Proceeding of ICMR 6(1), 131-139 DOI: https://doi.org/10.32672/picmr.v6i1.1162

One-Step Sputtering CuInGaSe 2 (CIGSe) Process for Thin Film Solar Cells: Progress and Challenges

Maliya Syabriyana[1*], Zeni Ulma[2], Rosalia Dwi Werena[3]

[1]Department of Chemical Engineering, Universitas Serambi Mekkah, Aceh, Indonesia
[2]Department of Renewable Energy, State Polytechnique of Jember, East Jawa, Indonesia
[3]Department of Environmental Engineering, The University of Lampung, Indonesia

*Corresponding Author: maliya.syabriyana@serambimekkah.ac.id

Abstract. *The one-step sputtering for fabricating CuInGaSe2 (CIGSe) solar cells has been gaining attention due to its potential for simplifying the manufacturing process, large area uniformity, and environmentally friendly as less reliance on toxic Se precursors such as H 2 Se. Despite these advantages, several drawbacks remain. To date, devices fabricated by quaternary sputtering without additional selenization have been limited in efficiency to about 16%, and realizing bandgap grading in order to match the performance of the best evaporated devices presents a challenge. We discuss the prospects for quaternary sputtering as a fabrication technique for CIGSe and highlight areas of research that may result in improved performance. It also delves into the challenges faced in optimizing the material properties and device performance, and the ongoing research efforts to overcome these hurdles. The paper concludes with a perspective on the future directions for the field, emphasizing the importance of this research in the context of sustainable energy solutions.*

Keywords: *one-step sputtering, performance enhancement, challenges*

1. Introduction

The Copper Indium Gallium Selenide (CIGSe) solar cells industry is currently experiencing significant growth and development. The global CIGSE solar cell market size is projected to grow from USD 1.02 Billion in 2017 to a significant value by 2028, at a Compound Annual Growth Rate (CAGR) of 13.5% during the forecast period[2]. The market growth can be attributed to the increasing demand for renewable energy sources and rising concerns about greenhouse gas emissions and climate change.

This thin film solar cell (SC) has high efficiency similar to crystalline silicon SC, but presenting lower cost due to thinner absorber layer (2-2.5µm thickness) (Ramanujam et al., 2020). This material, part of the direct band gap chalcopyrite semiconductor compounds family, boasts exceptional optical properties such as a high absorption coefficient ($\alpha \sim 105\ cm^{-1}$), long-term stability, and high radiation tolerance. Furthermore, the ability to engineer its band gap through the partial substitution of indium with gallium adds a layer of flexibility, allowing for the manipulation of optical absorption. There are several techniques currently in use for the fabricating of CIGSe absorber layers. These are co-evaporation (Chantana et al., 2016), sputtering (Brozak et al., 2017; Chen et al., 2012), pulsed laser deposition (Nicolaou et al., 2020), as well as non-vacuum methods like ink-printing, spin coating, and electrochemical deposition[6]. Despite the variety of methods available, the production of high-quality CIGSE thin films for use in laboratory-scale or module-level solar cells is typically achieved through the use of either co-evaporation or sputtering processes.

One-step sputtering deposition of CIGSe absorber, a method that prepares both the metals and Se in a single target, has been suggested as a potentially scalable deposition

Proceeding of ICMR 6(1), 131-139 DOI: https://doi.org/10.32672/picmr.v6i1.1162

technique for manufacturing. This method provides straightforward process control, uniformity over large areas, and eliminates the need for an expensive and potentially dangerous H2Se gas step. However, devices fabricated by quaternary target sputtering without additional salinization have been limited in efficiency to about 11% (CIGSe Solar Cell Market Report). Thus, make it remain on laboratory research. However, ongoing research and development efforts are aimed at improving this efficiency and realizing bandgap grading to match the performance of the best evaporated devices.

In this review, we discuss the ongoing research, future potential, and challenge of one-step sputtering of CIGSe. Section II offers an overview of single-step deposition techniques for CIGSe, outlining the benefits and hurdles of this method. Section III provides an in-depth explanation of the various approaches that have been done to enhance performance of one-step CIGSe process SCs. Lastly, Section IV contemplates the challenge of one-step sputtering CIGSe, addressing current performance limitations and potential solutions.

