RESEARCH ARTICLE

PROGRESS IN PHOTOVOLTAICS WILEY

Comparative study of cadmium telluride solar cell performance on different TCO-coated substrates under concentrated light intensities

Rosemary Davis | Ochai Oklobia | Stuart J. C. Irvine | Dan Lamb

Oxide and Chalcogenide MOCVD Centre, in the Centre for Integrative Semiconductor Materials (CISM), Faculty of Science & Engineering, Bay Campus, Swansea University, Swansea, UK

Correspondence
Dan Lamb, Oxide and Chalcogenide MOCVD Centre, in the Centre for Integrative Semiconductor Materials, Faculty of Science & Engineering, Bay Campus, Swansea University, SA1 8EN Swansea, UK.
Email: d.a.lamb@swansea.ac.uk

Abstract

Concentrating photovoltaics is an attractive route for achieving high power output with thin film solar cells, using low-cost optics. In this work, the performance of CdTe:As thin film solar cells on two different transparent conducting oxide (TCO)-coated substrates is investigated and compared under varying concentrated light intensities (1–6.3 Suns). Samples tested had CdZnS/CdTe:As devices deposited atop of either a soda-lime glass with a fluorine-doped tin oxide TCO or an ultra-thin glass (UTG) with an aluminium zinc oxide TCO and ZnO high-resistive transparent (HRT) layer. Device current density was found to increase linearly with increased light intensities, for both sample configurations. Power conversion efficiencies of both device samples decreased with increased light intensity, due to a decrease in fill factor. The fill factor, for both sample configurations, was affected by reducing shunt resistance with increasing illumination intensity. The two device types performed differently at the high illumination intensities due to their series resistance. Light-soaking devices under 6.3 Suns illumination intensity for 90 min showed no significant performance degradation, indicative of relatively stable devices under the highest illumination intensity tested. Efficiency limiting factors are assessed, evaluated and discussed.

KEYWORDS
CdTe:As, concentrated light intensity, concentrated photovoltaic, solar cells, thin films, ZnO HRT layer

1 | INTRODUCTION

Cadmium telluride (CdTe) has gained much interest from both academia and industry due to its direct bandgap, large absorption coefficient, high charge carrier mobility and low production cost.[1,2] These properties have made it a successful semiconductor for use in energy conversion and storage devices, particularly in solar cell applications. CdTe-based solar cells have the added benefit of being less expensive to produce than those made from crystalline silicon. First Solar Inc. is the world's largest manufacturer of thin film, holding the world record for efficiencies of both laboratory cells and modules with power conversion efficiencies (PCEs) of 22.1 ± 0.5% and 19.5 ± 1.4%, respectively, with Cu doing in the active absorber layer.[3] The lowest energy payback time and rising PCE make CdTe competitive with Si technology in the utility solar energy market.[4–6] Cu doping has played a longstanding role in the majority of high efficiency CdTe solar cells.

However, hole concentration levels are still limited to $<10^{15}$ cm^{-3}, and long-term stability issues related to Cu have yet to be overcome.[7,8] This has limited device open circuit voltage (V_{OC}) to below 1 V. Group V doping has been shown to exceed such doping concentration limits, with the potential for achieving $V_{OC} > 1$ V and thus higher PCE.[9] Kartopu et al.[10] showed good control of in-situ As doping in polycrystalline CdTe thin films, with cells presenting high acceptor concentration $>10^{16}$ cm^{-3}. By depositing the absorber under Cd overpressure conditions, Metzger and co-workers[9] reported polycrystalline-graded CdSeTe/CdTe solar cell doped with As, by vapour transport deposition (VTD), with $\sim$21% efficiency, whilst $\sim$17% efficient As-doped CdTe-only absorber cells by metalorganic chemical vapour deposition (MOCVD) in-situ Cd-saturated growth were also reported in another study.[11] Further, First Solar Inc. recently reported an impressive 22.3% efficient As-doped CdSeTe solar cell, achieving a record efficiency with no Cu doping.[12]

By concentrating sunlight onto multi-junction solar cells, concentrating photovoltaics (CPV) systems have achieved efficiencies of up to 47%,[13] significantly higher than traditional photovoltaic systems. CPV systems require less land area and fewer semiconductor materials to produce the same amount of electricity, making it a potentially cost-effective solution for large-scale solar energy projects. Developing CPV for terrestrial CdTe has the potential to significantly reduce costs and increase its market competitiveness. Furthermore, CPV could be important for large area space (extra-terrestrial) applications requiring low weight, low cost but high power such as solar electric propulsion and space-based solar power. Recently, CdTe solar cells have been successfully flight tested onboard a low-earth-orbit CubeSat[14] paving the way for the investigation of CPV of CdTe for space applications.

