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# Effect of bending test on the performance of CdTe solar cells on flexible ultra-thin glass produced by MOCVD

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ABSTRACT

The development of lightweight and flexible solar modules is highly desirable for high specific power applications, building integrated photovoltaics, unmanned aerial vehicles and space. Flexible metallic and polyimide foils are frequently used, but in this work an alternative substrate with attractive properties, ultra-thin glass (UTG) has been employed. CdTe solar cells with average efficiency reaching 14.7% AM1.5G efficiency have been produced on UTG of 100 μm thickness. Little has been reported on the effects on PV performance when flexed, so we investigated the effects on J-V parameters when the measurements were performed in 40 mm and 32 mm bend radius, and in a planar state before and after the bend curvature was applied. The flat J-V measurements after 32 mm bending test showed some improvement in efficiency, Voc and FF, with values higher than the first measurement in a planar state. In addition, two CdTe solar cells with identical initial performance were subjected to 32 mm static bending test for 168 hours, the results showed excellent uniformity and stability and no significant variation on J-V parameters was observed. External quantum efficiency and capacitance voltage measurements were performed and showed no significant change in spectral response or carrier concentration. Residual stress analysis showed that no additional strain was induced within the film after the bending test and that the overall strain was low. This has demonstrated the feasibility of using CdTe solar cells on UTG in new applications, when a curved module is required without compromising performance.

## 1. Introduction

CdTe is the leading commercial thin film technology, 6% of the photovoltaic (PV) production is covered by CdTe [1]. Its success, over other thin film technologies, is due to its remarkable qualities such as, having a direct energy band gap of 1.45eV, a high absorption coefficient ($>1 \times 10^4 cm^{-1}$) and excellent thermodynamic stability [1,2].

CdTe PV is manufactured using a superstrate approach where a 3 mm float glass provides the outward facing environmental barrier and gives mechanical stability to the thin film stack. For some applications it is desirable to produce a flexible PV module which, for CdTe, would require a transparent, flexible and thermally stable substrate material. Transparent polyimides are not well suited to the relatively high thermal exposure of the CdTe deposition processes. Ultra-thin glass (UTG) however is far better suited and can yield a lightweight and flexible, in 1-dimension, PV module. The suitability of UTG substrates to roll-to-roll processes could significantly reduce the manufacturing cost of large area lightweight flexible modules [3]. Flexible thin film PV, other than CdTe, has been well researched looking at the deposition processes, mechanical behaviour and electronic properties when using substrates such as metallic foil [4,5] and polyimide [6,7]. There is little literature for the flexing of CdTe on UTG, but the few reports show promising results [3,8].

The UTG substrate used in this work offers several advantages such as low chemical contamination, low surface roughness, mechanical flexibility and high temperature resistance. The UTG is specifically designed for use in space applications such as a cover glass for PV whereby it is laminated atop of the solar cells. Its cerium content provides protection from high energy radiation. Its inherent mechanical flexibility, allowing it to be rolled and un-rolled, could lead to cost savings when considering production, storage, transport and deployment for both terrestrial and space applications. In addition, lightweight and flexible modules on UTG could find application in building integrated photovoltaics (BIPV), low load surfaces and unmanned aerial vehicles (UAVs).

Understanding of solar cell performance, when flexed, is important

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for flexible devices applications. Also, knowledge of any changes in the mechanical and electrical properties under flexing could provide fundamental information on the device stability. Very little has been reported on the effects of flexing PV devices on UTG. Gerthoffer et al. reported the fabrication of CIGS solar cells with 11.2% efficiency grown on flexible glass as thin as 100 μm. The results when flexing through 3 cycles each with a progressive increase of sample curvature showed a significant drop of efficiencies. The degradation induced by bending was irreversible when the sample was reset into planar state [9]. Rance et al. produced CdTe on Corning Willow Glass™ and the solar cells efficiency was measured in the flexed and flat state. It was demonstrated that a bend radius of 51 mm can be achieved without decreasing device performance [3]. Lamb et al. measured the adhesion strength of a device structure analogous to the work presented here and found it to be well adhered to the UTG resisting tensile stresses, exerted by a pull test, of up to 38 MPa [8].

CdTe thin film semiconductor materials have been deposited employing various techniques, these include: molecular beam epitaxy (MBE) [10], thermal evaporation [11], electrodeposition [12], closed space sublimation [13], physical vapour deposition [14], all-sputtered [15], pulsed laser [16], and metal organic chemical vapour deposition (MOCVD) [17]. Out of these deposition methods, MOCVD employs a versatile apparatus that allows independent control of the organometallic fluxes and substrate temperature to produce thin films semiconductor materials with high quality, uniformity and controllable film thickness [18]. The thin film microstructure will be strongly affected by the deposition method and annealing treatment, and the solar cell performance will be influenced by different factors, such as the substrate cleaning process, thickness, growth rate, induced residual strain, and the variation of the light intensity and temperature [19].

In this work we describe the results of current density-voltage (J-V) measurements under a previously unreported severe compressive strain of 32 mm bend radius of thin film CdTe solar cells on UTG. We also report on the solar cell performance versus duration of bending, up to 168 h in the flexed state. The results reveal valuable information on the solar cell's stability under flexion demonstrating the feasibility of CdTe thin films on UTG for applications that require a flexed solar cell architecture.