2. Overview of One-Step Sputtering CIGSe Process

The chalcopyrite materials, CIGSe, is a direct transition bandgap p-type semiconductor. The term "chalcopyrite" comes from the mineral CuFeSe2, which forms in the tetragonal crystal system space group I42d, as depicted in Fig. 1(a). While these I–III–VI2 ternary compounds and their quaternary alloys encompass a wide variety of material systems, our main focus is on CuInxGa1xSe2 systems. In this quaternary mixed alloy systems, the lattice constants, a and c, change linearly with respect to x. A composition of x = 0.8 is observed to achieve the ideal c = 2a ratio. As a promising absorber material, it has attracted considerable attention due to its direct band (1.0 ~1.12 eV), high absorption co-efficient (10^5 cm^{-1}) and low wasted material.

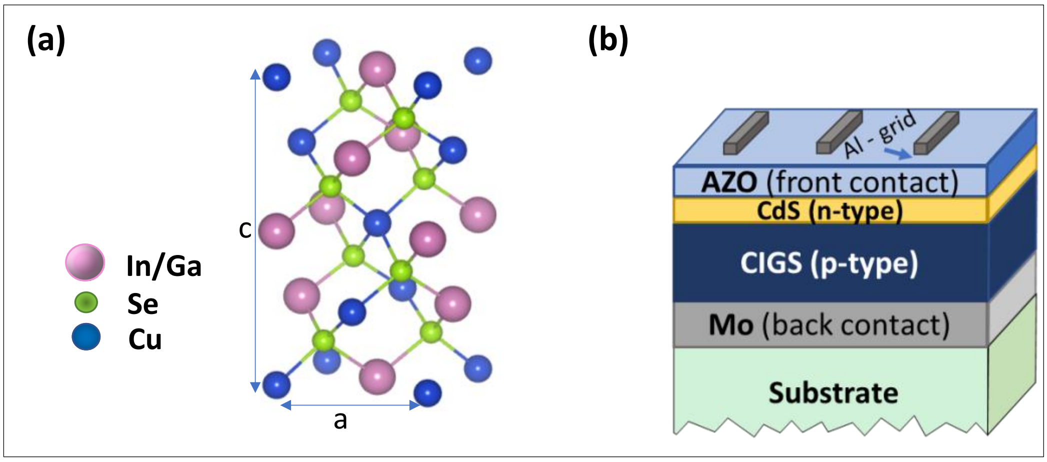

Figure 1. (a) CIGSe chalcopyrite crystal structure, and (b) CIGSe solar cell structure.

Figure 1 (b) illustrates a CIGSe-based solar cell with a structure that includes substrate/Mo/p-CIGSe/n-CdS/intrinsic ZnO/ZnO:Al/ARC/metal-grid. In this architecture, the light enters the cell through the Transparent Conductive Oxide (TCO), and a back contact is applied to the substrate. It is important to note that in the superstrate configuration, light enters the cell through a glass substrate, which serves as a window for illumination. The operation of the CIGSe solar cell is as follows: The n-type CdS buffer layer (with a bandgap energy, Eg, of approximately 2.4 eV) allows light up to 2.4 eV to reach the absorber, where the majority of electron-hole pairs are generated. Photons

Proceeding of ICMR 6(1), 131-139 DOI: https://doi.org/10.32672/picmr.v6i1.1162

with energy greater than 2.4 eV are absorbed by the CdS layer. Due to the built-in electric field at the p–n junction interface (between CIGSe/CdS), electrons within the diffusion length region are driven from the p-type absorber to the n-type buffer layer and collected by the n-type electrode. Similarly, holes are driven from the n-type layer to the p-type layer and collected by the p-type electrode.

An additional mechanism is the back surface field (BSF) in the CIGSe layer, created by a Ga gradient near the Mo back contact. This BSF reflects electrons towards the p–n junction, where they are ultimately collected by the n-type electrode. The BSF also reduces minority carrier recombination at the rear side of the device, near the CIGSe and Mo interface. More details about the BSF can be found in other sources.