Although CPV is well developed for both single and multi-junction GaAs solar cells,[13,15] there are few studies in the literature for CdTe CPV. Li et al. measured the performance of 2×2 mm^2 CdTe solar cells under different light intensities ranging from 1 to 25.89 Suns.[16] The short circuit current density (J_{SC}) increased linearly with light intensity. However, the fill factor (FF) and PCE decreased with increasing light intensity. Under high-intensity irradiation, the authors observed the resistance of transparent conducting oxide (TCO) layer to remain constant but the CdTe layer resistance to significantly reduce. At higher light intensity, the resistance of the TCO was seen to become a limiting factor to the current flow. Thus, the major finding was that CdTe could be effective under higher than a few concentration factors if the TCOs were to have conductivities analogous to metallic electrodes.

The present work seeks to add to the literature based on CdTe by investigating the properties of As-doped CdTe solar cells under concentrated illumination (<7 Suns) and comparing their performance on both terrestrial and space application glass substrates. The utilization of concentrated light has the potential to elucidate some of the current limitations on CdTe cell performance, thereby facilitating the advancement of CdTe thin films for concentration photovoltaic applications.

2 | EXPERIMENTAL DETAILS

CdTe solar cells were fabricated using MOCVD, according to the superstrate structure on two different glass substrates: fluorine-doped tin oxide (FTO)-coated soda-lime glass substrate (2.8 mm) and aluminium-doped zinc oxide (AZO)-coated ultra-thin (0.1 mm) cerium containing cover glass substrate (CMG). FTO on soda-lime glass is the standard TCO for CdTe device structures. The cover glass is not commercially supplied with a TCO, and thus, the in-house developed MOCVD AZO was used. The schematic of the device structure is shown in Figure 1. Device samples based on FTO- and AZO-coated glass substrates will be herein described as terrestrial and space solar cells, respectively.

The FTO-coated soda-lime glass substrates were commercially sourced. The cerium containing ultra-thin glass was supplied by Qioptiq Space Technology Ltd, and a bilayer of AZO ($\sim$640 nm) and ZnO ($\sim$30 nm) was deposited by MOCVD at a substrate temperature of 400°C with nitrogen as the carrier gas. The precursors for Zn, O and Al were diethylzinc, tertiary butyl alcohol and trimethylaluminium in a ratio of 1:3:0.1 for the AZO and 1:3:0 for the ZnO.

The CdZnS/CdTe:As solar cell structure was fabricated by first depositing a window bilayer of CdS/CdZnS ($\sim$50 nm/100 nm), followed by the CdTe:As absorber layer in a horizontal atmospheric-pressure MOCVD reactor, using hydrogen carrier gas. The absorber layer comprises of an $\sim$3.0 μm As-doped ($\sim$1.0 $\times$ 10^{18} As cm^{-3}) CdTe layer terminated with an $\sim$300 nm, more heavily doped ($>1.0 \times 10^{19}$ As cm^{-3}), back contact layer. Further experimental details can be found elsewhere.[11,17] The ubiquitous chlorine treatment was performed without taking the structure out of the reactor, by depositing a 1 μm layer of CdCl$_2$ at 200°C, then annealing for 10 min at 440°C under hydrogen ambient. Dimethylcadmium (DMCd), diisopropyltelluride (DIPTe), diethylzinc and tertiarybutylchloride were used as the metalorganic precursors for Cd, Te, Zn and Cl, respectively, whilst tris(dimethylamino)arsenic was used for the As dopant. The DMCd/DIPTe partial pressure ratio of 3 was used during in-situ Cd-saturated CdTe absorber deposition at 350°C in the Cd-rich phase boundary to promote efficient As incorporation.[11] The CdS/CdZnS bilayer merges to yield the n-type emitter layer, CdZnS, upon device completion, following CdCl$_2$ heat treatment. After cooling to room temperature, the device structure was taken out of the reactor and excess CdCl$_2$ rinsed with deionized (DI) water, and a secondary post-deposition annealing was carried out at 170°C for 90 min in air ambient. Finally, the solar cell was completed by evaporation of Au metal back contacts through a shadow mask. The effective area of the Au contact is $\sim$0.25 cm^2 for terrestrial and 0.27 cm^2 for space device samples. For each sample, four cells in a grid formation were measured to provide confidence of materials performance uniformity.

