

Chemical Bath Deposition of $\text{Zn}_{1-x}\text{Sn}_x\text{O}_y$ Films as Buffer Layers for $\text{Cu}(\text{In,Ga})\text{Se}_2$ Solar Cells

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$\text{Cu}(\text{In,Ga})\text{Se}_2$ (CIGSe) thin-film solar cells are a commercial photovoltaic technology that provides sustainable power. Herein, the formation of $\text{Zn}_{1-x}\text{Sn}_x\text{O}_y$ (ZTO) thin films is studied as Cd-free buffer layer by chemical bath deposition (CBD) suitable for CIGSe solar cell devices. ZTO films are obtained by CBD onto soda lime glass, by modifying a reported procedure otherwise leading to columnar ZnO thin films. These ZTO films show a flatter morphology compared to the reference ZnO due to inhibition of the columnar growth. In addition, a nontrivial increase in the bandgap is observed by enhancing Sn concentration. When a concentration of 20% $[\text{Sn}]/([\text{Sn}] + [\text{Zn}])$ (where $[\text{Sn}]$ and $[\text{Zn}]$ are the molar concentrations of Sn and Zn, respectively) is employed in the chemical bath, the resulting buffer layer allows the CIGSe solar cell to achieve similar performance as with a CdS buffer layer (average efficiency of $(11 \pm 2)\%$), yielding a maximum efficiency of 10.4%, with an average of $(9 \pm 2)\%$.

over its properties, notably its tunable bandgap (1.0–1.7 eV),^[5,6] and high absorption coefficient ($>10^5 \text{ cm}^{-1}$)^[5,6] with a record power conversion efficiency (PCE) of 23.4% achieved by SolarFrontier.^[7]

A key component in CIGSe solar cells is the buffer layer, which forms the charge-separating pn-junction with the absorber and provides a good electrical and optical interface with the front contact layers, ensuring charge carrier transport, and minimal interface recombination. CdS deposited by chemical bath deposition (CBD) is the traditional buffer material due to its electrical and structural matching with the absorber.^[8] This n-type material only yields high-efficiency solar cells when it is deposited by CBD, due to the action of ammonia on the surface of CIGSe and

1. Introduction

$\text{Cu}(\text{In,Ga})\text{Se}_2$ (CIGSe) thin-film solar cells present an opportunity for flexible, tandem, or semitransparent applications, together with easy and cheap manufacturing for large-area modules due to milder processing temperatures compared to silicon solar cells.^[1–4] This technology has been widely studied because CIGSe can be prepared by several methods that give high control

the complete and conformal coverage over the polycrystalline CIGSe.^[9] The CBD technique consists of the deposition of inorganic (oxide, sulfide, or selenide) thin films by immersion of a substrate in a precursor solution. It is based on a controlled chemical reaction (normally hydrolysis) performed typically in an aqueous solution that yields coating of the substrate (heterogeneous nucleation at the solution/substrate interface) while also resulting in a colloidal suspension (homogeneous nucleation occurring in solution). Generally, the precursor aqueous solution involves a soluble metal salt, a pH agent, and a complexing agent, used to control the hydrolysis rate.

However, the relatively low direct bandgap of CdS, $E_g = 2.4\text{--}2.5 \text{ eV}$,^[10] prevents high energy photons from being absorbed by the p-CIGSe.^[11] In addition, the presence of toxic Cd presents health and environmental concerns.^[12,13] Therefore, wider bandgap and less toxic materials have been researched to produce Cd-free CIGSe solar cells.^[11,14,15] Among these materials, zinc tin oxide ($\text{Zn}_{1-x}\text{Sn}_x\text{O}_y$, ZTO) has attracted much attention due to its nontoxicity, fast light responsivity, and tunable wide bandgap. CIGSe solar cells based on ZTO buffers have resulted in PCE comparable to or even higher than CdS ones.^[8,11,14,16]

Until now, ZTO buffer layers on CIGSe solar cells have been only fabricated by atomic layer deposition (ALD) with atomically precise resolution in vacuum conditions by sequential vapor reactions of organometallic precursors and gases. Although ALD allows excellent control over ZTO composition and assures excellent coverage,^[17] it is hardly scalable, time-consuming, and expensive. In contrast, the production of record CIGSe-based solar cells makes use of the CBD to produce CdS and other inorganic thin

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films as buffer layers.^[7] Moreover, CBD is known for being a low-temperature (<100 °C) process that yields conformal growth in a fast, reliable, cheap, and batch-scalable manner.^[18–20]

Studies on CBD for ZnO thin films have shown diverse nanostructured morphologies obtained by tuning parameters such as ligands, counter-ions of the metal salts, pH, temperature, and nature of the substrate.^[21,22] Furthermore, the electrical and optical properties of ZnO thin films have also been modified by doping with other metals such as aluminum, gallium, indium, etc.^[23] Hence, the CBD of ZnO lends itself to relatively simple modifications in the bath, substrate, or temperature to tune the thin-film composition and properties.

Here, we develop the deposition of ZTO thin films by CBD. We first study the deposition on soda lime glass (SLG) and the alloying with Sn, to understand the effect of Sn cations. Subsequently, the application as buffer layer for CIGSe-based solar cells was investigated, and we compare the current density–voltage (JV) characteristics of solar cell devices based on ZTO buffer layers with those of CdS-based CIGSe solar cells.

