal of Photovoltaics*, vol. 3, no. 3, pp. 1079–1083, 2013.

[36] M. A. Mughal, R. Engelken, and R. Sharma, "Progress in indium (III) sulfide (In_2S_3) buffer layer deposition techniques for CIS, CIGS, and CdTe-based thin film solar cells," *Solar Energy*, vol. 120, pp. 131–146, 2015.