A single quaternary target, CIGSe, was prepared by hot sintering process from the uniformed mixture of high purity Cu_2Se, In_2Se_3, and Ga2Se3 powders at 600^o-800^o sintering temperature (Chen et al., 2012). Elements composition has percentage close to its stoichiometry with Cu 25% (known as rich copper target) or <23% (known as poor Copper target), In 17.5%-19%, Ga 7-8% and Se 51-52% (Chen et al., 2012; Lin et al., 2013; Zhang et al., 2017). The CIGSe film are growth on Mo/substrate via magnetron sputtering (Frantz et al., 2016) (Hsu et al., 2017; A. J. Zhou et al., 2012), pulse DC sputtering (Wang et al., 2021), or Radio Frequency sputtering (Brozak et al., 2017; Kim et al., 2020) at high temperature substrate 500^oC-550^oC (Chen et al., 2012; D. Zhou et al., 2016). Although the deposition is simple, less toxic and a good film uniformity, poor Se content becomes challenge to obtain high quality CISGS absorber. Thus, many approaches have been done to improve device efficiency in order to make this process reliable for mass production.

3. Efficiency Enhancement Approach

Since one-step process has a lack of Se which cause Se vacancy (V_{Se}) that result to poor absorber, adding enough Se is necessary to have preferable performance. Shi et al. fabricated CIGSe SCs by implemented post deposition selenization step using solid Se source after growing CIGSe layer (Hsu et al., 2017; Shi et al., 2011). Recently, efficiency of 16.7% has been achieved by utilizing H_2Se after absorber (Ouyang et al., 2015). Although these methods are significantly improving the efficiency, environmentally friendly process is preferable. Some ways to enhance single-step CIGSe deposition is elaborated in the section below.

CIGS Absorber Modification

Absorber crystallinity and its crystal prefer orientation determines the device performance. Peng et al. controlled CIGSe layer growth by vary Cu composition, post annealing, and having bilayer absorber. This group found that double layer, rich and poor Cu layer followed by annealing thievingly improve performance by almost 3% due to larger grain size (see Fig. 2) of absorber and higher current density compared to annealed one-layer CIGS (Peng et al., 2017). Sputtering rich copper content CIGSe followed by In_2Se_3 layer are able to change absorber into Cu poor surface which result in higher short circuit current and bigger grain size (Peng et al., 2018). Inserting of Sb in the bottom and middle of CIGS layers could significantly increase the grain size (Zhang et al., 2017). In addition, controlling CIGSe prefer orientation is also important to improve device performance. This can be done by inserting a thin In_2Se_3 precursor before growing absorber (Yan et al., 2016), controlling Mo orientation (Jingxue et al., 2016; Kamikawa-Shimizu et al., 2009; Lin et al., 2012).

Proceeding of ICMR 6(1), 131-139 DOI: https://doi.org/10.32672/picmr.v6i1.1162

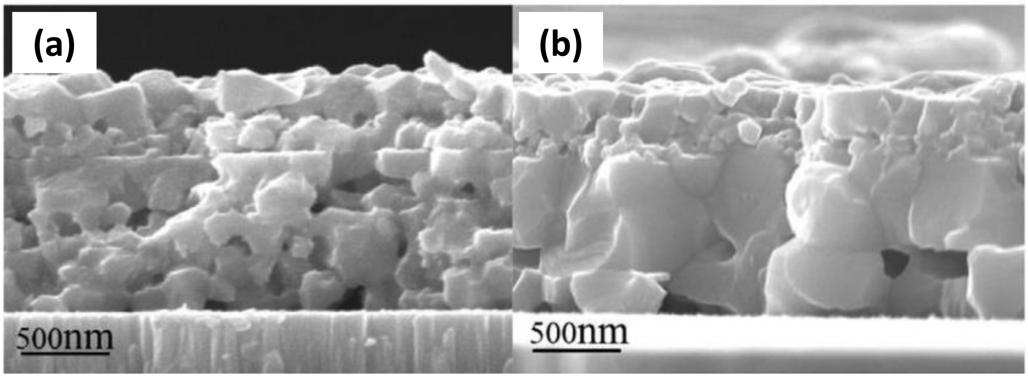

Figure 2. (a) the single layer annealed CIGS thin film consisting of 1100 nm-thickness bottom layer of CIGS with Cu content of 0.97 and 500 nm-thickness top layer with Cu content of 0.82; (b) the bilayer annealed CIGS thin film consisting of 1100 nm-thickness bottom layer of CIGS with Cu content of 0.97 and 500 nm-thickness top layer with Cu content of 0.82 (Peng et al., 2017)