2. Results and Discussion

The morphology of the ZTO thin films depends strongly on the Sn concentration in the bath solution (Figure 1a). The Sn-free

ZnO thin film on SLG exhibits a columnar growth, with a preferential (002) plane orientation, also reported by Kokotov, et al.^[19] Surprisingly, such a columnar structure was not observed even for TTZ as low as 1%, where TTZ represents the molar $([\text{Sn}]/([\text{Sn}] + [\text{Zn}]))$ ratio in the solution. In the range 1%–10%, TTZ the morphology corresponds to truncated columns. Samples grown at 15% TTZ show a compact film, due to lateral growth constrained by the contact between neighboring crystals. Higher Sn concentrations give rise to compact films with small elongated grains. ZTO with 50% TTZ shows an almost cubic morphology, consistent with earlier reports.^[24,25] Substrates subject to 50% and higher TTZ baths show a poor coverage of the SLG, with only small regions displaying material, probably due to the high amount of homogenous nucleation in the bath (not shown).

To better understand these changes in morphology, X-ray diffraction (XRD) was performed on all films (Figure 1b). The addition of Sn in the solution modifies the intensity of the ZnO peaks without introducing any additional reflection. Thus, no additional phase detectable by XRD appears to form up to 40% TTZ. It is worth to note that some of the peaks of the references are not present in the diffractograms of the samples. This inconsistency might be explained considering that the samples experience preferential orientation favored by their thin-film organization while typically the references are acquired

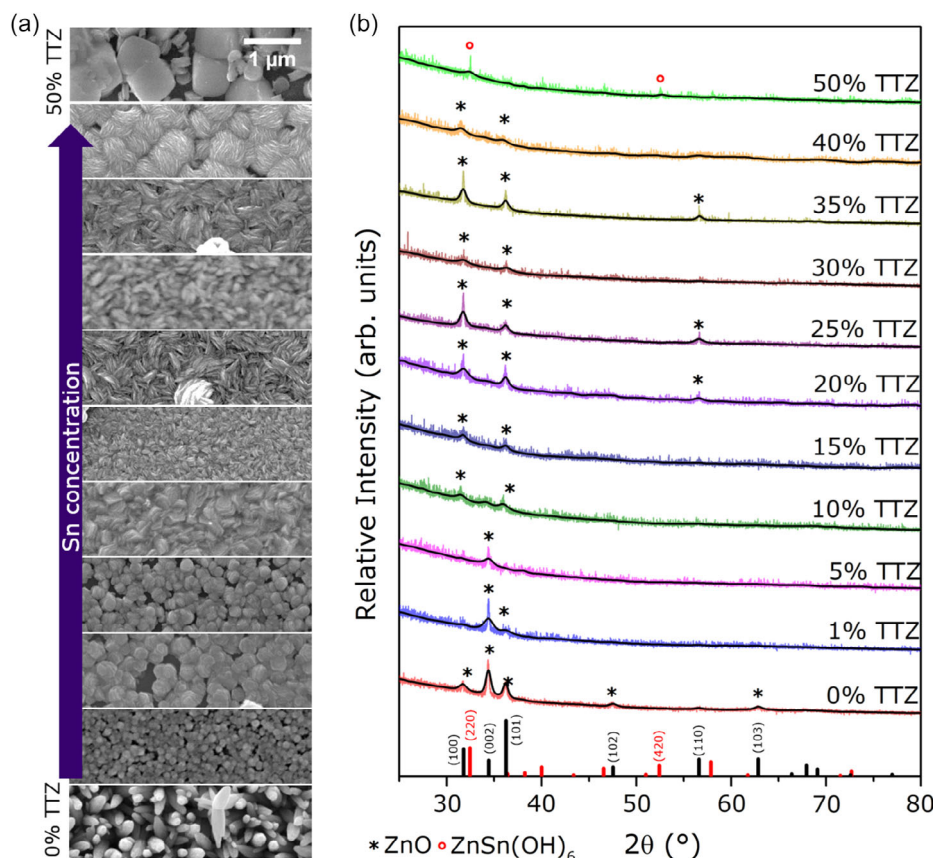


Figure 1. a) High magnification scanning electron microscopy (SEM) images of the ZnO thin films obtained at different Sn nominal doping concentrations. b) XRD patterns for ZTO thin films onto SLG. The black line corresponds to a fitting (HighScore software), TTZ is the molar $[\text{Sn}]/([\text{Sn}] + [\text{Zn}])$ ratio. The reference patterns at the bottom correspond to ZnO (black bars) and $\text{ZnSn}(\text{OH})_6$ (red bars).

onto powders that are randomly oriented and hence do not display any preferential orientation.

However, the intensity of the peak related to the ZnO (002) plane decreases with the addition of Sn, until it is no longer visible for concentrations greater than 10% TTZ. This phenomenon has been reported for ZnO depositions where additional metals were added as well as in ZTO films deposited by ALD.^[3] In these cases, the charged complexes of foreign ions appear to passivate differently from the crystal facets of ZnO-columns by electrostatic interactions.^[26,27] At 50% TTZ, the peaks observed correspond to reflections of the (220) and (420) planes associated with the ZnSn(OH)₆ phase.^[28] Thus, an oxidation of Sn from the precursor Sn(II) to the Sn(IV) present in the hydroxide phase must be occurring in the bath.