## 2. Experimental details

The UTG used in this work was a chemically toughened, 100 μm thick cerium-doped glass of 60 × 60 mm dimensions supplied by Qioptiq Space Technology (QST). All thin films were deposited by atmospheric-pressure MOCVD with the exception of the final evaporated gold back contact. The films thicknesses were monitored real-time using in-situ laser interferometry. Firstly, an 800 nm aluminium-doped zinc oxide (AZO) followed by a 100 nm high resistivity zinc oxide (ZnO) layer were deposited onto the UTG using a nitrogen carrier gas. Both films were deposited at a substrate temperature of 400 °C. This yielded a transparent bilayer with a sheet resistance of 8 Ω/square as measured by the 4-point probe method. The UTG/AZO/ZnO sample was then transported to a second MOCVD reactor where a hydrogen carrier gas was used. A 25 nm cadmium sulphide film at 315 °C was followed by a 125 nm cadmium zinc sulphide film at 360 °C to form the buffer layer. 3 μm of CdTe was deposited at 390 °C with an arsenic incorporation of $2 \times 10^{18}$ atoms $cm^{-3}$ which yielded a carrier density of $1 \times 10^{16}$ $cm^{-3}$. Further to this a subsequent 330 nm CdTe was deposited which received an increased incorporation of $1 \times 10^{19}$ $cm^{-3}$, which led to a carrier density of $3 \times 10^{16}$ $cm^{-3}$. Finally, a cadmium chloride film of 1 μm thickness was deposited at 200 °C and all of the films annealed at 420 °C for 10 min.

The CdTe was scrapped on two opposite sides to expose the front contact AZO/ZnO. 8 individual back contacts were achieved by evaporating 0.27 $cm^2$ gold squares on the CdTe. The front contacts were made by evaporating two rectangular gold strips to the revealed AZO/ZnO. A gold probe contact was used to measure each of the 0.27 $cm^2$ gold back contacts with gold wire soldered onto both front contacts completing the circuit.

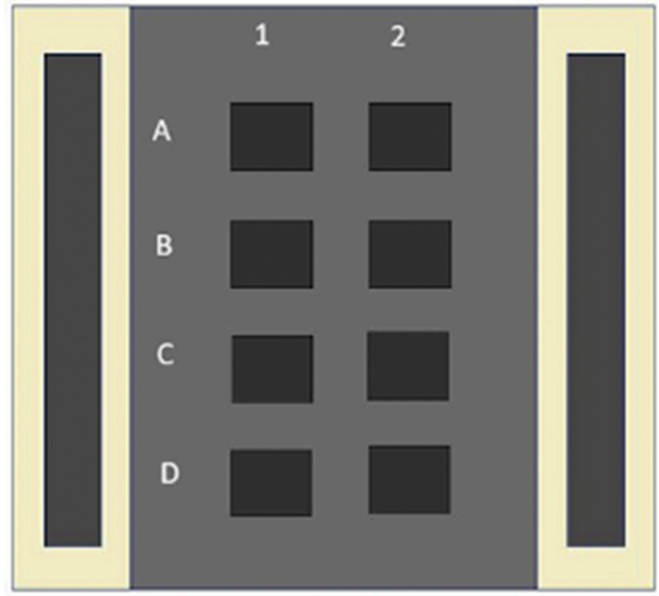


**Fig. 1.** CdTe layout showing the 8 × 0.27 $cm^2$ back contacts and the two front contacts gold strips on opposite sides.

The photovoltaic performance was measured by J-V under AM1.5G at 25 °C, using a Keithley 2400 source meter and an ABET Technologies Sun 2000 Solar Simulator calibrated to AM1.5G using a spectrally matched GaAs reference cell supplied by RERA Solutions. Before measurement a 10-minAM1.5G light soak was applied which is known to either depopulate or fill deep level recombination traps stabilising the open circuit voltage [20]. The measurements were performed when the cell was in a planar state, and then when flexed to a 40 mm and subsequent 32 mm bend radius. After flexion the device was relaxed and measured flat. Angle of incidence and distance from the light source could be expected to influence the J-V measurements when the sample was held in the flexed state. However, no significant change in $J_{sc}$, the parameter most likely affected by these factors, for each of the 8 cells was observed between plan and flexed measurements. To avoid cumulative effects of light soaking the measurements were carried out every 1 h with a 10 min light soak before each new batch of measurements. In addition, the sample was held at a bend radius of 32 mm for 168 h with measurement at 0, 24, 48, 120, 144 and 168 h. Again, the sample was measured flat before and after the bending test. Additionally, external quantum efficiency (EQE) and capacitance voltage (C-V) measurements were performed before and after 168 h bending test. A Bentham PVE300 photovoltaic spectrometer was used for EQE measurements and a Solartron analytical modulab model 2100A was used for C-V measurements.