It should be noted that the terrestrial samples in this work were fabricated 15 months prior to the study. The terrestrial samples' current density (J_{SC}), open circuit (V_{OC}) and shunt resistance (R_{SH}) did not significantly vary over the 15-month period, although there was an absolute drop in PCE of $\sim$2%. The reduction in PCE is attributed to a significant drop in FF due to an increased series resistance (R_S), from
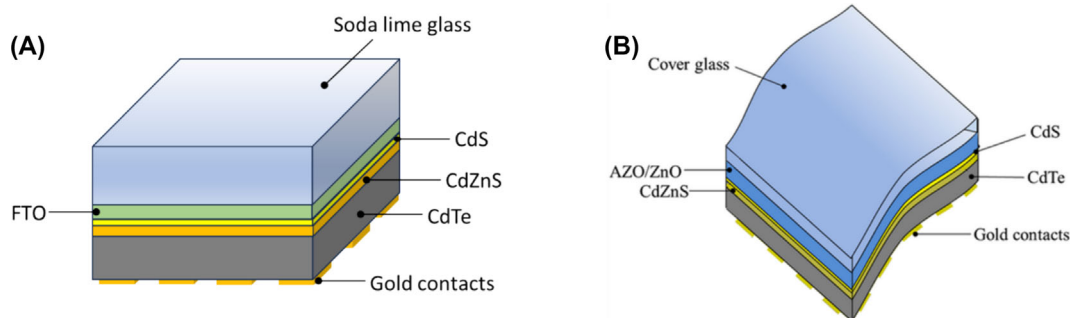
FIGURE 1 Schematic of cadmium telluride (CdTe) device structure on (A) fluorine-doped tin oxide (FTO)-coated soda-lime glass substrate, (B) aluminium-doped zinc oxide (AZO)/ZnO coated ultra-thin glass substrate (adapted from Lamb et al.[14]).
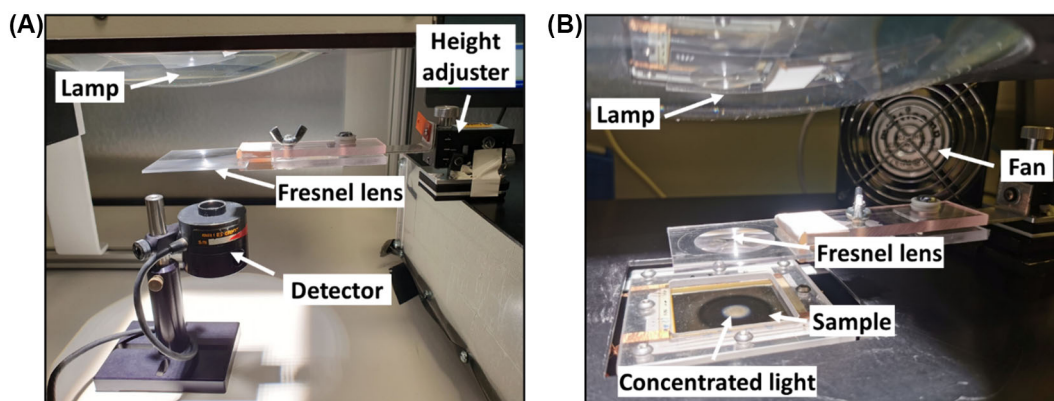

FIGURE 2 Photographs of (A) set-up for light intensity calibration using a Fresnel lens, (B) solar cell illuminated at the highest concentration of 6.3 Suns (no neutral density filter inserted between Fresnel lens and sample).

an average (for eight cells) of 3.4 to 11.3 Ω cm^2 over the 15-month period. The 1 Sun R_S was stable during the measurements collected for this concentrator photovoltaic investigation. The study looks at relative changes of J-V parameters between the terrestrial and space samples due to the effects of light concentration.

Light J-V properties of CdTe solar cells were measured using a Keithley 2400 source meter and an Abet Technologies Ltd. Sun 2000 solar simulator (Class A) with the AM 1.5 G light intensity calibrated using a GaAs reference cell (ReRa Solutions). Prior to any new measurement of devices on either the terrestrial or space samples, a 10-min 1 Sun light soak was conducted.