All obtained ZTO films with TTZ up to 50% are highly transparent with transmission above 76% in the wavelength range between 500 and 1200 nm (Figure 2a); the reflectance and absorption spectra are shown in Figure S1, Supporting Information. The bandgap (Figure 2b), extracted from the transmittance and reflectance spectra by the Tauc method (Figure 2c,d), presents a nonlinear increase with increasing Sn concentration, ranging between the values for ZnO (3.2 eV) and SnO₂ (3.9 eV).^[29,30] This optical behavior has been reported in ZTO films deposited by several methods, such as spray pyrolysis, magnetron sputtering, and ALD.^[31–33] This effect has been understood as a mixture of the concentration of the dopant (Sn) and changes in the microstructure of the material.^[32] The bandgap behavior can be correlated with the changes in XRD patterns and morphology, where there were significant changes for lower TTZ films together with similar morphology in the range

20%–40% TTZ. The latter opens the possibility of tuning the bandgap from 3.2 to 3.6 eV.

In the following, we explore the suitability of ZTO films deposited by the developed CBD process as buffer layer for CIGSe solar cells (Figure 3a). The deposition of ZTO on SLG substrates required an activation step with potassium permanganate. Nevertheless, the deposition of ZTO performed directly on CIGSe yielded good thin films even without the activation step. We studied concentrations between 10% and 40% TTZ and, for all concentrations, a deposition time of 30 min resulted in a thickness of (350 ± 15) nm as measured by SEM cross-section imaging (Figure 3c,e,g,i). As observed for the growth on SLG substrates, the change of Sn nominal concentration produces different ZTO morphologies also on CIGSe substrates (Figure 3). For 10% TTZ, truncated columns are observed (Figure 3d), whereas 20% TTZ yields a morphology with small grains elongated in parallel to the substrate (Figure 3f). In the case of 30% TTZ, the grains assume a spherical shape (Figure 3h), while for the highest concentration tested the spheres become round-edged cuboids (Figure 3j). In all cases, the ZTO thin films display smaller grains than the underlying CIGSe substrate (Figure 3b).

Quantification of the TTZ ratio in the ZTO buffer layer was performed by dissolving the respective layer in an acidic solution and measuring the concentration of Zn and Sn by inductively coupled plasma atomic emission spectroscopy (ICP-AES) (Figure 4a). The data show that an increase of the TTZ in the solution leads to an enhancement of the Sn content in the film. However, the incorporation of Sn into the thin films does not exhibit a simple linear dependence on the concentration in

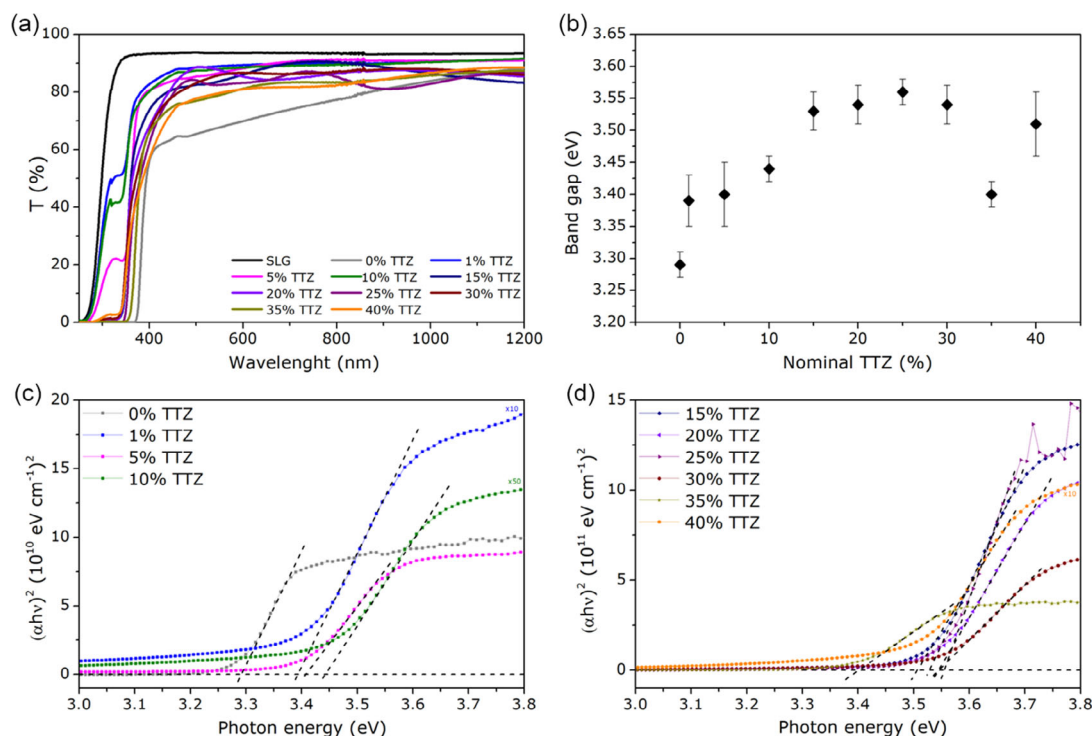


Figure 2. a) Transmittance spectra and b) variation of the band gap of ZTO films as a function of nominal TTZ, obtained by c,d) extrapolation in the Tauc method.