Alkali Metals Incorporation

The effects of diffusion of alkali metal such as Na, K, Cs, Rb on CIGS SCs been studied (Cho et al., 2018; Li et al., 2017; Sun et al., 2017). Hsu and teams have revealed that efficiency can be boosted up to 11% by introducing NaF after CIGSe layer to suppress effect of Se-deficient (Hsu et al., 2015). The same group also has done double post deposition of alkali by depositing NaF and KF in sequent (Hsu et al., 2017). The effect of Na has been widely studied. It increases the net acceptor concentration (Sun et al., 2017, 2017), it affects grain growth (Hsu et al., 2015), surface passivation, the diffusion of Ga towards back contact, and resulting better p-type properties (Salomé et al., 2015). When Na or K is incorporated, Na can reduce both InCu and VSe, while K can significantly promote the oxidation of VSe which can be observed on short circuit Voltage (V_{OC}) improvement (Fig. 3(a)). However, when NaF deposited followed by KF after CIGSe, it further enhances absorber quality because of effective passivation of both defects (Hsu et al., 2017) which shown on Photo-luminescence (PL) spectra Fig 3(b).

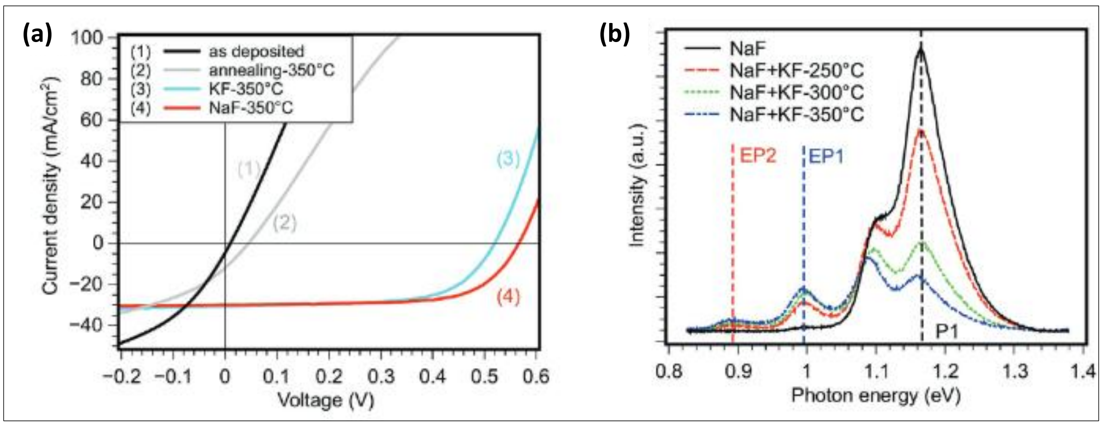

Figure 3. (a) J-V curves of CIGSe solar cell with different post-treatment, (b) PL spectra of Na-PDT without and with KF-PDT (Hsu et al., 2017)

Band-Gap Engineering

The bandgap engineering of CIGSe absorber layers proves to be highly beneficial

Proceeding of ICMR 6(1), 131-139 DOI: https://doi.org/10.32672/picmr.v6i1.1162

in boosting cell performance. This is because it minimizes recombination losses and maximize carrier collection within the cell (Park et al., 2016). In co-sputtering method, bandgap of CIGSe can be easily tuned by adjusting Ga/(Ga+In) ratio during absorber deposition. In the process of quaternary target sputtering, the capacity to alter the elemental ratio of the sputtered atoms from a single target is somewhat restricted. To achieve compositional variation, one must either employ a combination of ternary targets or use stoichiometric quaternary and elemental targets. Ga grading or controlling Ga concentration to replace In in single step CIGSe deposition can be done by using a combinatorial magnetron sputtering system from a CIS/CGS stoichiometric single target (Park et al., 2016; Lyu et al., 2019).