A sample holder was designed to measure the samples performance under bending. It was formed of two sliding plates fixed on two opposite sides, on which it was possible to apply a lateral force to achieve the bend radius required. This created a convex surface for the PV cells, so the films are considered to have been under tensive strain.

Residual stress measurements were made with a Bruker D8 Discover X-ray diffraction system. The equipment was set up in a point mode with a polycapillary element and nickel filter. Scans were made with a 0.02° step size, at a time of 1 s per step. The scans were over the full 0–0.45 $\sin^2(\psi)$ in both positive and negative ψ tilts to confirm the absence of shear stress. Peak evaluation was undertaken using the Pearson VII fitting and stresses were calculated using a normal stress model. The Diffrac, Leptos software was used to model the peaks, then the peak shift was changed to strain using the Poisson's ratio of 0.2 and Young's

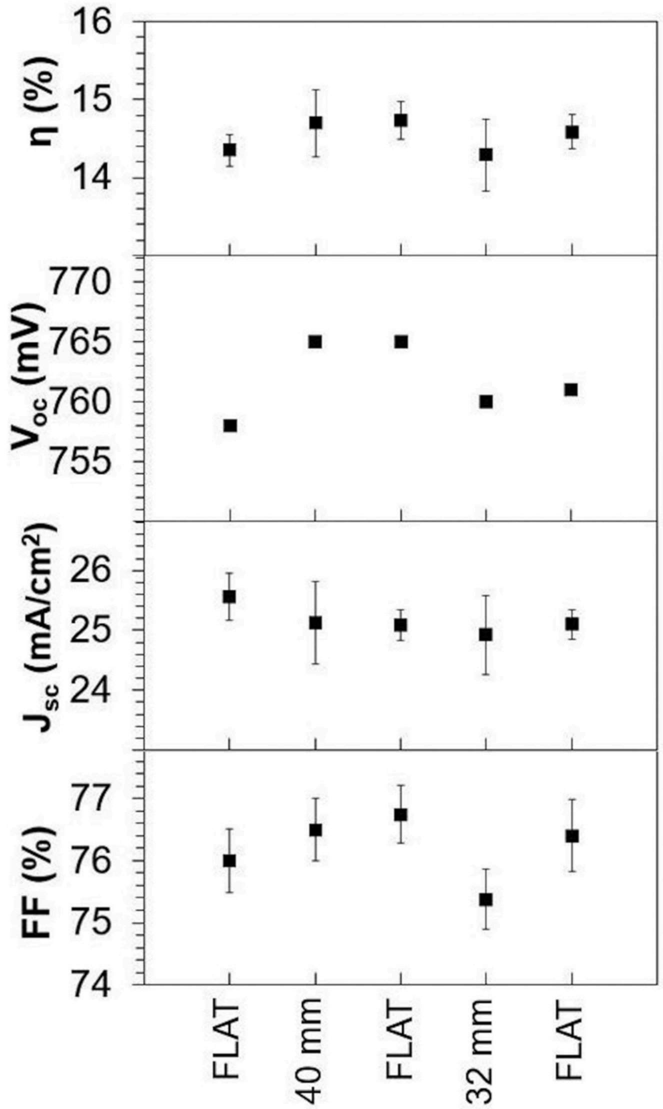


**Fig. 2.** Average J-V results of 8 CdTe solar cells on UTG measured in different conditions; flat, 40 mm and 32 mm bend radius.

Modulus of 77000 MPa. The Poisson ratio and Young's module was obtained from the cover glass manufacturers technical specification data sheet. This data was then plotted with strain vs the $\sin^2(\psi)$ value. Stress was calculated by Ref. [21]:

$$\sigma_{\varnothing} = \left(\frac{E}{1+\upsilon}\right)_{(hkl)} \frac{1}{d_{\varnothing 0}} \left(\frac{\partial d_{\varnothing \psi}}{\partial \sin^2 \psi}\right) \quad (1)$$

where $E$ is the modulus of elasticity, $v$ is the Poisson's ratio.

## 3. Results and discussion

Fig. 1 shows the 8 × 0.27 cm² gold back contacts are labelled according to the alphanumeric grid, identified using areas A, B, C, D and 1 & 2. The rectangular gold strips at either side provide the common front contact.

Fig. 2 shows the mean current density-voltage (J-V) performance of 8 CdTe solar cells measured using a solar simulator.

The cells were measured in 40 mm and 32 mm bend radius, and in a planar state before and after the bend curvature was applied (Fig. 3). An increase in average efficiency was observed when the device was measured in 40 mm bend radius, from 14.3% to 14.7%, although this is at the margin of the error bars. The same trend was observed for the $V_{oc}$ and FF, and this improvement remained when the device was relaxed to a planar state. Similar bend radius of 39 mm was applied for Rance et al. They observed a significant drop in $V_{oc}$ and $J_{sc}$, that led to an overall reduced efficiency [3]. It is suggested that the reduction seen in the Rance samples was because the cells were p-type doped with Cu, which is a faster diffuser, where the defect chemistry is heavily compensated and restricts the hole density to $<10^{15}$ cm$^{-3}$, that consequently influences the fill factor, photovoltage and efficiency [22,23]. On the other hand, the devices studied here were As doped, which is a much slower diffusing dopant and less likely to be influenced by stress, hence maintaining the $V_{oc}$ [24]. When the measurements were carried out in 32 mm bend curvature a drop in $V_{oc}$ and FF was observed but again this is at the margin of the error bars. The efficiency dropped and recovered to the initial state within experimental error. Moreover, the flat J-V measurements after 32 mm bending test showed some improvement in efficiency, $V_{oc}$ and FF, with values higher than the first measurement in a planar state.

