

RESEARCH ARTICLE | FEBRUARY 20 2024

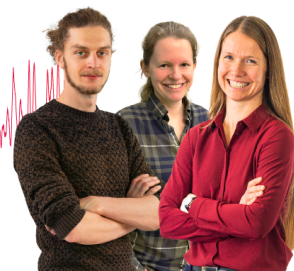
17.2% Efficient $\text{CdSe}_x\text{Te}_{1-x}$ solar cell with $(\text{In}_x\text{Ga}_{1-x})_2\text{O}_3$ emitter on lightweight and flexible glass

Manoj K. Jamarkattel ; Ali Abbas ; Xavier Mathew ; Sabin Neupane ; Ebin Bastola ; Deng-Bing Li ; Samuel Seibert ; Aesha P. Patel ; Zhaoning Song ; Xiaolei Liu ; John Michael Walls ; Sean M. Garner ; Adam B. Phillips ; Randy J. Ellingson ; Yanfa Yan ; Michael J. Heben  

*Appl. Phys. Lett.* 124, 080601 (2024)<https://doi.org/10.1063/5.0193628> CHORUS

Webinar From Noise to Knowledge

May 13th – Register now

Zurich
InstrumentsUniversität
Konstanz

17.2% Efficient $\text{CdSe}_x\text{Te}_{1-x}$ solar cell with $(\text{In}_x\text{Ga}_{1-x})_2\text{O}_3$ emitter on lightweight and flexible glass

Cite as: Appl. Phys. Lett. **124**, 080601 (2024); doi: [10.1063/5.0193628](https://doi.org/10.1063/5.0193628)

Submitted: 22 December 2023 · Accepted: 30 January 2024 ·

Published Online: 20 February 2024



Manoj K. Jamarkattel,¹ Ali Abbas,² Xavier Mathew,^{1,3} Sabin Neupane,¹ Ebin Bastola,¹ Deng-Bing Li,¹ Samuel Seibert,¹ Aesha P. Patel,¹ Zhaoning Song,¹ Xiaolei Liu,² John Michael Walls,² Sean M. Garner,⁴ Adam B. Phillips,¹ Randy J. Ellingson,¹ Yanfa Yan,¹ and Michael J. Heben^{1,a)}

AFFILIATIONS

¹Department of Physics and Astronomy, and Wright Center for Photovoltaics Innovation and Commercialization, University of Toledo, Toledo, Ohio 43606, USA

²Centre for Renewable Energy Systems Technology (CREST), Loughborough University, Loughborough, Leicestershire LE11 3TU, United Kingdom

³Instituto de Energías Renovables, Universidad Nacional Autónoma de México, Temixco, Morelos 62580, Mexico

⁴Corning Research and Development Corporation, One River Front Plaza, Corning, New York 14831, USA

^{a)}Author to whom correspondence should be addressed: Michael.Heben@Utoledo.edu

ABSTRACT

High-efficiency, lightweight, and flexible solar cells are sought for a variety of applications particularly when high power density and flexible form factors are desired. Development of solar cells on flexible substrates may also offer production advantages in roll-to-roll or sheet-to-sheet processes. Here, we report device efficiencies of 17.2% and 14.6%, under AM1.5G and AM0 irradiances, respectively, for a flexible, lightweight, CdTe-based solar cell. To advance the efficiency relative to the highest previously reported AM1.5G value of 16.4%, we used an indium gallium oxide (IGO) emitter layer on a cadmium stannate (CTO) transparent conductor, which was deposited on 100- μm thick Corning® Willow® Glass. A sputtered CdSe layer was employed to incorporate Se into a CdTe absorber that was deposited by close-space sublimation, and CuSCN was used as a hole transport layer between the CdTe and the back metal electrode. The IGO and CTO layers remained intact during the high temperature film processing as seen in cross-sectional imaging and elemental mapping. This device configuration offers great promise for building-integrated photovoltaics, space applications, and higher rate manufacturing.