A Fresnel lens from Edmund Optics (5 $\times$ 5 cm^2 and 2.5 cm focal length) was used to concentrate the illumination from the AM 1.5 G solar simulator. The set-up for light concentration is shown in Figure 2A. A maximum concentrated light intensity of $\sim$6.3 Suns, with an illumination area larger than that of the maximum device area (>0.27 cm^2), was first measured using a power meter (Melles Griot 13PEM001). Then, by keeping the same focal length but inserting neutral density (ND) filters with different optical densities, lower light concentrations were obtained. This methodology provided repeatable concentration factors of 1.8, 3.6, 4.5, 5.6 and 6.3 Suns. An Ocean Optics spectrometer was used to confirm that for each concentration factor, there was no distortion to the AM1.5 G solar spectrum across

the CdTe absorption range, measured with both the Fresnel lens and each ND filter in place, and that it was only the intensity that was being modulated. A cooling fan was used to circulate the laboratory air over the illuminated samples. The temperature on the glass side of the solar cells was monitored with a thermocouple. The area of concentrated illumination was set to be slightly larger than the area of the individual cells. The power meter reading was an absolute figure and thus, the non-uniformity of concentration should be assumed within the illuminated area.

3 | RESULTS AND DISCUSSION

3.1 | J-V characteristics at different light intensities

The J-V curves from the best cell of each of the terrestrial and space CdTe solar cell samples and at different incident light intensities are shown in Figure 3A,B. The series and shunt resistances were calculated from the straight line portion of the slope close to V_{OC} in the positive current quadrant and from the straight line portion of the slope close to J_{SC} in the negative voltage quadrant, respectively.
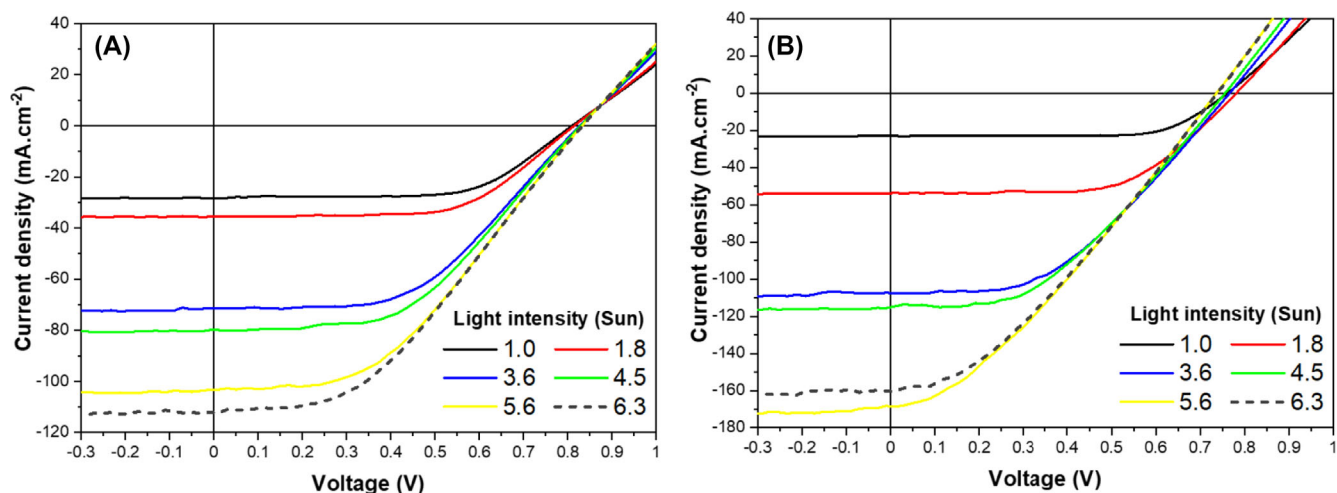
FIGURE 3 Illuminated J-V characteristics of (A) terrestrial cadmium telluride (CdTe) solar cell and (B) space CdTe solar cell, measured over a range of 1 to 6.3 Sun light intensities.
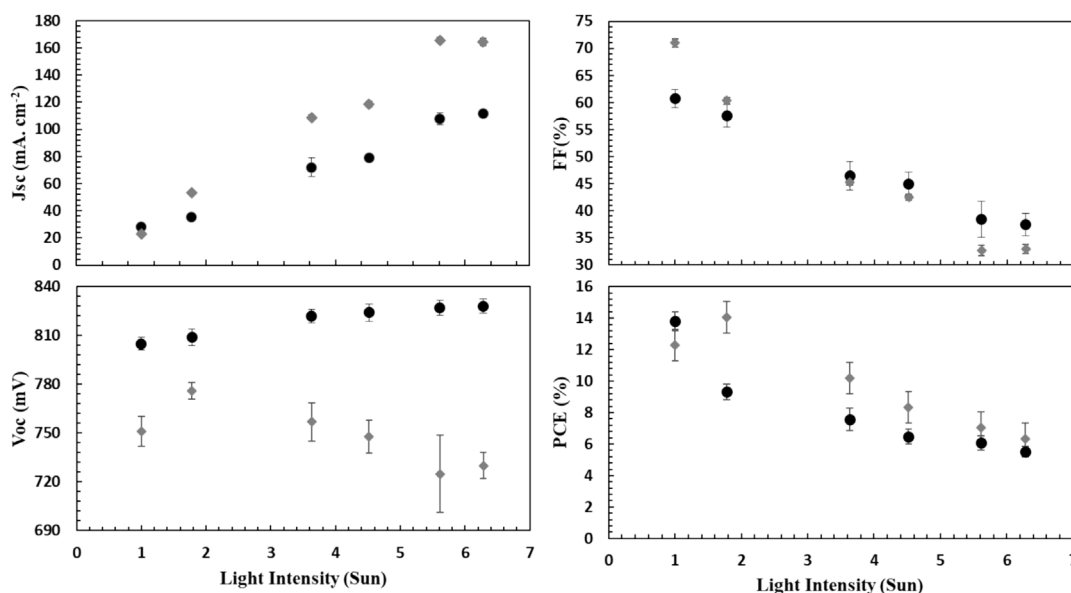