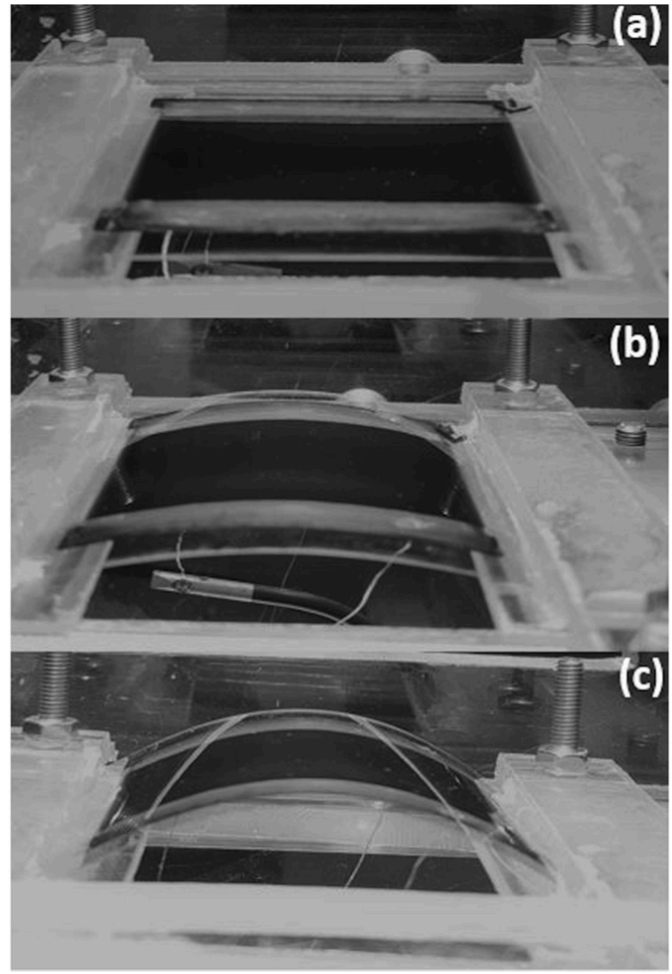


**Fig. 3.** CdTe device on UTG placed in a sample stage showing the solar cell flat (a), 40 mm (b), and 32 mm bend radius (c). The error bars are the standard deviation of the 8 solar cells.

In addition, a static 32 mm bending test was performed for 168 h (Fig. 4). The J-V was measured before and after bending and in 32 mm bend radius at 0, 24, 48, 120, 144 and 168 h. The mean value of efficiency for 8 solar cells was 13.7% with a best cell performance of 14.1% for the best cell. For this work we focused on the performance of two solar cells (A2 and B2) with identical initial performance (Table 1) but located in different areas (Fig. 1).