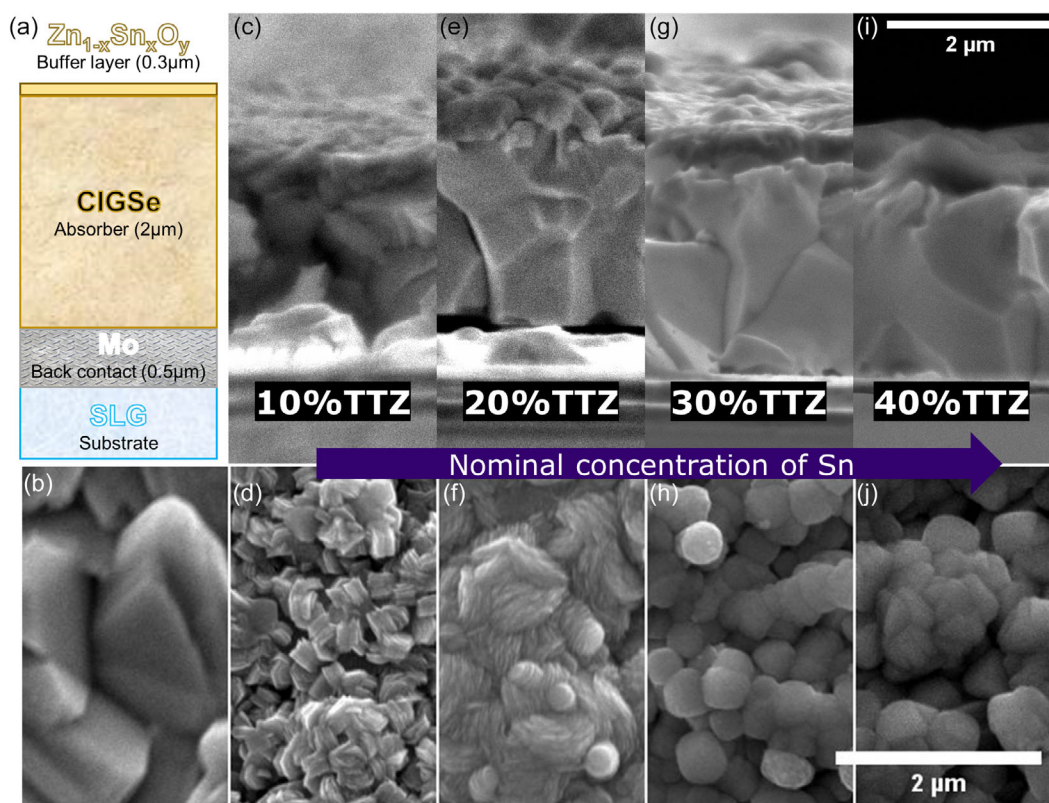


Figure 3. a) Schematic of the SLG/Mo/CIGSe substrate used for the deposition of the ZTO thin films. b) Top view SEM image of the CIGSe thin film. Cross-section and top-view SEM images of ZTO thin films with c,d) 10% TTZ, e,f) 20% TTZ, g,h) 30% TTZ, and i,j) 40% TTZ as grown onto CIGSe.