© 2024 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). <https://doi.org/10.1063/5.0193628>

Cadmium telluride-based (CdTe) photovoltaics (PV) is a commercialized technology that has achieved records of 22.3% and 19%, at the cell¹ and module levels, respectively. CdTe PV has an industry leading leveled cost of electricity,² and an energy payback time less than half of that of silicon modules.³ As of 2021, CdTe PV had ~5% of the total global PV market and 40% of the US utility scale market,^{3,4} corresponding to 30 GW_{DC} of installed capacity.^{4,5} High efficiency CdTe modules for utility scale and residential applications are fabricated on rigid glass substrates that are typically 2–3 mm thick in automated factories. CdTe also has promise for applications where a lightweight and flexible format is preferred, such as in aerospace applications. While large scale production methods remain to be determined for these cases, CdTe has already demonstrated good performance in space where radiation hardness is required.⁶

While research on lightweight polymer,^{7,8} ceramic substrates,⁹ and liftoff techniques¹⁰ is being pursued to achieve high specific power (W/kg), efficiencies to date are below 14%. Though a variety of approaches to achieve high specific power are being examined, the simplest way of transferring the high efficiencies obtained for rigid CdTe solar cells to a lightweight format may be to maintain the superstrate configuration and use thin glass substrates that are compatible with the high temperatures (~600 °C) that are currently necessary. In fact, the standing record efficiency of 16.4% for a lightweight, flexible CdTe device was obtained using 100- μm thick Corning® Willow® Glass as a substrate,¹¹ with a $\text{SnO}_2\text{:F}/\text{SnO}_2/\text{CdS:O}/\text{CdTe}/\text{ZnTe:Cu}/\text{Au}$ device stack. The current state-of-the-art rigid device, however, relies on a graded bandgap $\text{CdSe}_x\text{Te}_{1-x}$ (CST) region at the front of the device, as opposed to CdS. When CdSe is substituted for CdS and

processing is optimized, the CdSe interdiffuses with the CdTe and is nearly completely consumed, leaving a low bandgap (~ 1.39 eV) layer at the front, which remains photoactive.^{1,5} The Se also diffuses into the bulk CdTe and is thought to passivate a deep-level, non-radiative recombination center in the CdTe bandgap that is assigned to the $\Sigma 3$ (112) grain boundary (GB) in the polycrystalline absorber. It has been proposed that Se segregates to the GB and substitutes for Te dimers, thereby pushing the GB deep levels toward valence band edge, resulting in higher carrier lifetime.¹² Thus, introduction of Se into CdTe not only increases the carrier lifetime, leading to higher open-circuit voltage, but also extends the response into the red region due to the presence of a lower bandgap¹³ and significantly improves the blue response as a result of the near-complete consumption of the buffer layer due to the higher solubility of Se in CdTe as compared to S.¹⁴

The conduction band offset (CBO) at the front interface is also critical in high efficiency devices since interface recombination near the illuminated electrode is often a dominant limiting factor.¹⁵ Magnesium zinc oxide (MZO) and indium gallium oxide (IGO) are the only two buffer materials in the literature that have shown the ability to tune the CBO with the absorber.^{16,17} The MZO buffer has resulted in devices with higher efficiencies, in the range of 19%,¹⁶ but it is unstable in oxygen-containing environments, especially during cadmium chloride (CdCl_2) treatment.¹⁸ IGO is more robust during thermal processing and allows CdCl_2 treatments to be done in air ambient.¹⁷ Zinc oxide has also been introduced as a possible buffer material.¹⁹

In this contribution, we are utilizing the latest in device science to advance the efficiency of lightweight, flexible CdTe PV solar cells. We implemented a cadmium stannate transparent conductor (Cd_2SnO_4 , CTO) as the front electrode on Corning® Willow® Glass, employed IGO as the buffer layer, used a graded CST absorber at the front, and utilized CuSCN as a back contact with the dual function of acting as a hole transport layer and a source of Cu for doping.^{20,21} Device efficiencies of 17.2% and 14.6% were measured under AM1.5G and AM0 irradiance, respectively.