However, Ga_2Se_3 as co-sputtering target may lead to Ga2O3 formation which degrades device's efficiency. Wang et al. and coworkers have used different co-sputtering targets, $CuGaSe_2$ (Wang et al., 2020) and In_2Se_3 (Wang et al., 2021) with CIGSe to modified the bandgap. The prior co-sputtering technique inhibit the creation of secondary phases and attain a customizable normal grading which results in a peak efficiency of 15.63%, achieved without the need for post-selenization on flexible substrates (Wang et al., 2020). While the later effectively passivated surface Se vacancies (VSe) due to optimize surface sulfurization (Wang et al., 2021). With increasing Ga/(In + Ga) ratio, diffraction peak positions shifted to high angle for both (112) and (220) planes. Similar trend also observed on Raman spectra.

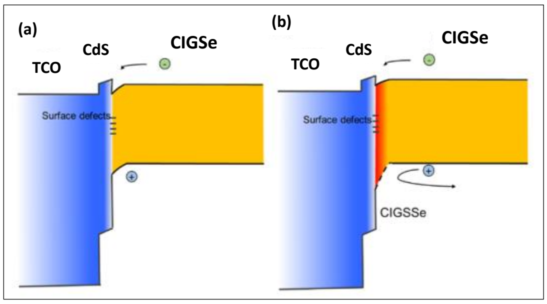

Figure 4. Diagram illustrating the band structure of samples: (a) without any treatment, and (b) treated with In2S3 (Wang et al., 2021)

Increasing Ga content leads to an increase in VOC as result of reduction of recombination and a decrease in JSC due to absorber quality improvement, witnessed on both studies. From Fig. 4 (a)(b), enlargement of surface bandgap formed due to formation of a thin layer of CIGSSe at the interface between buffer layer and absorber layer. Moreover, the presence of this layer on the surface results in a downward shift of the valence band. This, in turn, reduces the interface recombination.

4. Challenges

Improving the efficiency of CIGS solar cells using a one-step sputtering technique can present several challenges:

a. Impurity issue: in the sputtering process produces a film composition that mirrors the target composition, meaning any impurities present in the target will be transferred to the final film. Thus well care need to taken to make sure target fabrication and sputtering chamber free from contaminant (Frantz et al., 2016)
b. Optimization of deposition parameters: The deposition pressure and RF-Power used during the sputtering process can significantly affect the properties of the

Proceeding of ICMR 6(1), 131-139 DOI: https://doi.org/10.32672/picmr.v6i1.1162

CIGS thin film². Finding the optimal parameters to achieve a smooth surface and good crystallinity can be challenging (Desarada et al., 2023).

c. Post-deposition annealing: After the CIGS thin film is deposited, a post-annealing process is often required to improve the crystallinity, grain size, and compactness of the CIGS samples (Desarada et al., 2023; Suryavanshi & Panchal, 2023). The choice of annealing technique and parameters can greatly influence the properties of the CIGS thin film.
d. Stoichiometry control: The energy bandgap of CIGS semiconductors can be tuned in the range of 1.05eV to 1.65 eV by changing the stoichiometry of indium (In) to gallium (Ga) of the sample. However, achieving the desired stoichiometry can be difficult in a one-step sputtering process (Suryavanshi & Panchal, 2023).
e. Formation of defects: High Ga contents can lead to the formation of deep-level defects, which can degrade the performance of the CIGS solar cells (Huang et al., 2018).
f. Cost and scalability: While the one-step sputtering technique can potentially reduce the cost and increase the scalability of CIGS solar cell production, achieving high efficiency at a low cost and large scale remains a challenge (Desarada et al., 2023).

These challenges highlight the complexity of the one-step sputtering process for CIGS solar cells and the need for ongoing research and development to optimize this process.

5. Conclusion

The prominent advantages of single step CIGSe sputtering is suitable for large area deposition due to its good uniformity and simplicity. However, the solar cells efficiency is still below from co-sputtering or multistep methods. In order to achieve feasibility for scale up, many approaches have need implemented. CIGSe layer quality can be improved by controlling Mo layer phase, inserting wetting layer or barrier layer. Secondly, alkali metal atoms deployment, Na or K, improves carrier concentration and give some passivation effects on CIGSe surface and later reduce recombination at interface, thus the Voc of devices. The last, bandgap grading can be introduced into single-step process by co-sputtering with other targets to adjust Ga/(Ga+In) ratio. This results in an elevation of VOC due to the reduction in recombination, and a decline in JSC as a consequence of the improvement in absorber quality. Despite the performance slowly elevated, there are some challenges remained. Impurity levels in the target, stoichiometry issue, defects formation, and cost for scaling up are need to be solved in order to be able to compete with other CIGSe thin film SCs fabrication methods.