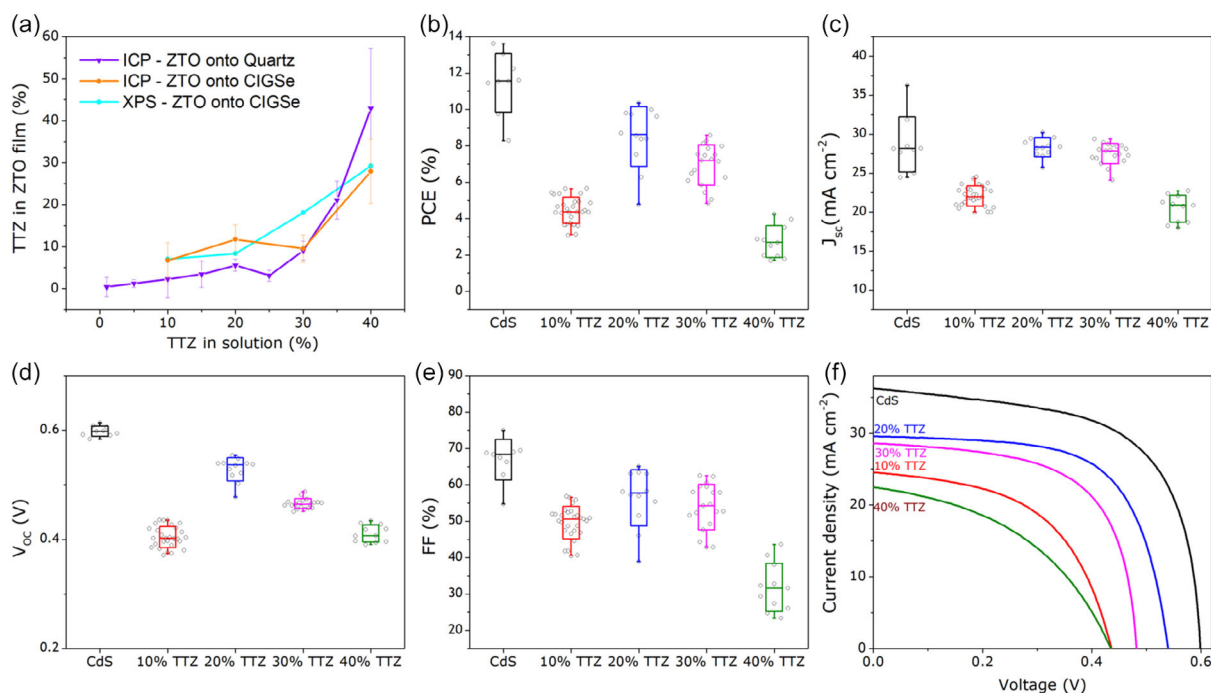


Figure 4. a) Measured TTZ in the ZTO thin film on CIGSe and Quartz by XPS and ICP as a function of nominal TTZ in the bath solution. Solar cell parameters for CdS-based and ZTO-based devices with different compositions of ZTO buffer layers: b) power conversion efficiency, c) short-circuit current density, d) open-circuit voltage, and e) fill factor. f) JV curves under illumination for the solar cells with CdS and ZTO buffer layers.

the solution. This difference may originate from the precipitation of tin oxides and hydroxides during the deposition, which competes with the incorporation of Sn in the growth of the thin film. For comparison, the TTZ of thin films deposited on Quartz is also shown, revealing that increasing Sn concentrations in solution lead to Sn-rich films, with a similar dependence as the one observed for CIGSe. This result supports the hypothesis that the precipitation of tin oxides might play a role; nevertheless, some differences in the film TTZ (TTZ_{film}) versus solution TTZ (TTZ) are observed, which could indicate that the substrate also plays a role in the inclusion of Sn ions into the film during the deposition.

The ZTO thin films on CIGSe were also analyzed by XPS to confirm the electronic state and composition. The survey spectra show the presence of Zn, O, and Sn (Figure S2a, Supporting Information) for all the studied TTZ compositions. Regarding the samples with 10% and 20% TTZ, the peak at 531 eV is related to the O²⁻ position in the wurtzite structure, while the peak at 530 eV corresponds to oxygen vacancies and/or -OH group.^[3,34–36] Furthermore, concentrations with TTZ higher than 20% show only the peak related to oxygen vacancies and/or -OH group (Figure S2b, Supporting Information). Therefore, the chemical formula is conservatively identified as Zn_{1-x}Sn_xO_y.

The XPS analysis (Figure S2c, Supporting Information) also shows peaks related to the spin-orbit coupling of Zn 2p_{3/2} and Zn 2p_{1/2} at 1,021 and 1,044 eV, respectively. The latter indicates a normal Zn²⁺ state with a difference between the peaks of 23 eV.^[34,37] In addition, XPS scans exhibit peaks corresponding to the spin-orbit coupling of Sn 3d_{5/2} and Sn 3d_{3/2} at 486.68 and 495.14 eV, respectively, and a peak corresponding to the Auger Zn L₃M₄₅M₄₅ transition at 498–499 eV that overlaps with the peak of Sn 3d_{3/2} (Figure S2d, Supporting Information). The Sn 3d_{5/2} peak at 486.68 eV is originated by Sn⁴⁺ by comparing its peak position to the literature (Table S1, Supporting Information)^[37–43] thus, confirming that during the bath there is an oxidation of the Sn, due to the instability of Sn(II) at alkaline pH.^[44]

The relative intensity of the L₃M₄₅M₄₅ signal decreases with increasing TTZ and its position shifts to higher energy when the Sn concentration is higher than or equal to 30% TTZ. It is reported that the probability of this kind of transition is related to the morphology, which drastically changes after 30% TTZ.^[34,38] In addition, by the analysis of the Auger transition, the determination of interstitial Zn (Zn_i) and Zn–O is possible.^[45] Nevertheless, in our case, the overlapping of this peak with the Sn 3d_{3/2} does not allow a further understanding of the different states of Zn in the surface of the sample. Furthermore, the XPS data was also used to quantify the TTZ_{film} in the ZTO films, confirming the trends observed by ICP (Figure 4a and S2e, Supporting Information). Nevertheless, the ICP measurements correspond to the bulk TTZ, which was preferred in the following discussion.