Devices were fabricated on $3'' \times 3''$ coupons of 100 μm thick Corning Willow Glass. The front electrode was prepared by depositing ~ 300 nm of CTO by sputtering at room temperature in 10 mTorr of 80% Ar and 20% O_2 . The CTO films were then subjected to a proximity anneal with a CdS source at 600 °C for 30 min under a vacuum of

2×10^{-6} Torr to improve the transparency, conductivity, and help to maintain a 2:1 ratio for Cd:Sn in CTO film.²² Approximately 55 nm of IGO was then deposited by co-sputtering at 250 °C under 4 mTorr pressure of 2% O_2 in Ar to obtain a film with a bandgap of 4.1 eV and a composition of approximately $(\text{In}_{0.28}\text{Ga}_{0.72})_2\text{O}_3$. This composition has been shown to produce a near-optimal CBO for devices prepared on CTO.²³ A ~ 130 nm thick layer of CdSe was subsequently deposited by sputtering, and a 6- μm thick CdTe absorber was grown by high vacuum close spaced sublimation.^{17,24} The device stack was then CdCl_2 treated at 410 °C for 30 min in ambient air. The CuSCN hole transport layer was spin coated onto the rear of the device, followed by a rapid thermal anneal.^{20,21} The device fabrication was completed by depositing ~ 60 nm of Au as a back electrode, and the cell area was defined to 0.085 cm^2 by laser scribing. Prior to current density–voltage (J–V) measurements, the devices were light-soaked for 10 min at 85 °C and, after soaking, an anti-reflection (AR) layer was applied.^{20,21} J–V measurements were performed at room temperature using both AM1.5G and AM0 simulated irradiance. The former is for evaluation of terrestrial deployment while the latter is relevant for deployment above the Earth's atmosphere, in space. The simulated AM1.5G irradiance spectrum was obtained from a Class ABA LED MiniSol Model LSH-7320 solar simulator from Newport, Inc., and the light intensity was adjusted using a calibrated silicon solar cell provided by PV Measurements, Inc. The AM0 irradiance was produced by a G2V Sunbrick large area AAA LED solar simulator. The AM0 power density was calibrated using a GaAs certified reference cell from PV Measurements, Inc.

The J–V plots for the champion cell (AR/Willow Glass/CTO/IGO/CST/CdTe/CuSCN/Au) under simulated AM1.5G and AM0 irradiance are presented in Fig. 1(a), while the external quantum efficiency (EQE) data are shown in Fig. 1(b). Under AM1.5G illumination, the device has an efficiency of 17.2% with $V_{oc} = 861$ mV, $J_{sc} = 27.8$ mA/cm^2 , and FF = 71.7%, while the corresponding parameters under AM0 illumination are 14.6%, $V_{oc} = 861$ mV, $J_{sc} = 32.3$ mA/cm^2 , and FF = 71.2%. Including CST in the device extended the EQE to wavelength beyond 855 nm, which is the absorption onset of CdTe. Compared to the previous best CdTe device on flexible glass,¹¹ the major improvements are in the V_{oc} (+30 mV) and J_{sc} (+2.2 mA/cm^2), leading to a 4.9% relative increase in the efficiency. Based on EQE the bandgap is 1.39 eV, which is slightly lower than the

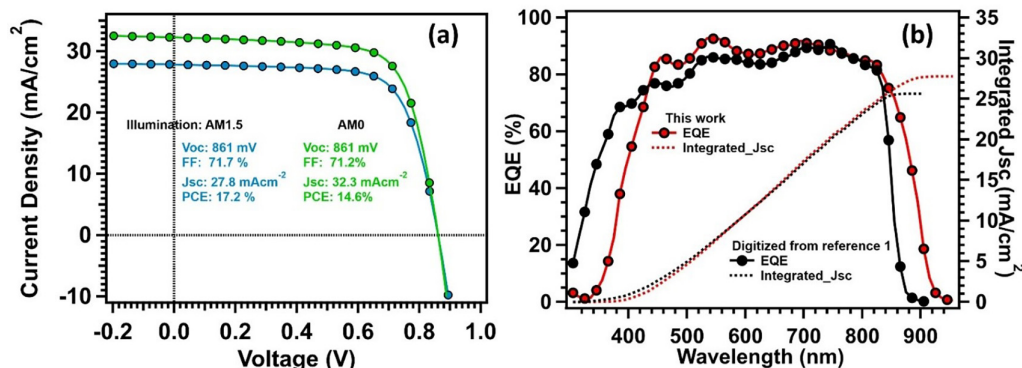


FIG. 1. (a) J–V characteristics under AM0 and AM1.5 illumination and (b) external quantum efficiency plots for the champion device presented here (red line) and that of the record device (black line) taken from Ref. 11. The integrated short-circuit current is for the AM1.5G spectrum.

TABLE I. Statistics of measured device parameters for 15 different devices (AM1.5G illumination).