The average J-V performance of two solar cells, A2 and B2, measured

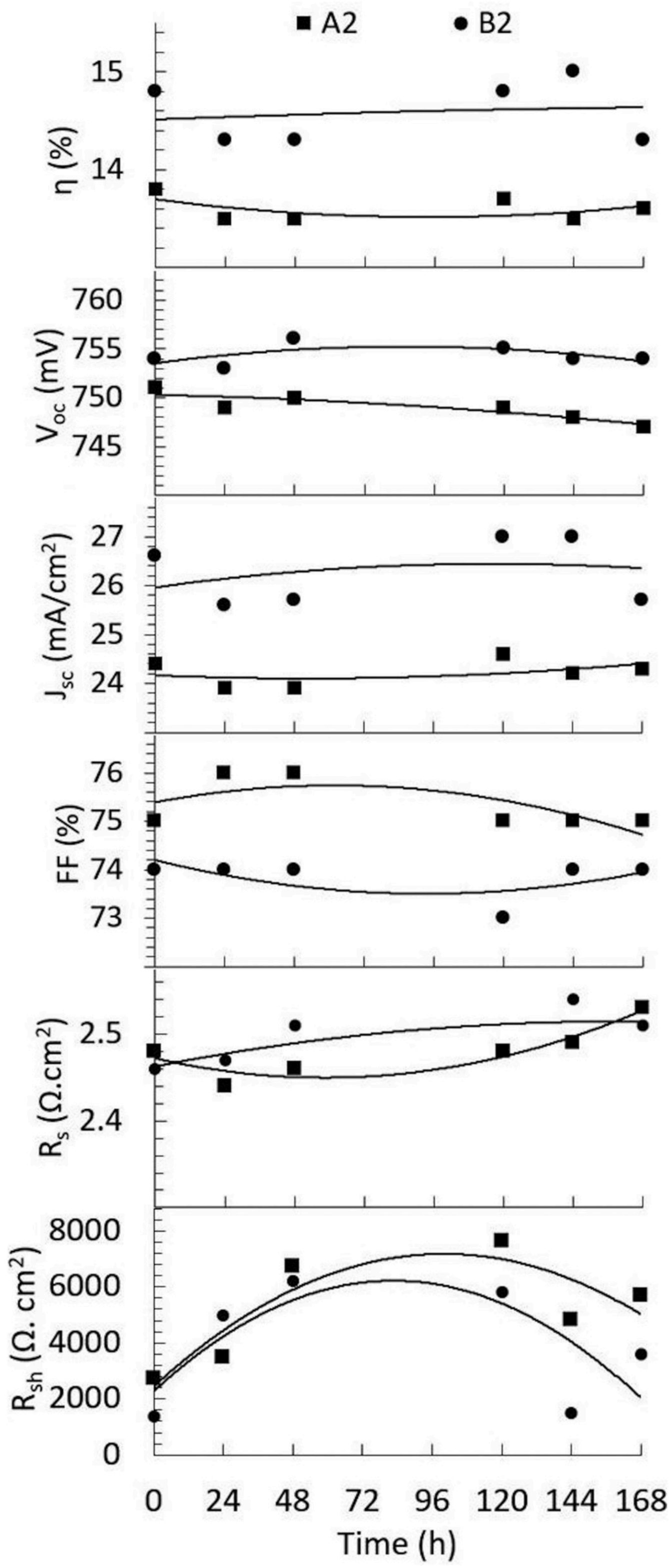


**Fig. 4.** J-V measurements at 32 mm bend radius of two solar cells (A2 and B2) while under a prolonged bending test.

in different flexing conditions is shown in Fig. 4. The results show no significant variation in efficiency for both samples with time. Furthermore, both samples didn't show any degradation and measured as per their initial values within experimental error when the measurement was reset to a flat state after 168 h of bending test.

**Table 1**
J-V measurements of solar cells A2 and B2 in a flat state before and after bending.

| Solar Cell | Time (h) | η (%) | $J_{sc}$ (mA/cm$^2$) | $V_{oc}$ (mV) | FF (%) | $R_s$ (Ω.cm$^2$) | $R_{shunt}$ (Ω.cm$^2$) |
|---|---|---|---|---|---|---|---|
| A2 | 0 | 14.1 (±0.3) | 25.4 | 747 | 74 | 2.4 | 3233 |
| | 168 | 13.8 (±0.3) | 24.7 | 745 | 75 | 2.4 | 3254 |
| B2 | 0 | 14.1 (±0.3) | 25.4 | 752 | 74 | 2.4 | 3627 |
| | 168 | 14.2 (±0.3) | 25.7 | 751 | 74 | 2.5 | 5122 |

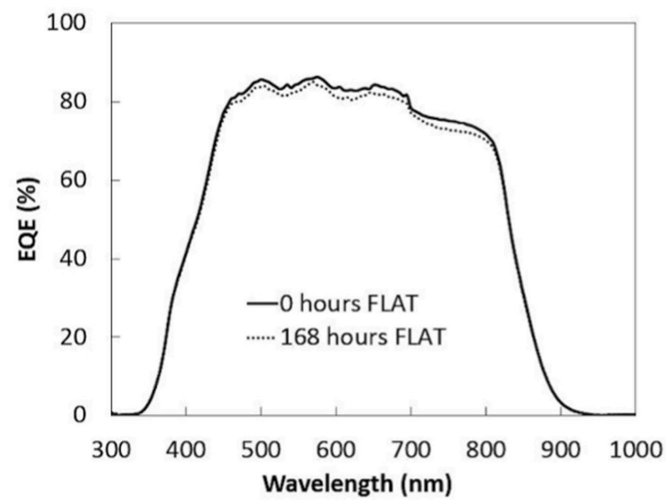


**Fig. 5.** External quantum efficiency of a CdTe solar cell on UTG before and after 168 h bending test.

Conflicting results were found by some authors when studying the evolution of solar cells when they are held under flexed conditions. Micro-cracks were observed after bending tests of various transparent conduction oxides on polyethylene terephthalate foils and proved that this material was not effective in flexible applications. In addition, the commercial flexible modules were measured and confirmed significant degradation, caused by a shunt resistance drop [25]. Gerthoffer et al. performed J-V measurements on CIGS solar cells on flexible UTG after bending cycles and observed an increase of the recombination rate with the evolution of $R_{sh}$ and $J_{sc}$, probably caused by the deterioration of the electrical and optical properties of the window layer [10]. Kreiml et al. carried out cyclic bending tests on Al/Mo bilayer thin films on flexible substrates. They observed that the thickness ratio influences the rate of damage formation. Thicker Al layers promote less surface damage in the form of cracks, this is because the thicker Al layer can accommodate more plastic deformation. Additionally, they concluded that tensile bending induces more cracks compared to compressive bending and it is seen as a more severe test of performance [26].