6. References

CIGSe Solar Cell Market Report; Global Forecast From 2023 To 2031 - Dataintelo. https://dataintelo.com/report/CIGSe-solar-cell-market/

Brozak, M., Cansizoglu, H., & Karabacak, T. (2017). Deposition of quaternary sputtered CIGS nanorods via glancing angle deposition. *Physica Status Solidi (RRL) - Rapid Research Letters*, *11*(1), 1600326. https://doi.org/10.1002/pssr.201600326

Chantana, J., Arai, H., & Minemoto, T. (2016). Trap-assisted recombination for ohmic-like contact at p-type Cu (In,Ga)Se $_2$ /back n-type TCO interface in superstrate-type solar cell. *Journal of Applied Physics*, *120*(4), 045302. https://doi.org/10.1063/1.4959210

Proceeding of ICMR 6(1), 131-139 DOI: https://doi.org/10.32672/picmr.v6i1.1162

Chen, C.-H., Shih, W.-C., Chien, C.-Y., Hsu, C.-H., Wu, Y.-H., & Lai, C.-H. (2012). A promising sputtering route for one-step fabrication of chalcopyrite phase Cu(In,Ga)Se2 absorbers without extra Se supply. *Solar Energy Materials and Solar Cells*, *103*, 25–29. https://doi.org/10.1016/j.solmat.2012.04.008

Cho, Y., Jeong, I., Gang, M. G., Kim, J. H., Song, S., Eo, Y.-J., Ahn, S. K., Shin, D. H., Cho, J.-S., Yun, J. H., Gwak, J., & Kim, K. (2018). Alkali incorporation into Cu(In,Ga)Se2 determined by crystal orientation of Mo back contact: Implications for highly efficient photovoltaic devices. *Solar Energy Materials and Solar Cells*, *188*, 46–50. https://doi.org/10.1016/j.solmat.2018.08.014

Desarada, S. V., Chavan, K. B., & Chaure, N. B. (2023). Effect of Different Annealing Techniques on CIGS Deposited Using One-Step Single-Target Sputtering. *Journal of Electronic Materials*, *52*(5), 3413–3419.

Frantz, J. A., Myers, J. D., Bekele, R. Y., Nguyen, V. Q., Sadowski, B. M., Maximenko, S. I., Lumb, M. P., Walters, R. J., & Sanghera, J. S. (2016). Quaternary sputtered Cu (In, Ga) Se 2 absorbers for photovoltaics: A review. *IEEE Journal of Photovoltaics*, *6*(4), 1036–1050.

Hsu, C.-H., Ho, W.-H., Wei, S.-Y., & Lai, C.-H. (2017). Over 14% Efficiency of Directly Sputtered Cu(In,Ga)Se_2 Absorbers without Postselenization by Post-Treatment of Alkali Metals. *Advanced Energy Materials*, *7*(13), 1602571. https://doi.org/10.1002/aenm.201602571

Hsu, C.-H., Su, Y.-S., Wei, S.-Y., Chen, C.-H., Ho, W.-H., Chang, C., Wu, Y.-H., Lin, C.-J., & Lai, C.-H. (2015). Na-induced efficiency boost for Se-deficient Cu(In,Ga)Se_2 solar cells: Na-induced efficiency boost for Se-deficient CIGS solar cells. *Progress in Photovoltaics: Research and Applications*, *23*(11), 1621–1629. https://doi.org/10.1002/pip.2600

Huang, C.-H., Chuang, W.-J., Lin, C.-P., Jan, Y.-L., & Shih, Y.-C. (2018). Deposition technologies of high-efficiency CIGS solar cells: Development of two-step and co-evaporation processes. *Crystals*, *8*(7), 296.