Devices		V_{oc} (mV)	J_{sc} (mA/cm ²)	FF (%)	PCE (%)
This work	Average	850 ± 4	27.8 ± 0.3	69.2 ± 1.6	16.4 ± 0.4
	Champion	861	27.8	71.7	17.2
From Ref. 11	Record	831	25.5	77.4	16.4

best CdTe device at 1.47 eV. As discussed earlier, the improved V_{oc} in our devices can be attributed to Se passivating deep-defects and recombination centers resulting in longer minority carrier lifetime.¹² Additionally, we used IGO and CuSCN as front emitter and back contact buffer, respectively; this helped to further improve the V_{oc} . IGO has favorable band alignment with the absorber,¹⁷ which minimizes carrier recombination at the front, and CuSCN helps to minimize recombination at the back interface.²⁰ The higher current for our devices is due to the overall improvements in EQE due to the use of CST.¹⁴ Table I shows the statistics for 15 individual devices.

Even though the maximum efficiency for our device is higher than the reported record by 0.8% points, there is still more room for improvement. For example, the FF in our device is lower than that of the record device (71.7% vs 77.4%), suggesting that tuning of the IGO composition or improved composition control in the CTO (vide infra) may be required to improve the band alignment in the front of the device. Fill factors in excess of 76% have been demonstrated on rigid glass with IGO on fluorine-doped SnO₂ (FTO).²⁵ Another area for improvement would be reducing the amount of light absorbed in the CTO. The sharp falloff in EQE in the short wavelength region coincides with the onset of absorption in our CTO film. The previous record device constructed with FTO shows significant photoresponse at wavelengths as short as 310 nm [Fig. 1(b)]. It is clear from the previous work that the IGO layer can transmit such short wavelengths.¹¹ While the lower short wavelength response with our CTO amounts to an ~ 0.3 mA/cm² loss in J_{sc} with AM1.5G irradiance, an additional 0.3 mA/cm² is lost under AM0. Thus, the J_{sc} for this device could be significantly larger.

To investigate the front of the device in more detail, scanning transmission electron microscopy and energy dispersive x-ray spectroscopy (EDXS) data were collected from the CTO/IGO/CST portion of the device after a thin lamella was prepared by the lift-out method using focused ion beam milling.²⁶ The electron image in Fig. 2 is typical of other locations in the sample and shows a conformal IGO layer ~ 55 nm in thickness, well-formed CdTe grains, a few voids, and some pitting in the CTO layer adjacent to the IGO. The elemental maps for Cd, Cl, Se, Ga, and In are also displayed in Fig. 2. The EDXS map for Cd is fairly uniform in intensity on either side of the IGO layer, although a small reduction in intensity can be seen on the CTO side of the layer at the CTO/IGO interface. The Cl map shows that Cl has diffused through the 6 μ m thick sample and accumulated at the IGO/CST interface.^{27,28} The Se map shows a reduction in concentration from the interface consistent with the formation of a graded CST layer. The In and Ga signals are localized within the IGO films, suggesting that the film is fairly stable under the deposition and processing conditions used here. EDXS line scan data for several elements are also shown in Fig. 2. Here, we see that, unexpectedly, the O to Cd increases and the Cd to Sn ratio approaches unity in the CTO layer as the CTO/