Additional analysis were performed in order to further understand the J-V results from both solar cells, A2 and B2. Fig. 5 shows the EQE measurements of a CdTe solar cell on UTG measured before and after bending test. The cut-off in the short wavelength region is dominated by the bandgap of the AZO/ZnO. In the region between 450 nm and 810 nm the EQE of the solar cell measured after 168 h is slightly lower and this is consistent with the $J_{sc}$ current being 0.4 mA/cm$^2$ reduced. In addition, the long wavelength region shows the CdTe absorption edge at 850 nm, corresponding to the band gap of 1.45 eV. C-V measurements shown in Fig. 6 show no change in carrier density before and after 168 h bending test. The carrier density remains constant at 1–2 x 10$^{16}$ atom/cm$^3$, which

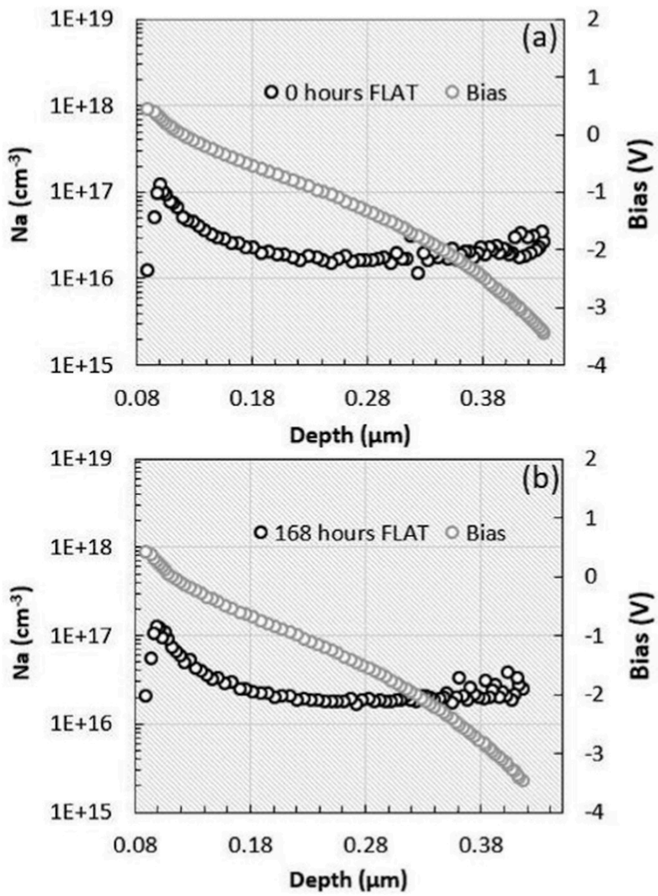


**Fig. 6.** C-V measurements before (a) and after 168 h bending test (b).

confirms the stability of As doping following bending.

Residual stress measurements were performed using XRD. Knowing the thickness and Young's modulus of the thin film and substrate, it was possible to determine the stress induced in the CdTe device. The value of residual stress before the bending test was 48.3 ± 6.5 MPa and after 168 h of being held at a bend radius of 32 mm was 48.1 ± 6 MPa. The results indicate that the residual strain is low when bending forces are removed, and no significant change was observed when the device was measured after the 168 h bending test, confirming the mechanical stability of this device under the relatively severe 32 mm bend radius. The relatively low internal stress in the CdTe devices reported here is indicative of the excellent thermal expansion coefficient (CTE) match between UTG (CTE = 6 ppm/°C) and CdTe (CTE = 5.7 ppm/°C) [27].

A residual stress of 1.61 GPa for ZnO in ZnO/Ag/ZnO thin films produced by magnetron sputtering technique was reported [28]. This value, significantly higher, is likely due to the lower thickness of 660 nm, in contrast to our device stack of 4 μm. According to Gerthoffer et al. the strain during the flexion of devices can be reduced using a substrate with low Young's modulus and low thickness [29].

## 4. Conclusion

A thin film CdTe solar cell on UTG was successfully produced with average efficiency across 8 × 0.27 cm$^2$ cells reaching 14.7%. The J-V measurements when the solar cells were subject to a 40 mm bend radius showed no significant change. Additionally, a static 32 mm bending test was performed for 168 h to study its effect on cell performances. Both solar cells studied, A2 and B2, showed excellent uniformity and stability and no significant variation on J-V parameters was observed after the 168 h. The sample A2 decreased slightly the efficiency value from 14.1% to 13.8% and sample B2 increased from 14.1% to 14.2%, both at the margin of the error bars. In addition, EQE and C-V measurements also showed no significant change in the optical and electrical properties of the CdTe before and after 168 h bending test. The residual stress analysis performed using XRD data showed that no strain was induced within the film after the bending test and that the overall strain was low. These results have demonstrated the feasibility of using the CdTe solar cells on UTG, where storage in a flexed state before use is beneficial or to produce curved modules for different applications without compromising photovoltaic performance. This has demonstrated for the first time that these CdTe thin film solar cells on UTG can be subjected to a bend radius as small as 32 mm and not showing any significant deterioration in performance.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## CRediT authorship contribution statement

**A.C. Teloeken:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing - original draft. **D.A. Lamb:** Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Writing - review & editing. **T.O. Dunlop:** Data curation, Formal analysis, Software. **S.J.C. Irvine:** Conceptualization, Funding acquisition, Methodology, Writing - review & editing.