Jingxue, F., Zhao, W., Wei, W., Ye, Y., Lin, Z., Xin, W., Ruijiang, H., Hui, S., & Chen, M. Z. Q. (2016). Preparation and optimization of a molybdenum electrode for CIGS solar cells. *AIP Advances*, *6*(11), 115210. https://doi.org/10.1063/1.4967427

Kamikawa-Shimizu, Y., Shimada, S., Watanabe, M., Yamada, A., Sakurai, K., Ishizuka, S., Komaki, H., Matsubara, K., Shibata, H., Tampo, H., Maejima, K., & Niki, S. (2009). Effects of Mo back contact thickness on the properties of CIGS solar cells. *Physica Status Solidi (a)*, *206*(5), 1063–1066. https://doi.org/10.1002/pssa.200881200

Kim, D., Shin, S. S., Lee, S. M., Cho, J., Yun, J. H., Lee, H. S., & Park, J. H. (2020). Flexible and Semi-Transparent Ultra-Thin CIGSe Solar Cells Prepared on Ultra-Thin Glass Substrate: A Key to Flexible Bifacial Photovoltaic Applications. *Advanced Functional Materials*, *30*(36), 2001775. https://doi.org/10.1002/adfm.202001775

Li, W., Yan, X., Aberle, A. G., & Venkataraj, S. (2017). Effect of a TiN alkali diffusion barrier layer on the physical properties of Mo back electrodes for CIGS solar cell

Proceeding of ICMR 6(1), 131-139 DOI: https://doi.org/10.32672/picmr.v6i1.1162

applications. *Current Applied Physics*, *17*(12), 1747–1753. https://doi.org/10.1016/j.cap.2017.08.021

Lin, T.-Y., Chen, C.-H., Hong, T.-J., & Lai, C.-H. (2013). Cu(In, Ga)Se2 absorbers prepared by one-step sputtering process with Cu-rich quaternary target. *2013 IEEE 39th Photovoltaic Specialists Conference (PVSC)*, 2612–2614. https://doi.org/10.1109/PVSC.2013.6745009

Lin, T.-Y., Chen, C.-H., & Lai, C.-H. (2012). Mo effect on one-step sputtering chalcopyrite CIGS thin films. *2012 38th IEEE Photovoltaic Specialists Conference*, 001999–002002. https://doi.org/10.1109/PVSC.2012.6317989

Lyu, X., Zhuang, D., Zhao, M., Zhang, N., Wei, Y., Wu, Y., Ren, G., Wang, C., Hu, L., Wei, J., & Gong, Q. (2019). Influences of Ga concentration on performances of CuInGaSe2 cells fabricated by sputtering-based method with ceramic quaternary target. *Ceramics International*, *45*(13), 16405–16410. https://doi.org/10.1016/j.ceramint.2019.05.169

Nicolaou, C., Zacharia, A., Delimitis, A., Itskos, G., & Giapintzakis, J. (2020). Single-step growth of high quality CIGS/CdS heterojunctions using pulsed laser deposition. *Applied Surface Science*, *511*, 145547.

Ouyang, L., Zhuang, D., Zhao, M., Zhang, N., Li, X., Guo, L., Sun, R., & Cao, M. (2015). Cu (In, Ga) Se2 solar cell with 16.7% active-area efficiency achieved by sputtering from a quaternary target. *Physica Status Solidi (a)*, *212*(8), 1774–1778.

Park, J.-C., Lee, J.-R., Al-Jassim, M., & Kim, T.-W. (2016). Bandgap engineering of Cu (In 1-x Ga x) Se 2 absorber layers fabricated using CuInSe 2 and CuGaSe 2 targets for one-step sputtering process. *Optical Materials Express*, *6*(11), 3541–3549.