FIGURE 4 J-V parameter comparison of the average of four cells for each of the terrestrial (black circle) and space (grey diamond) samples, under varying concentrated light intensities in Suns.

The average J-V parameters, for each of the four cells, at the different illumination intensities were extracted from the J-V curves and are displayed in Figure 4. The J_{SC} increases with rising input light intensity in both terrestrial and space cells that is consistent with the behaviour that have been reported for other solar cell technology such as GaAs concentrator solar cells. J_{SC}s measured under varying intensities are consistent with previously reported data for CdTe CPV.[16] It is also noted that relatively higher J_{SC}s were obtained at intensities greater than 1 Sun (Figure 4) for the space solar cells. This can be explained in terms of the varying R_S between the terrestrial and space cells due to the aging effect described in Section 2. For an ideal cell, with zero R_S, the J_{SC} is equal to the J_{PH} (photocurrent density). However, Taretto et al. show that R_S will affect the J_{SC} to J_{PH}

relationship.[18] As R_S increases, cells J_{SC} will increase less with increasing J_{PH} as is the case for the terrestrial cells that exhibit a 1 sun R_S 2.5 greater than the space cells.

FFs for both sample devices were observed to decrease with increasing light intensities that contributed to the decreasing PCEs measured in this study (see Figure 4). From the J-V curves in Figure 3, it can be seen that higher concentration is forcing the maximum power point to lower voltage as the J_{SC} increases, due to a high series resistance. The reduction in FF can be seen as a direct consequence of high series resistance and increasing J_{SC}. The extracted series and shunt resistances for both cells were plotted against varying light intensities to better understand their impact on FF with increasing light intensities. The plot of average series and shunt resistances
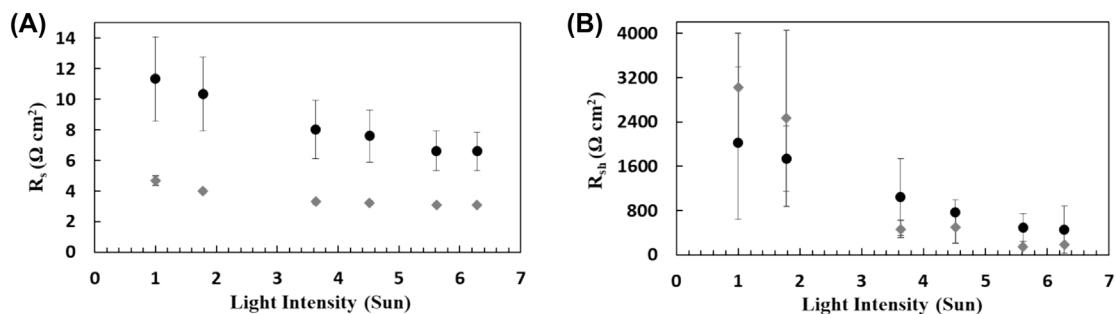
FIGURE 5 The variation according to the concentration of (A) R_S and (B) R_{SH} of terrestrial (black circles) and space (grey diamond) solar cells.
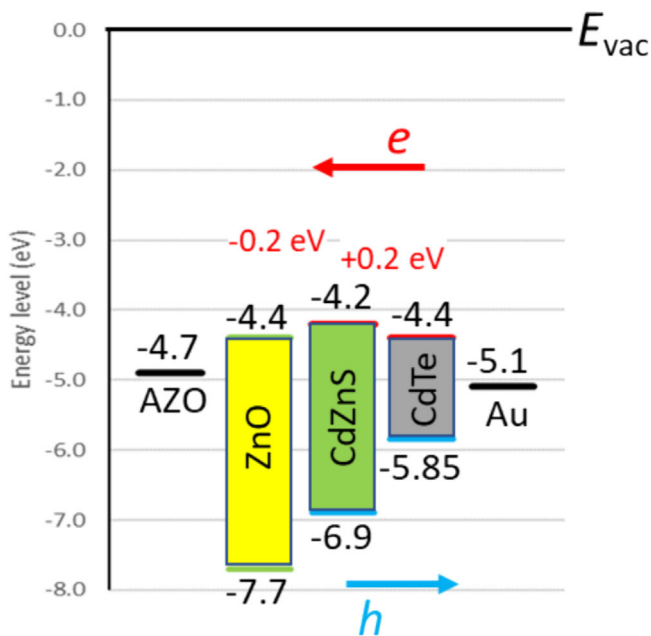