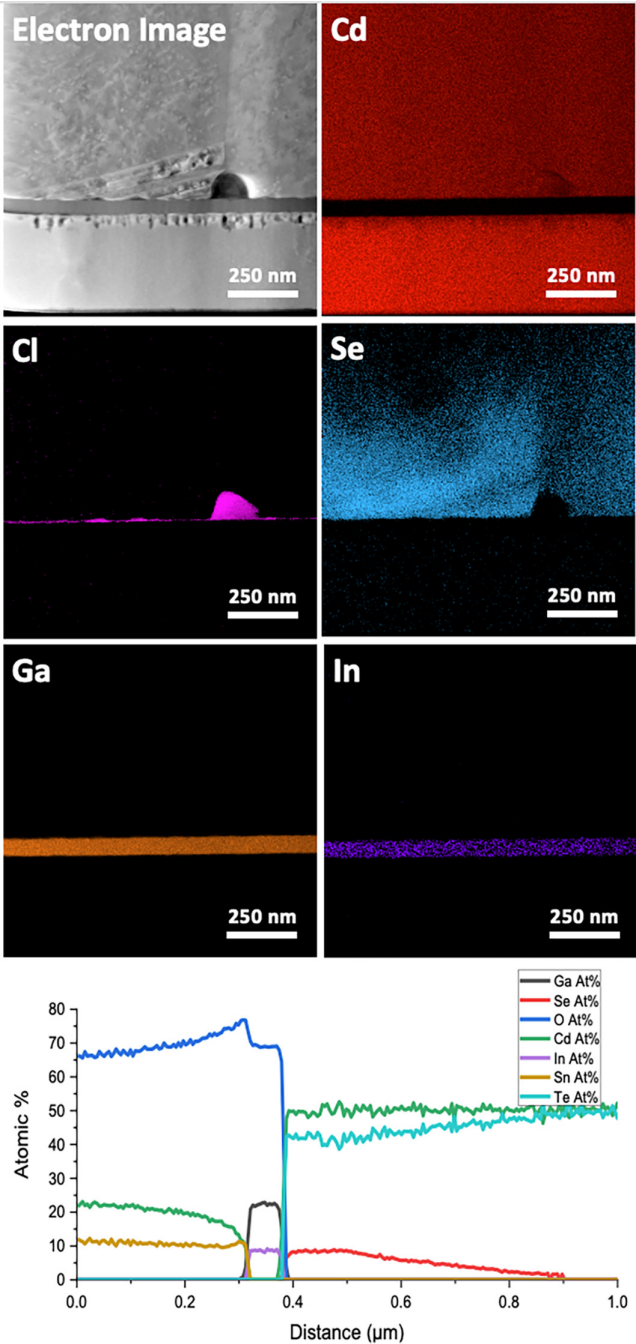


FIG. 2. STEM cross-sectional image of the device stack, EDXS mappings of cadmium, chlorine, selenium, gallium, and indium and EDXS line-scan data.

IGO interface is approached. Thus, the CTO composition deviates appreciably from the intended Cd₃SnO₄ stoichiometry. Note that EDXS measurements performed with excitation normal to the film would not reveal this variation. Since the composition of the elements in the IGO layer appears uniform, we can speculate that the variation

in the CTO film is not due to reaction with the sputtered IGO layer. It is more likely that the sputtered Cd_2SnO_4 film disproportionates to CdSnO_3 and CdO with the latter evolving when the sample was heated in vacuum prior to the sputter deposition of the IGO. Production of a surface layer of CdSnO_3 could move the conduction band as much as 0.4 eV higher in energy,^{29,30} which would disrupt the optimization of the front band alignment. Optimization of the CTO/IGO interface during processing is a key area for targeting further improvements in the device performance.

In conclusion, we have advanced the efficiency of lightweight, flexible CdTe PV to 17.2% and 14.6%, under AM1.5G and AM0 irradiance, respectively, by employing the latest advances in device fabrication using 100- μm thick Corning[®] Willow[®] Glass as a superstrate. The transparent conductor was CTO, produced by sputtering in conjunction with a proximity anneal with CdS, and the front buffer layer was comprised of an IGO alloy, prepared by co-sputtering. The graded CST layer at the front was prepared by first depositing CdSe by sputtering followed by CdTe deposited by close-space sublimation and CdCl_2 processing. CuSCN was used as a Cu doping source and a hole-transporting back-buffer layer. STEM imaging and EDXS analysis revealed key features of the front interface, including In and Ga concentrations that remained constant across the IGO layer. This device configuration offers great promise for building-integrated photovoltaics, space applications, and higher rate manufacturing.

This report is based on research sponsored by the U.S. DOE's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement No. DE-EE0008974, through the Alliance for Sustainable Energy, LLC, Managing and Operating Contractor for the National Renewable Energy Laboratory for the U.S. Department of Energy, under Award No. 37989, and Air Force Research Laboratory under Agreement Nos. FA9453-19-C-1002 and FA9453-21-C-0056. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes not withstanding any copyright notation thereon. Distribution is unlimited. Public Affairs release Approval No. 2023-6323. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of Air Force Research Laboratory or the U.S. Government. The Loughborough authors are grateful to UKRI through EPSRC for funding under Grant No. EP/W00092X/1.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Manoj K. Jamarkattel: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (lead); Validation (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (lead). **Ali Abbas:** Data curation (supporting); Formal analysis (supporting); Investigation (supporting); Methodology (supporting); Validation (supporting); Writing – review & editing (supporting). **Xavier Mathew:** Data curation (supporting); Investigation (supporting); Supervision (supporting); Writing – review