Last, solar cell devices with the ZTO buffer layers were fabricated and their respective JV curves and parameters are shown in Figure 4, together with CdS-based reference devices. The CdS-based solar cells show a narrow distribution of PCE with an average of (11 ± 2)%, and a J_{sc} and V_{oc} of (29 ± 4) mA cm⁻² and (598 ± 9) mV, respectively. Conversely,

the ZTO-based solar cell, achieved the best efficiency for the 20% TTZ sample (9 ± 2)% and a champion cell showing 10.4% efficiency (champion cell values are presented in Table S2, Supporting Information). This performance is due to a greater J_{sc}, V_{oc}, and FF with averages of (28 ± 1) mA cm⁻², (528 ± 21) mV, and (56 ± 8)%, respectively, compared to the other ZTO-based devices. (Figure 4, average values presented in Table S3, Supporting Information). Comparing the average values, the 20% TTZ ZTO-based devices behave similarly to the CdS-based devices for the short-circuit current, even though the ZTO buffer layer has larger thickness. The latter is related to the larger bandgap of ZTO (3.5 eV) compared to that of CdS (2.4 eV), which in principle can reduce the parasitic light absorption compared to the latter, as can be seen in the shape of the external quantum efficiency (EQE) measurement (Figure S2f, Supporting Information).^[8] In addition, the EQE spectra show an oscillatory behavior in the low wavelength range for all the ZTO-based devices, which can be attributed to the reflectance (Figure S3a, Supporting Information), and is significantly reduced in the internal QE (IQE) spectra (Figure S3b, Supporting Information). Additionally, a gain at wavelengths greater than 900 nm is observed, which has been reported in the literature.^[17,46]

Nevertheless, the open-circuit voltage obtained for the 20% TTZ ZTO-based devices is (70 ± 23) mV less on average than the V_{oc} of the CdS devices. This decrease in the open-circuit voltage has been related to higher surface recombination in the ZTO/CIGSe interface and a mismatch in the band alignment.^[3,47] Nevertheless, in the present case, a slightly lower effective bandgap (by ≈ 50 meV, according to the EQE data in Figure S2f, Supporting Information) of the ZTO-based devices might also contribute to their lower V_{oc}.

Additionally, the FF for the 20% TTZ ZTO-based devices is lower than the CdS reference. This comes, in part, from the lower open-circuit voltage, which affects the FF by an empirical expression.^[47,48] Moreover, the ZTO-based solar cells exhibit a higher series resistance that has a negative impact on the FF and is related to the poor conductivity of ZTO thin films and the relatively large thickness of the studied buffer layers, compared to the CdS reference. The latter has been already reported for CIGSe solar cells with ZTO deposited by ALD.^[3,8,47]

According to the ICP measurements, the TTZ_{film} in the ZTO film is around 10%–12% for the TTZ of 20% and 30%, for which the better-performing solar cells were obtained. For the samples with 10% and 40% TTZ, the resulting solar cells show significantly poorer performance. The corresponding ZTO films have TTZ_{film} of 8% and 28%, respectively, according to the ICP analysis. These observations are in good agreement with reports in the literature where TTZ values in the range of 15%–21% gave the best performance.^[8,46] The wider distribution for all the parameters in the ZTO-based devices could be related to inhomogeneities present in the p–n junction, possibly originating from the unstirred deposition bath.

It is noteworthy that the ZTO-buffered solar cells exhibit excellent performance, despite the large thickness of this buffer layer (≈ 350 nm) compared to the standard CdS buffer layer (≈ 50 nm). Therefore, we further investigated the ZTO buffer layer by high-resolution transmission electron microscopy (HRTEM) imaging (Figure 5). Specifically, the high-angle annular dark-field

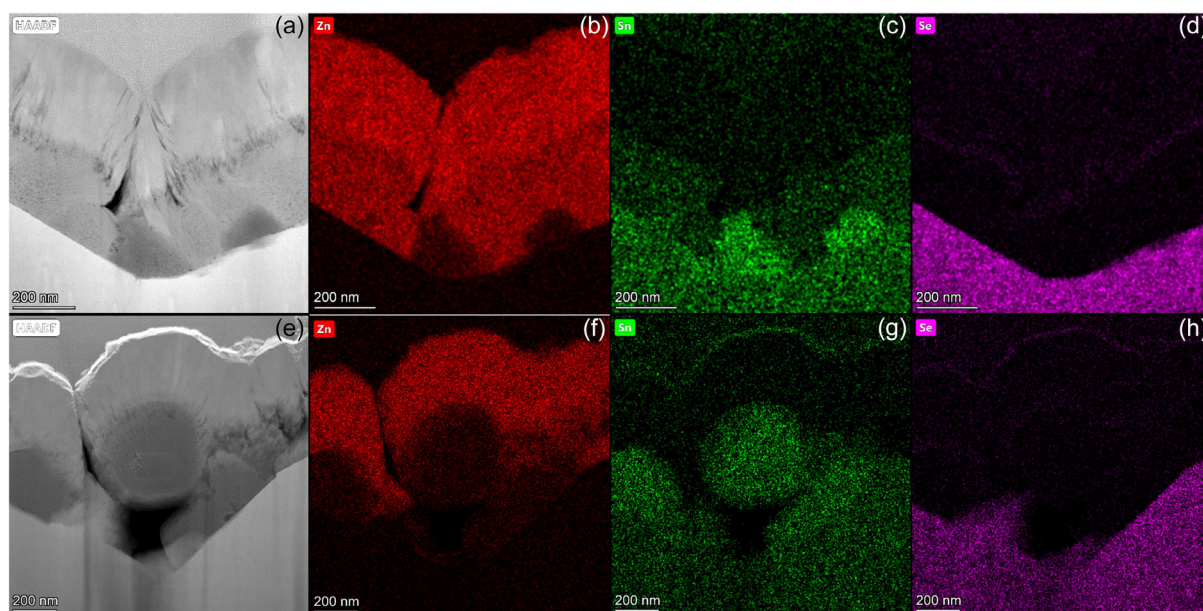


Figure 5. HAADF-STEM images of the ZTO-CIGSe solar cells: a) ZTO buffer layer with 20% TTZ, b–d) corresponding elemental maps from the area of the HAADF image for Zn (red), Sn (green), and Se (violet) acquired by EDS, respectively; e) ZTO buffer layer with 40% TTZ and f–h) corresponding elemental maps from the area of the HAADF image for Zn, Sn and Se.