FIGURE 6 Energy bands of aluminium-doped zinc oxide (AZO)/ZnO/CdZnS/CdTe:As, showing work function of front and back contacts (AZO and Au) and electron affinity of ZnO (−4.4 eV), CdZnS (−4.4 eV) and cadmium telluride (CdTe) (4.4 eV). The work function and electron affinity values were taken from Clayton et al. and Kim et al.[19,20]

versus light intensity is displayed in Figure 5. As the light concentration increases, R_S decreases for both types of cells that should benefit cell performance, but the FF decrease is dominated by the effect of the increase in J_{sc}. However, R_{SH} also decreases with increasing light concentration that will make a small contribution to reducing PCE for both types of cells.

From Figure 4, the V_{OC} displays different trends for terrestrial and space cells. In terrestrial cells, V_{OC} gradually increased from ∼805 mV (at 1 Sun) and plateaued at around ∼830 mV with light intensity greater than 3.6 Suns. Therefore, a gain of about 25 mV was measured with concentrating light intensity of up to 6.3 Suns. But, for space cells, V_{OC} first improved from 751 mV (at 1 Sun) to ∼776 mV at 1.8 Sun, then at concentrated light intensities greater than 1.8 Sun, V_{OC} decreased with intensity, to 730 mV.

The V_{OC} change with light intensity is in sharp contrast between terrestrial and space cells that requires further explanation. Both samples have the same emitter and absorber structure. However, the different TCOs are suspected to play a crucial role in device performance. First, we examine the influence of band offset at the front interfaces. ZnO has an electron affinity of 4.4 eV that will induce a flat band at the n-type emitter/absorber interface as shown in Figure 6. This is expected to reduce V_{OC}, compared to a positive conduction band offset.[19,21] The flat band condition with ZnO, in the space sample, could be a limiting factor for V_{OC}, when combined with the low donor doping concentration in the CdZnS emitter, potentially causing depletion back to the ZnO layer. This argument is supported by a previous study, where an aluminium zinc sulphide (AZS) layer was inserted between the TCO and n-type emitter layer, in a CdTe device structure, inducing a positive conduction band offset at the emitter/absorber interface. This resulted in improved V_{OC}.[19] The improved interface band alignment was a consequence of lower electron affinity of AZS, compared to the ZnO used in the space sample device structure (see Figure 6).[20]

A decrease in V_{OC} with light intensity could also result from photo-activation of trap states at the absorber interface. This could arise from non-conformal coverage of the very thin ZnO layer creating high defect regions in the absorber layer, leading to a high concentration of trap states. The effect of these defective regions is believed to be enhanced with high current injection due to increasing the conductivity of the CdTe layer as shown in the work by Li et al.[16] This is indicative of the critical role of the front TCO and its buffer to the device V_{OC}.