& editing (supporting). **Sabin Neupane:** Data curation (supporting); Investigation (supporting). **Ebin Bastola:** Investigation (supporting). **Deng-Bing Li:** Investigation (supporting). **Samuel Seibert:** Data curation (supporting). **Aesha P. Patel:** Investigation (supporting). **Zhaoning Song:** Investigation (supporting). **Xiaolei Liu:** Investigation (supporting); Writing – review & editing (supporting). **John Michael Walls:** Investigation (supporting); Resources (supporting); Writing – review & editing (supporting). **Sean Matthew Garner:** Resources (supporting); Writing – review & editing (supporting). **Adam B. Phillips:** Conceptualization (supporting); Data curation (supporting); Formal analysis (supporting); Funding acquisition (supporting); Investigation (supporting); Methodology (supporting); Project administration (supporting); Resources (supporting); Supervision (supporting); Validation (supporting); Visualization (supporting); Writing – review & editing (supporting). **Randy J. Ellingson:** Funding acquisition (supporting); Writing – review & editing (supporting). **Yanfa Yan:** Funding acquisition (supporting); Writing – review & editing (supporting). **Michael J. Heben:** Conceptualization (supporting); Data curation (supporting); Formal analysis (supporting); Funding acquisition (lead); Investigation (supporting); Methodology (supporting); Project administration (lead); Resources (lead); Supervision (lead); Validation (supporting); Visualization (supporting); Writing – review & editing (supporting).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

REFERENCES

- ¹R. Mallick, X. Li, C. Reich, X. Shan, W. Zhang, T. Nagle, L. Bok, E. Bickaci, N. Rosenblatt, D. Modi, R. Farshchi, C. Lee, J. Hack, S. Grover, N. Wolf, W. K. Metzger, D. Lu, and G. Xiong, “Arsenic-doped CdSeTe solar cells achieve world record 22.3% efficiency,” *IEEE J. Photovoltaics* **13**(4), 510–515 (2023).
- ²see <https://iucrc.nsf.gov/centers/achievements/next-generation-photovoltaics/#:~:text=The%20levelized%20cost%20of%20energy,same%20amount%20of%20energy%20generated> for “Catalyzing Commercialization: Next-Generation Photovoltaics for Economic, Clean Energy.”
- ³H. M. Wikoff, S. B. Reese, and M. O. Reese, “Embodied energy and carbon from the manufacture of cadmium telluride and silicon photovoltaics,” *Joule* **6**(7), 1710–1725 (2022).
- ⁴See <https://www.energy.gov/eere/solar/cadmium-telluride> for information about cadmium telluride representing 5% of the world market.
- ⁵M. A. Scarpulla, B. McCandless, A. B. Phillips, Y. Yan, M. J. Heben, C. Wolden, G. Xiong, W. K. Metzger, D. Mao, D. Krasikov, I. Sankin, S. Grover, A. Munshi, W. Sampath, J. R. Sites, A. Bothwell, D. Albin, M. O. Reese, A. Romeo, M. Nardone, R. Klie, J. M. Walls, T. Fiducia, A. Abbas, and S. M. Hayes, “CdTe-based thin film photovoltaics: Recent advances, current challenges and future prospects,” *Sol. Energy Mater. Sol. Cells* **255**, 112289 (2023).
- ⁶D. A. Lamb, S. J. C. Irvine, M. A. Baker, C. I. Underwood, and S. Mardhani, “Thin film cadmium telluride solar cells on ultra-thin glass in low earth orbit—3 years of performance data on the AlSat-1N CubeSat mission,” *Prog. Photovoltaics* **29**(9), 1000–1007 (2021).
- ⁷A. Romeo, G. Khrypunov, F. Kurdesau, M. Arnold, D. L. Bätzner, H. Zogg, and A. N. Tiwari, “High-efficiency flexible CdTe solar cells on polymer substrates,” *Sol. Energy Mater. Sol. Cells* **90**(18), 3407–3415 (2006).
- ⁸J. Perrenoud, “Low temperature grown CdTe thin film solar cells for the application on flexible substrates,” Ph.D. thesis, ETH Zürich 2012.
- ⁹M. K. Jamarkattel, A. B. Phillips, G. K. Liyanage, F. K. Alfadhili, E. Bastola, V. V. Plotnikov, A. D. Compaan, R. J. Ellingson, and M. J. Heben, “Ultra-thin and lightweight CdS/CdTe solar cell fabricated on ceramic substrate for space applications,” in *IEEE 49th Photovoltaics Specialists Conference (PVSC)*, 2022.