Peng, X., Zhao, M., Zhuang, D., Guo, L., Ouyang, L., Sun, R., Zhang, L., Wei, Y., Zhan, S., Lv, X., Wu, Y., & Ren, G. (2017). Multi-layer strategy to enhance the grain size of CIGS thin film fabricating by single quaternary CIGS target. *Journal of Alloys and Compounds*, *710*, 172–176. https://doi.org/10.1016/j.jallcom.2017.02.016

Peng, X., Zhao, M., Zhuang, D., Sun, R., Zhang, L., Wei, Y., Lv, X., Wu, Y., & Ren, G. (2018). Two-stage method to enhance the grain size of Cu(In,Ga)Se2 absorbers based on sputtering quaternary Cu(In,Ga)Se2 target. *Materials Letters*, *212*, 165–167. https://doi.org/10.1016/j.matlet.2017.10.033

Ramanujam, J., Bishop, D. M., Todorov, T. K., Gunawan, O., Rath, J., Nekovei, R., Artegiani, E., & Romeo, A. (2020). Flexible CIGS, CdTe and a-Si:H based thin film solar cells: A review. *Progress in Materials Science*, *110*, 100619. https://doi.org/10.1016/j.pmatsci.2019.100619

Salomé, P. M. P., Rodriguez-Alvarez, H., & Sadewasser, S. (2015). Incorporation of alkali metals in chalcogenide solar cells. *Solar Energy Materials and Solar Cells*, *143*, 9–20. https://doi.org/10.1016/j.solmat.2015.06.011

Shi, J. H., Li, Z. Q., Zhang, D. W., Liu, Q. Q., Sun, Z., & Huang, S. M. (2011). Fabrication of Cu(In, Ga)Se2 thin films by sputtering from a single quaternary chalcogenide target. *Progress in Photovoltaics: Research and Applications*, *19*(2), 160–164. https://doi.org/10.1002/pip.1001

Proceeding of ICMR 6(1), 131-139 DOI: https://doi.org/10.32672/picmr.v6i1.1162

Sun, Y., Lin, S., Li, W., Cheng, S., Zhang, Y., Liu, Y., & Liu, W. (2017). Review on Alkali Element Doping in Cu(In,Ga)Se 2 Thin Films and Solar Cells. *Engineering*, *3*(4), 452–459. https://doi.org/10.1016/J.ENG.2017.04.020

Suryavanshi, P. S., & Panchal, C. J. (2023). Low-cost fabrication of single chalcogenide CuInGaSe2 sputter target and its thin films for solar cell applications. *Journal of Optics*, 1–19.

Wang, Y.-H., Ho, P.-H., Huang, W.-C., Tu, L.-H., Chang, H.-F., Cai, C.-H., & Lai, C.-H. (2020). Engineering a Ga-Gradient by One-Step Sputtering to Achieve Over 15% Efficiency of Cu (In, Ga) Se2 Flexible Solar Cells without Post-selenization. *ACS Applied Materials & Interfaces*, *12*(25), 28320–28328.

Wang, Y.-H., Tu, L.-H., Chang, Y.-L., Lin, S.-K., Lin, T.-Y., & Lai, C.-H. (2021). Surface sulfurization of Cu (In, Ga) Se2 solar cells by cosputtering In2S3 in the one-step sputtering process. *ACS Applied Energy Materials*, *4*(10), 11555–11563.

Yan, Y., Jiang, F., Liu, L., Yu, Z., Zhang, Y., & Zhao, Y. (2016). Control over the preferred orientation of CIGS films deposited by magnetron sputtering using a wetting layer. *Electronic Materials Letters*, *12*(1), 59–66. https://doi.org/10.1007/s13391-015-5263-y

Zhang, L., Zhuang, D., Zhao, M., Gong, Q., Guo, L., Ouyang, L., Sun, R., Wei, Y., Zhan, S., Lyu, X., & Peng, X. (2017). A study on mechanisms of Sb-doping induced grain growth for Cu(InGa)Se2 absorbers deposited from quaternary targets. *Journal of Alloys and Compounds*, *727*, 572–578. https://doi.org/10.1016/j.jallcom.2017.07.340

Zhou, A. J., Mei, D., Kong, X. G., Xu, X. H., Feng, L. D., Dai, X. Y., Gao, T., & Li, J. Z. (2012). One-step synthesis of Cu (In, Ga) Se2 absorber layers by magnetron sputtering from a single quaternary target. *Thin Solid Films*, *520*(19), 6068–6074.

Zhou, D., Zhu, H., Liang, X., Zhang, C., Li, Z., Xu, Y., Chen, J., Zhang, L., & Mai, Y. (2016). Sputtered molybdenum thin films and the application in CIGS solar cells. *Applied Surface Science*, *362*, 202–209. https://doi.org/10.1016/j.apsusc.2015.11.235