scanning transmission electron microscopy (HAADF-STEM) images and elemental maps are compared for the best and worst performing ZTO-based solar cell devices, i.e., for 20% and 40% TTZ, respectively. Surprisingly, the ZTO film presents inhomogeneities with Zn-poor and Sn-rich regions close to the ZTO/CIGSe interface for both 20% and 40% TTZ devices. The 40% TTZ ZTO-based device exhibits a greater quantity of these Zn-poor Sn-rich regions (Figure S4, Supporting Information) which also cover the full thickness of the ZTO film in some places (Figure 5e–h). The elemental maps of selenium are displayed to indicate the position of the ZTO/CIGSe interface

After an elemental quantification by energy-dispersive X-ray spectroscopy (EDS) (Figure S5, Supporting Information), the darker (in the HAADF image) Sn-rich regions for both devices present an average of $(33 \pm 4)\%$ TTZ_{film}, while the brighter regions exhibit a $(3.1 \pm 0.5)\%$ TTZ_{film}. These results obtained by STEM agree with the reported TTZ_{film} by ICP, where a higher TTZ_{film} is related to higher TTZ, due to the existence of more Sn-rich regions. It seems that the presence of too many Sn-rich regions can deteriorate drastically the performance of the solar cell, whereas a small number of Sn-rich regions at the interface, as in the case of the 20% TTZ ZTO-based device, gives the best performance compared to the CdS reference. The latter feature could be related to point-contact-like passivation of the interface, which would decrease the charge carrier recombination in the Sn-rich regions, as has been reported for nanostructured buffer layers.^[49,50] Further investigation regarding the interface of ZTO/CIGSe is needed to fully understand the role of these Sn-rich regions.

3. Conclusion

ZTO thin films were obtained by the addition of Sn cations during the chemical bath deposition of ZnO thin films onto

soda-lime glass. These cations and their respective complexes in solution affect the growth of the film by electrostatic interactions via the occupation of specific crystallographic sites at the surface of the ZnO wurtzite structure. The resulting films display highly diverse final morphologies. The addition of Sn allows tuning the bandgap from 3.2 to 3.6 eV. CIGSe solar cells with a ZTO buffer layer prepared with a TTZ of 20% (corresponding to $11.7\% \pm 0.6\%$ TTZ_{film}, as measured by ICP) show a maximum efficiency of 10%, nearly matching CdS-based reference devices, with an average of $(11 \pm 2)\%$. STEM images revealed compositional inhomogeneities with Sn-rich regions close to the ZTO/CIGSe interface. However, a higher density of these Sn-rich regions, obtained for higher TTZ, deteriorates drastically the performance of respective solar cells, as in the case of the 40% TTZ ZTO buffer layer. Further investigation is required to understand the role of the Sn-rich regions at the absorber/buffer interface. Overall, ZTO thin films obtained by CBD are a viable and nontoxic alternative to CdS-based CIGSe solar cells with comparable PCE.

4. Experimental Section

Deposition of Zinc Tin Oxide (ZTO) Thin Films onto Soda-Lime Glass (SLG): Zinc tin oxide thin films were deposited onto SLG by chemical bath deposition (CBD) based on the process reported by Kokotov et al.^[19] Substrates were cleaned by sonication with deionized water (DIW) and soap. Then, the SLG was activated with a fresh solution of potassium permanganate 5 mM and 25 μ L of 1-butanol per 10 mL of solution at 85 °C for 20 min. The deposition bath was prepared by the consecutive addition of aliquots of ZnSO₄, NH₄OH, ethanolamine, and SnCl₂ stock solutions to obtain a final concentration of 75 mM of cations ($[\text{Zn}^{2+}] + [\text{Sn}^{2+}]$), 0.2 M NH₄OH, and 1.6 M ethanolamine. The depositions were carried out at 92 °C with a variation of the $[\text{Sn}]/([\text{Sn}] + [\text{Zn}])$ ratio (TTZ) for 10–70 min in a range of 0%–50% TTZ by adding different aliquots of stock

solutions of ZnSO_4 and SnCl_2 . The stock solution of tin (II) chloride 1.5 M was prepared in an acidic medium with sufficient concentrated HCl to obtain a clear solution (≈ 1.7 M HCl), the latter to prevent the hydrolysis and precipitation of tin hydroxides. Moreover, a solid precipitates during the deposition, due to the formation of tin oxides and hydroxides.