- ¹⁰S. S. Bista, D.-B. Li, S. Rijal, S. Neupane, R. A. Awni, C.-S. Jiang, C. Xiao, K. K. Subedi, Z. Song, A. B. Phillips, X. Wen, R. J. Ellingson, M. J. Heben, and Y. Yan, “Water-assisted lift-off process for flexible CdTe solar cells,” *ACS Appl. Energy Mater.* **6**(2), 885–891 (2023).
- ¹¹H. P. Mahabaduge, W. L. Rance, J. M. Burst, M. O. Reese, D. M. Meysing, C. A. Wolden, J. Li, J. D. Beach, T. A. Gessert, W. K. Metzger, S. Garner, and T. M. Barnes, “High-efficiency, flexible CdTe solar cells on ultra-thin glass substrates,” *Appl. Phys. Lett.* **106**(13), 133501 (2015).
- ¹²R. Wang, M. Lan, and S.-H. Wei, “Enhanced performance of Se-alloyed CdTe solar cells: The role of Se-segregation on the grain boundaries,” *J. Appl. Phys.* **129**(2), 024501 (2021).
- ¹³T. A. Fiducia, B. G. Mendis, K. Li, C. R. Grovenor, A. H. Munshi, K. Barth, W. S. Sampath, L. D. Wright, A. Abbas, J. W. Bowers, and J. M. Walls, “Understanding the role of selenium in defect passivation for highly efficient selenium-alloyed cadmium telluride solar cells,” *Nat. Energy* **4**(6), 504–511 (2019).
- ¹⁴N. R. Paudel and Y. Yan, “Enhancing the photo-currents of CdTe thin-film solar cells in both short and long wavelength regions,” *Appl. Phys. Lett.* **105**(18), 183510 (2014).
- ¹⁵T. Song, A. Kanevce, and J. R. Sites, “Emitter/absorber interface of CdTe solar cells,” *J. Appl. Phys.* **119**(23), 233104 (2016).
- ¹⁶G. Yeung, C. Reich, A. Onno, A. Bothwell, A. Danielson, Z. Holman, W. S. Sampath, and C. A. Wolden, “Robust passivation of CdSeTe based solar cells using reactively sputtered magnesium zinc oxide,” *Sol. Energy Mater. Sol. Cells* **233**, 111388 (2021).
- ¹⁷M. K. Jamarkattel, A. B. Phillips, I. Subedi, A. Abudulimu, E. Bastola, D.-B. Li, X. Mathew, Y. Yan, R. J. Ellingson, N. J. Podraza, and M. J. Heben, “Indium gallium oxide emitters for high-efficiency CdTe-based solar cells,” *ACS Appl. Energy Mater.* **5**(5), 5484–5489 (2022).
- ¹⁸D.-B. Li, Z. Song, R. A. Awni, S. S. Bista, N. Shrestha, C. R. Grice, L. Chen, G. K. Liyanage, M. A. Razooqi, A. B. Phillips, M. J. Heben, R. J. Ellingson, and Y. Yan, “Eliminating S-kink to maximize the performance of MgZnO/CdTe solar cells,” *ACS Appl. Energy Mater.* **2**(4), 2896–2903 (2019).
- ¹⁹X. L. Luksa Kujovic, M. Togay, L. C. Infante-Ortega, K. L. Barth, J. W. Bowers, J. M. Walls, O. Oklobia, S. J. C. Irvine, W. Zhang, D. W. Miller, T. Nagle, R. Mallick, D. Lu, W. Metzger, and G. Xiong, “19.5% efficient CdSeTe/CdTe solar cells using ZnO buffer layers,” in paper presented at 50th IEEE Photovoltaic Specialists Conference (PVSC 50), San Juan, Puerto Rico 2023.
- ²⁰D.-B. Li, Z. Song, S. S. Bista, F. K. Alfarhili, R. A. Awni, N. Shrestha, D. Rhiannon, A. B. Phillips, M. J. Heben, R. J. Ellingson *et al.*, “CuSCN as the back contact for efficient ZMO/CdTe solar cells,” *Materials* **13**(8), 1991 (2020).