3.2 | Extended 6.3 Sun illumination

Light soaking is a preconditioning protocol for CdTe solar cells.[22] A 10-min light soak is taken as a standard preconditioning procedure within this paper. The effects of longer term exposure of terrestrial and space CdTe cells were investigated to ensure that there were no stability issues at the highest 6.3 Sun illumination. Figure 7 shows a plot of V_{OC} versus duration of light soaking at 6.3 Suns for the best performing cell from each sample. The temperature of cells, at the glass side, were maintained in a range of 27–33°C throughout the
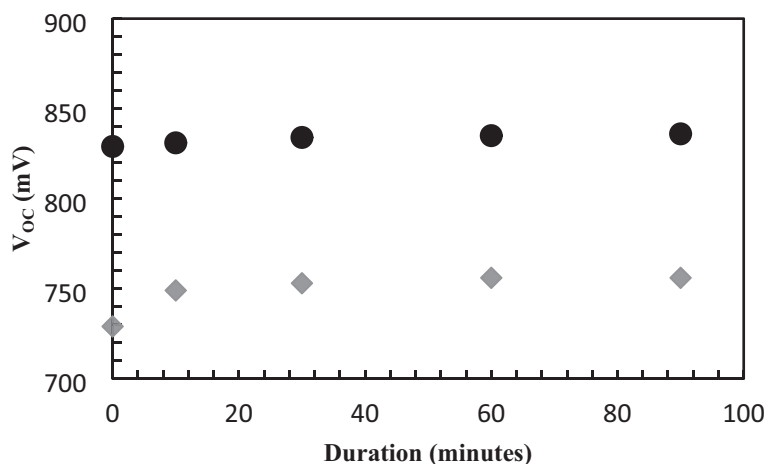
FIGURE 7 V_{OC} versus duration of light soaking at 6.3 Suns for terrestrial (black circle) and space (grey diamond) solar cells.

measurement. The experiment was repeated with an interval of 2 days, and the effects of long and high concentration light exposure were found to be consistent and reversible. A general increase in V_{OC} with light soaking is associated with a filling of trap states that in turn reduces the recombination rate.[22] The terrestrial cell shows little significant change in V_{OC} with extended exposure to 6.3 Suns. The space cell shows an increase from 729 to 749 mV in the initial 10 min. Beyond this, the V_{OC} of the space cell only increases by a further 7 mV over the duration of the test. The greater effect of high-intensity illumination, on the space solar cell V_{OC}, adds to the argument that there is a higher density of trap states associated with the ZnO/CdZnS front interface.

4 | CONCLUSIONS

The study provides insights into the behaviour of CdTe solar cells under different light intensities (from 1 to 6.3 Suns) and compares their performance in terrestrial and space applications. The findings indicate that the difference in the TCO using AZO/ZnO layer in space cells can affect the performance of the solar cells. The effect of series resistance upon the relationship between J_{SC} and J_{PH} was observed, where the terrestrial cells used in this study had a significantly higher initial R_S compared to the space samples. This demonstrates the importance of achieving a very low R_S for any solar cell platform employing concentration. Further, the contrast in performance between the space and terrestrial cells is attributed to the difference in front interface structure where different recombination rates can affect the V_{OC} and FF. This provides information about the limitation of current CdTe cells but with the potential for improvement with better front interfaces. The zero band offset, between the ZnO and CdZnS emitter, is likely the cause of higher interface recombination. The reduction in V_{OC} after 1.8 Sun is a limiting factor for CPV of CdTe space solar cells with the current front interface TCO/buffer structure. It is clear that good performance under higher concentration will be more demanding of this structure, that is, low trap density and positive conduction band offset. Future studies will focus on improving

the performance of solar cells under high-intensity environments by addressing the limiting factors discussed in this study. Aside from the issues with the front interface, the space cells show a 3.2-factor increase in maximum power output under 6.3 Suns illumination. This opens the door to the use of relatively cheap and environmentally friendly Fresnel lenses, reducing the area of CdTe material required to produce the required power output. Light soaking devices under 6.3 Suns illumination intensity for 90 min showed no significant performance degradation, indicative of stable devices under high illumination intensity. For concentrator CdTe, a front emitter structure that does not deteriorate with light intensity is required.

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

ORCID
Dan Lamb https://orcid.org/0000-0002-4762-4641

REFERENCES
1. Basol BM, McCandless B. Brief review of cadmium telluride-based photovoltaic technologies. *J Photonics Energy*. 2014;4(1):040996. doi: 10.1117/1.JPE.4.040996
2. Scarpulla MA, McCandless B, Phillips AB, et al. CdTe-based thin film photovoltaics: recent advances, current challenges and future prospects. *Sol Energy Mater Solar Cells*. 2023;255:112289. doi:10.1016/j.solmat.2023.112289
3. Green MA, Dunlop ED, Siefer G, et al. Solar cell efficiency tables (version 61). *Prog Photovolt Res Appl*. 2023;31(1):3-16. doi:10.1002/pip.3646

4. Baines T, Shalvey TP, Major JD. 10—CdTe solar cells. In: Letcher TM, Fthenakis VM, eds. *A Comprehensive Guide to Solar Energy Systems*. Academic Press; 2018:215-232, ISBN 9780128114797. doi:10.1016/B978-0-12-811479-7.00010