Fabrication of Thin-Film Solar Cells: For the solar cell fabrication, industry-grade CIGSe absorbers supplied by Nice Solar GmbH were employed. These absorbers have shown a PCE of 15.6%.^[51] They are composed of a soda-lime glass substrate with a thin layer (500 nm) of molybdenum as back contact and a layer of around 2–3 μm of CIGSe on top. Nevertheless, for a fair comparison among the two buffer layers, we treated the CIGSe with a fresh 5 wt% KCN solution for 1 min to remove any Cu-selenides and to refresh the surface.^[52,53] Immediately after the etching, the buffer layer (CdS or ZTO) was deposited by CBD. In the case of 50 nm thick CdS deposition, a solution of 1.33 g of thiourea, 0.13 g of cadmium acetate, 15 mL of NH_4OH , and 115 mL of DIW was used.^[54] The bath was prepared by the sequential addition of DIW, NH_4OH , $\text{Cd}(\text{CH}_3\text{CO}_2)_2$, and thiourea; it was set at 60 °C and the sample was immersed for 7 min. For the ZTO buffer, the same protocol described above was used, but without activation of the substrate and with a deposition time of 30 min at 92 °C. In this case, a range of 10%–40% TTZ was investigated.

To complete the solar cells, a double window layer was deposited by radio-frequency (RF) sputtering at room temperature in the window chamber of the sputtering for advanced research (STAR) system.^[51] First, an intrinsic ZnMgO layer was deposited at 6.1×10^{-3} mbar Ar pressure with 50 W for 14 min (thickness around 20 nm), and finally, an aluminum-doped ZnO layer was deposited at 4.0×10^{-3} mbar Ar pressure with 59 W for 51.5 min (≈ 300 nm).

Film and Device Characterization: The thin-film morphology was determined by top-view and cross-section micrographs obtained by scanning electron microscopy (SEM) in an FEI Quanta 50 FEG SEM and a dual-beam FEI Helios focused ion beam (FIB). The optical transmittance and reflectance of the thin films on SLG were measured in the range of 250–1200 nm with a PerkinElmer LAMBDA 950 UV-vis-NIR spectrophotometer coupled with an integrating sphere detector module. The optical bandgaps were determined by the Tauc method considering multiple internal reflections in a thin film,^[55] where the bandgap is equal to the abscissa of $(\alpha h\nu)^r$ as a function of photon energy ($h\nu$), with $r=2$ (for direct bandgap materials), $\alpha = (\ln((1-R)^2/T + ((1-R)^4/4T^2) + R^2)^{0.5})/t$, with T = the measured transmittance, R = the measured reflectance, and t = the film thickness.^[56] The thickness of the samples was assessed by contact profilometry with the Tencor P-16 Surface Profiler.

The crystal structure was determined by X-ray diffraction (XRD) using Cu K_α radiation in a Panalytical XPert PRO MRD. The XRD patterns were processed in HighScore, and the patterns shown correspond to the raw data and a fitting. The chemical composition of the thin films was determined by X-ray photoelectron spectroscopy (XPS) with the ESCALAB 250Xi (Thermo Scientific). First, an XPS survey was performed followed by high-resolution scans for C 1s, O 1s, Sn 3d, and Zn 2p. Last, the peaks were fitted and the TTZ_{film} was determined with the areas related to the Zn $2p_{3/2}$ and Sn $3d_{5/2}$. The C 1s peak (284.8 eV) was used as an internal standard for binding energy calibration.

Furthermore, a Varian (Springvale, Australia) Vista PRO ICP-AES with a sample introduction system consisting of a glass concentric K-style pneumatic nebulizer jointed to a glass cyclonic spray chamber was employed for the determination of TTZ_{film} . All samples were analyzed seven times using online internal standardization (10 mg L^{-1} Lu standard solution).

ZTO-based solar cells were analyzed by scanning transmission electron microscopy (STEM) and energy dispersive spectroscopy (EDS). These studies were carried out with a double-corrected FEI Titan G3 Cubed Themis equipped with a Super-X EDX System, operated at 200 kV. The samples for STEM/EDS analysis were prepared by a dual-beam FEI Helios focused ion beam (FIB) following the standard lift-out procedure. In order not to destroy the outer layers by Ga^+ ions during the milling steps, two Pt layers were deposited: ≈ 200 nm by electron (e^-) beam and $\approx 2 \mu\text{m}$ by ion (i^-) beam. 30 kV ion beam was performed for the bulk milling and thereafter the lamellae were thinned down to 100 nm in thickness. Finally, a 5 kV ion beam was used to remove the surface amorphization.

The current density–voltage (J/V) characteristics of solar cell devices were measured in a solar simulator (Oriol Sol3A class AAA) under AM1.5 illumination. Devices were manually scribed to $\approx 0.15 \text{ cm}^2$ and measured without a front grid at room temperature. External quantum efficiency (EQE) was measured by the QEX10 Solar Cell Quantum Efficiency Measurement (PV Measurement Inc.). A 75 W Xenon arc lamp was used as a white light source to generate a monochromatic beam. The DC mode was used in a spectral range of 300–1,100 nm. In addition, internal quantum efficiency (IQE) spectra were calculated based on the EQE, and the reflectance of the solar cells was measured by UV-vis NIR spectrophotometry with an integrated sphere detector module.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

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

Keywords

buffer layers, chemical bath deposition, CIGSe, thin film solar cells, zinc tin oxide

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