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## References

[1] A. Bosio, G. Rosa, N. Romeo, Past, present and future of the thin film CdTe/CdS solar cells, Sol. Energy 175 (2018) 31–43, https://doi.org/10.1016/j.solener.2018.01.018.

[2] A. Gupta, V. Parikh, A.D. Compaan, High efficiency ultra-thin sputtered CdTe solar cells, Sol. Energy Mater. Sol. Cell. 90 (2006) 2263–2271, https://doi.org/10.1016/j.solmat.2006.02.029.

[3] W.L. Rance, J.M. Burst, D.M. Meysing, C.A. Wolden, M.O. Reese, T.A. Gessert, W.K. Metzger, S. Garner, P. Cimo, T.M. Barnes, 14%-efficient flexible CdTe solar cells on ultra-thin glass substrates, Appl. Phys. Lett. 104 (2014) 143903, https://doi.org/10.1063/1.4870834.

[4] J. Chantana, T. Watanabe, S. Teraji, Takashi Minemoto, Influence of minimum position in [Ga]/([Ga]+[In]) profile of Cu(In,Ga)$Se_2$ on flexible stainless steel substrate on its photovoltaic performances, Sol. Energy Mater. Sol. Cell. 157 (2016) 750–756, https://doi.org/10.1016/j.solmat.2016.07.048.

[5] L. Zortea, S. Nishiwaki, T.P. Weiss, S. Haass, J. Perrenoud, L. Greuter, T. Feurer, G. Palaniswamy, S. Buechelera, A.N. Tiwari, Cu(In,Ga)$Se_2$ solar cells on low cost mild steel substrates, Sol. Energy 175 (2018) 25–30, https://doi.org/10.1016/j.solener.2017.12.057.

[6] J. Park, J.H. Heo, S.H. Park, K. Hong, H.G. Jeong, S.H. Im, H. Kim, Highly flexible InSnO electrodes on thin colourless polyimide substrate for high-performance flexible $CH_3NH_3PbI_3$ perovskite solar cells, J. Power Sources 341 (2017) 340–347, https://doi.org/10.1016/j.jpowsour.2016.12.026.

[7] S. Kang, H. Kim, Y. Noh, S. Na, H. Kim, Face-to-face transferred multicrystalline ITO films on colorless polyimide substrates for flexible organic solar cells, Nano Energy 11 (2015) 179–188, https://doi.org/10.1016/j.nanoen.2014.10.030.

[8] D.A. Lamb, S.J.C. Irvine, A.J. Clayton, G. Kartopu, V. Barrioz, S.D. Hodgson, M. A. Baker, R. Grilli, J. Hall, C.I. Underwood, Richard Kimber, Characterization of MOCVD thin-film CdTe photovoltaics on space-qualified cover glass, IEEE J. Photovoltaics 6 (2016) 557–561, https://doi.org/10.1109/JPHOTOV.2016.2520199.

[9] A. Gerthoffer, F. Roux, F. Emieux, P. Faucherand, H. Fournier, L. Grenet, S. Perraud, CIGS solar cells on flexible ultra-thin glass substrates: characterization and bending test, Thin Solid Films 592 (2015) 99–104, https://doi.org/10.1016/j.tsf.2015.09.006.

[10] X. Zhu, Qin Lian, K. Tang, W. Bai, Y. Li, J. Yang, Y. Zhang, R. Qia, R. Huang, X. Tang, J. Chu, Epitaxial processing optimization and photoluminescence spectra of CdTe thin films grown on highly dissimilar SrTiO3(001) by molecular beam epitaxy, Thin Solid Films 669 (2019) 551–557, https://doi.org/10.1016/j.tsf.2018.11.047[10].

[11] S.A. Fadaam, M.H. Mustafa, A.H.A. AlRazaK, A.A. Shihab, Enhanced efficiency of CdTe Photovoltaic by thermal evaporation Vacuum, Energy Procedia 157 (2019) 635–643, https://doi.org/10.1016/j.egypro.2018.11.229.

[12] B. Shan, W. Wu, K. Feng, H. Nan, Electrodeposition of wurtzite CdTe and the potential dependence of the phase structure, Mater. Lett. 166 (2016) 85–88, https://doi.org/10.1016/j.matlet.2015.12.060.

[13] C. Selvakumar, T. Venkatachalam, E. Ranjith Kumar, Preparation, characterization and *ab-initio* study of $CdSnTe_2$ thin films by closed space sublimation technique, Superlattice. Microst. 90 (2016) 38–44, https://doi.org/10.1016/j.spmi.2015.12.011.

[14] R. Luo, B. Liu, X. Yang, Z. Bao, B. Li, J. Zhang, W. Li, L. Wu, L. Feng, The large-area CdTe thin film for CdS/CdTe solar cell prepared by physical vapor deposition in medium pressure, Appl. Surf. Sci. 360 (2016) 744–748, https://doi.org/10.1016/j.apsusc.2015.11.058.