5. De Wild-Scholten MJ. Energy payback time and carbon footprint of commercial photovoltaic systems. *Sol Energy Mater Sol Cells*. 2013; 119:296-305. doi:10.1016/j.solmat.2013.08.037

6. Gessert TA. 1.19—cadmium telluride photovoltaic thin film: CdTe. In: Sayigh A, ed. *Comprehensive Renewable Energy*. Elsevier; 2012:423-438. doi:10.1016/B978-0-08-087872-0.00122-0

7. Corwine CR, Pudov AO, Gloeckler M, Demtsu SH, Sites JR. Copper inclusion and migration from the back contact in CdTe solar cells. *Sol Energy Mater Sol Cells*. 2004;82(4):481-489. doi:10.1016/j.solmat.2004.02.005

8. Grecu D, Compaan AD, Young D, Jayamaha U, Rose DH. Photoluminescence of Cu-doped CdTe and related stability issues in CdS/CdTe solar cells. *J Appl Phys*. 2000;88(5):2490-2496. doi:10.1063/1.1287414

9. Metzger WK, Grover S, Lu D, et al. Exceeding 20% efficiency with in-situ group V doping in polycrystalline CdTe solar cells. *Nat Energy*. 2019;4(10):837-845. doi:10.1038/s41560-019-0446-7

10. Kartopu G, Oklobia O, Turkay D, et al. Study of thin film polycrystalline CdTe solar cells presenting high acceptor concentrations achieved by in-situ arsenic doping. *Sol Energy Mater Sol Cell*. 2019; 194:259-267. doi:10.1016/j.solmat.2019.02.025

11. Oklobia O, Jones S, Kartopu G, et al. Impact of in-situ Cd saturation MOCVD grown CdTe solar cells on As doping and V_{OC}. *IEEE J Photovolt*. 2022;12(6):1296-1302. doi:10.1109/PVSC48317.2022.9938684

12. Mallick R, Li X, Reich C, et al. Arsenic-doped CdSeTe solar cells achieve world record 22.3% efficiency. *IEEE J Photovolt*. 2023;13(4):510-515. doi:10.1109/JPHOTOV.2023.3282581

13. Geisz JF, France RM, Schulte KL, et al. Six-junction III–V solar cells with 47.1% conversion efficiency under 143 suns concentration. *Nat Energy*. 2020;5(4):326-335. doi:10.1038/s41560-020-0598-5

14. Lamb DA, Irvine SJC, Baker MA, Underwood CI, Mardhani S. 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 Photovolt: Res Appl*. 2021;29(9):1000-1007. doi:10.1002/pip.3423

15. James LW, Moon RL. GaAs concentrator solar cell. *Appl Phys Lett*. 1975;26(8):467-470. doi:10.1063/1.88213

16. Li W, Yang R, Wang D. CdTe solar cell performance under high-intensity light irradiance. *Sol Energy Mater Sol Cell*. 2014;123:249-254. doi:10.1016/j.solmat.2014.01.021

17. Kartopu G, Phillips LJ, Barrioz V, et al. Progression of metalorganic chemical vapour-deposited CdTe thin-film PV devices towards modules. *Prog Photovolt: Res Appl*. 2016;24(3):283-291. doi:10.1002/pip.2668

18. Taretto K, Soldera M, Troviano M. Accurate explicit equations for the fill factor of real solar cells—applications to thin-film solar cells. *Prog Photovolt: Res Appl*. 2013;21(7):1489-1498. doi:10.1002/pip.2235

19. Clayton A, Abbas A, Siderfin P, et al. MOCVD of II-VI HRT/emitters for V_{oc} improvements to CdTe solar cells. *Coatings*. 2022;12(2):261. doi:10.3390/coatings12020261

20. Kim W-H, Maeng WJ, Kim M-K, Kim H. Low pressure chemical vapor deposition of aluminum-doped zinc oxide for transparent conducting electrodes. *J Electrochem Soc*. 2011;158(8):D495. doi:10.1149/1.3599055

21. Kephart JM, McCamy JW, Ma Z, Ganjoo A, Alamgir FM, Sampath WS. Band alignment of front contact layers for high-efficiency CdTe solar cells. *Sol Energy Mater Sol Cells*. 2016;157:266-275. doi:10.1016/j.solmat.2016.05.050

22. Gostein M, Dunn L. Light soaking effects on photovoltaic modules: overview and literature review. In: *Conference Record of the IEEE Photovoltaic Specialists Conference*. IEEE; 2011:003126-003131. doi:10.1109/PVSC.2011.6186605