- ²¹D.-B. Li, S. S. Bista, R. A. Awni, S. Neupane, A. Abudulimu, X. Wang, K. K. Subedi, M. K. Jamarkattel, A. B. Phillips, M. J. Heben, J. D. Poplawsky, D. A. Cullen, R. J. Ellingson, and Y. Yan, “20%-efficient polycrystalline Cd(Se,Te) thin-film solar cells with compositional gradient near the front junction,” *Nat. Commun.* **13**(1), 7849 (2022).
- ²²D. M. Meysing, J. M. Burst, W. L. Rance, M. O. Reese, T. M. Barnes, T. A. Gessert, and C. A. Wolden, “The influence of cadmium sulfide and contact annealing configuration on the properties of high-performance cadmium stannate,” *Sol. Energy Mater. Sol. Cells* **117**, 300–305 (2013).
- ²³M. K. Jamarkattel, A. B. Phillips, E. Bastola, S. Neupane, D. B. Li, Y. Yan, R. J. Ellingson, and M. J. Heben, “Enabling high efficiency, flexible, and lightweight CdTe solar cells with a cadmium stannate transparent conducting oxide,” in IEEE 50th Photovoltaic Specialists Conference (PVSC), 2023.
- ²⁴M. K. Jamarkattel, X. Mathew, A. B. Phillips, E. Bastola, K. K. Subedi, F. K. Alfarhili, A. Abudulimu, J. D. Friedl, R. A. Awni, D.-B. Li, M. A. Razooqi, P. Koirala, R. W. Collins, Y. Yan, R. J. Ellingson, and M. J. Heben, “Reduced recombination and improved performance of CdSe/CdTe solar cells due to Cu migration induced by light soaking,” *ACS Appl. Mater. Interfaces* **14**(17), 19644–19651 (2022).
- ²⁵M. K. Jamarkattel, A. B. Phillips, E. Bastola, S. Neupane, D. B. Li, A. Abudulimu, J. D. Friedl, T. Mariam, Y. Yan, R. J. Ellingson, and M. J. Heben, “Approaching 19% efficiency in $(\text{In}_x\text{Ga}_{1-x})_2\text{O}_3/\text{CdSe}/\text{CdTe}$ solar cells with improved front & back interfaces,” in IEEE 50th Photovoltaic Specialists Conference (PVSC), 2023.
- ²⁶T. Fiducia, A. Howkins, A. Abbas, B. Mendis, A. Munshi, K. Barth, W. Sampath, and J. Walls, “Selenium passivates grain boundaries in alloyed CdTe solar cells,” *Sol. Energy Mater. Sol. Cells* **238**, 111595 (2022).
- ²⁷A. H. Munshi, J. M. Kephart, A. Abbas, A. Danielson, G. Gélina, J.-N. Beaudry, K. L. Barth, J. M. Walls, and W. S. Sampath, “Effect of CdCl_2 passivation treatment on microstructure and performance of CdSeTe/CdTe thin-film photovoltaic devices,” *Sol. Energy Mater. Sol. Cells* **186**, 259–265 (2018).
- ²⁸C. L. Perkins, C. Beall, M. O. Reese, and T. M. Barnes, “Two-dimensional cadmium chloride nanosheets in cadmium telluride solar cells,” *ACS Appl. Mater. Interfaces* **9**(24), 20561–20565 (2017).
- ²⁹G. Brunin, F. Ricci, V.-A. Ha, G.-M. Rignanese, and G. Hautier, “Transparent conducting materials discovery using high-throughput computing,” *npj Comput. Mater.* **5**(1), 63 (2019).
- ³⁰X. Li, T. Gessert, C. DeHart, T. Barnes, H. Moutinho, Y. Yan, D. Young, M. Young, J. Perkins, and T. Coutts, “Comparison of composite transparent conducting oxides based on the binary compounds CdO and SnO_2 ,” Report No. NREL/CP-520-31017 (National Renewable Energy Laboratory, Golden, CO, 2001).