[15] E. Camacho-Espinosa, A. López-Sánchez, I. Rimmaudo, R. Mis-Fernández, J. L. Peña, All-sputtered CdTe solar cell activated with a novel method, Sol. Energy 193 (2019) 31–36, https://doi.org/10.1016/j.solener.2019.09.023.

[16] J. Liu, X. Liu, K. Yang, S. He, H. Lu, B. Li, G. Zeng, J. Zhang, W. Li, L. Wu, L. Feng, Preparation and characterization of pulsed laser deposited $Sb_2Te_3$ back contact for CdTe thin film solar cell, Appl. Surf. Sci. 453 (2018) 126–131, https://doi.org/10.1016/j.apsusc.2018.05.075.

[17] G. Kartopu, O. Oklobia, D. Turkay, D.R. Diercks, S.B.P. Gorman, V. Barrioz, S. Campbell, J.D. Major, M.K. Al Turkestani, S. Yerci, T.M. Barnes, N.S. Beattie, G. Zoppi, S. Jones, S.J.C. Irvine, Study of thin film poly-crystalline CdTe solar cells presenting high acceptor concentrations achieved by in-situ arsenic doping, Sol. Energy Mater. Sol. Cell. 194 (2019) 259–267, https://doi.org/10.1016/j.solmat.2019.02.025.

[18] J. Li, J. Wang, Y. Pei, G. Wang, Study on the uniformity of ZnO films grown by MOCVD, Ceram. Int. 45 (2019) 13971–13978, https://doi.org/10.1016/j.ceramint.2019.04.096.

[19] P.K.K. Kumarasinghe, A. Dissanayake, B.M.K. Pemasiri, B.S. Dassanayake, Effect of post deposition heat treatment on microstructure parameters, optical constants and composition of thermally evaporated CdTe thin films, Mater. Sci. Semicond. Process. 58 (2017) 51–60, https://doi.org/10.1016/j.mssp.2016.11.028.

[20] M. Gostein, L. Dunn, Light soaking effects on photovoltaic modules: overview and literature review, in: 37th IEEE Photovolt. Specialists Conference (PVSC), 2011, pp. 3126–3131, https://doi.org/10.1109/PVSC.2011.6186605.

[21] P.S. Prevéy, X-ray Diffraction Residual Stress Techniques, Metals Handbook 10, American Society for Metals, Metals Park, 1986, pp. 380–392.

[22] W.K. Metzger, S. Grover, D. Lu, E. Colegrove, J. Moseley, C.L. Perkins, X. Li, R. Mallick, W. Zhang, R. Malik, J. Kephart, C.-S. Jiang, D. Kuciauskas, D.S. Albin, M.M. Al-Jassim, G. Xiong, M. Gloeckler, Exceeding 20% efficiency with in situ group V doping in polycrystalline CdTe solar cells, Nat. Energy 4 (2019) 837–845, https://doi.org/10.1038/s41560-019-0446-7.

[23] J.-H. Yang, W.K. Metzger, S.-H. Wei, Carrier providers or killers: the case of Cu defects in CdTe, Appl. Phys. Lett. 111 (2017), 042106, https://doi.org/10.1063/1.4986077.

[24] D. Kuciauskas, D. Lu, S. Grover, G. Xiong, M. Gloeckler, Separating grain-boundary and bulk recombination with time-resolved photoluminescence microscopy, Appl. Phys. Lett. 111 (2017) 233902, https://doi.org/10.1063/1.5010931.

[25] M. Sibinski, K. Znajdek, Degradation of flexible thin-film solar cells due to a mechanical strain, Opto-Electron. Rev. 25 (2017) 33–36, https://doi.org/10.1016/j.opelre.2017.02.003.

[26] P. Kreiml, M. Rausch, V.L. Terziyska, J. Winkler, C. Mitterer, M.J. Cordill, Compressive and tensile bending of sputter deposited Al/Mo bilayers, Scripta Mater. 162 (2019) 367–371, https://doi.org/10.1016/j.scriptamat.2018.11.048.

[27] S.M. Garner, M. He, P.-Y. Lo, C.-F. Sung, C.-W. Liu, Y.-M. Hsieh, R. Hsu, J.-M. Ding, J.-P. Hu, Y.-J. Chan, J. Lin, X. Li, M. Sorensen, J. Li, P. Cimo, C. Kuo, Electrophoretic displays fabricated on ultra-slim flexible glass substrates, J. Disp. Technol. 8 (2012) 590–595, https://doi.org/10.1109/JDT.2012.2206558.

[28] B. Sarma, B.K. Sarma, Role of residual stress and texture of ZnO nanocrystals on electro-optical properties of ZnO/Ag/ZnO multilayer transparent conductors, J. Alloys Compd. 734 (2018) 210–219, https://doi.org/10.1016/j.jallcom.2017.11.028.

[29] A. Gerthoffer, C. Poulain, F. Roux, F. Emieux, L. Grenet, S. Perraud, CIGS solar cells on ultra-thin glass substrates: determination of mechanical properties by nanoindentation and application to bending-induced strain calculation, Sol. Energy Mater. Sol. Cell. 166 (2017) 254–261, https://doi.org/10.1016/j.solmat.2016.11.022.