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Abstract

This work describes progress towards achieving a flexible, high specific power and low-cost photovoltaic for emerging large area space applications. The paper reports the highest conversion efficiency of 15.3 % AM1.5G for a CdTe device on ultra-thin cerium-doped cover glass, the standard protective material for extra-terrestrial photovoltaics. The deposition technique used for all of the semiconductor layers comprising the device structure was atmospheric pressure MOCVD. Improvements to the device structure over those previously reported led to a V_{oc} of 788 mV and a relatively low series resistance of 3.3 $\Omega \cdot cm^2$. These were largely achieved by introduction of a post-growth air anneal and a refinement of the front contact bus bars respectively. The aluminium-doped zinc oxide TCO, being the first layer applied to the cover glass, was subject to thermal shock cycling +80 °C to (–) 196 °C to test the adhesion under the extreme conditions likely to be encountered for space application. Scotch Tape testing and sheet resistance measurements before and after the thermal shock testing demonstrated that the AZO remained well adhered to the cover glass and its electrical performance unchanged.

Introduction

In the near-future extra-terrestrial photovoltaics (PV) will require higher power and larger arrays than are currently in operation. High performance triple junction PV is the current product of choice for space applications but does not lend itself well to scale-up due to its inherent cost and low specific power. Specific power refers to the peak power output (kW_{peak}) to weight (kg) ratio and is a useful metric for comparison of different solar cell technologies when the application, such as extraterrestrial arrays, benefits from any potential reduction in mass.

Extra-terrestrial PV plays a key role in powering communication and global positioning satellites, Martian rovers and the International Space Station. Emergent applications will require a far higher specific power and much reduced production cost technology. Examples of large area PV applications predicted for space are; space-based solar power arrays [1], transmitting their power to earth based rectennas, Lunar and Martian bases [2] and solar electric propulsion [3] through the use of ion thrusters.

This work details a novel solution for the requirement of a high specific power and low cost photovoltaic array namely, by directly depositing cadmium telluride (CdTe) onto a flexible and radiation hard cerium-doped micro-sheet cover glass. Assuming a relatively modest target module efficiency of 14 % the CdTe thin film, applied directly to the cover glass, has the potential to double the specific power output compared to the current industry standard triple junction cells. Table 1 shows a comparison between the formerly used silicon, current triple junction and projected CdTe technologies.

Technology	B.O.L Efficiency AM0 (%)	Cell weight (kg/m^2)	Specific Power (kW_{peak}/kg)
Triple Junction	30*	1.06	0.38
Silicon	16.9*	0.52	0.44
CdTe	14**	0.24	0.80

Tab. 1. Specific power potential of CdTe: *manufacturers values, **projected efficiency. Cell weight includes 80 microns thickness of cover glass for all 3 technologies. B.O.L designates beginning of life efficiency.

Radiation protective cover glass is currently laminated to all PV deployed in space. Coating the cover glass directly offers the potential of a significant weight reduction as well as facilitating new deployment mechanisms through exploiting its flexible nature. The challenge is not only to produce as high efficiency and lightweight solar cell as possible but to design the structure such that delamination or other failure mechanisms do not occur [4].

CdTe PV, for space application, has received attention from research groups but no working devices have been flight tested or indeed deposited directly onto the space qualified cover glass. Previous studies have highlighted the potential radiation stability of CdTe space applications such as detectors due to its inherent radiation hardness [5]. Its use as a PV material for space has been investigated by authors who demonstrated that CdTe devices remained undamaged when subjected to electron and proton irradiation of energy and fluence comparable to those found in Earth orbit [6 and 7].

The work presented in this paper describes one avenue for achieving a high specific power PV for future space application. Competing technologies are also in development such as; copper indium gallium diselenide (GIGS) [8 and 9], amorphous silicon [10] and inverted metamorphic multi-junction (IMM) [11]. The German Joint Project [8] targets the development of a flexible CIGS thin film solar cell technology on a polyimide substrate. The IMM is an example of gallium arsenide based triple junction technology where the usual sequence for cell growth is reversed with the top cell being deposited first and the bottom cell last. The cell is then turned over and mounted to a "handle" material such as polyimide or metal foil before the substrate that the cell was deposited upon is removed. This yields a lightweight and flexible cell with performance equivalent to conventionally deposited triple junction cells (31% B.O.L, AM0) [11]. The IMM structure is still required to be protected from radiation by lamination to a cerium-doped cover glass. Of all the thin film technologies in development the IMM has the potential to yield the highest specific power. However, if a successful process can be developed, the cost of this technology is predicted to be at least as expensive current triple junction products [12].

The research presented in this paper, funded by the UK's Engineering and Physical Sciences Research Council (EPSRC), sees the project lead the Centre for Solar Energy Research, Glyndwr University (CSER) in strong collaboration with the Materials Engineering and Surrey Space Centre research groups at the University of Surrey, and key industrial partners Qioptiq Space Technology

Limited (QST) and Surrey Satellite Technology Limited (SSTL). The paper considers some of the challenges of this new device structure where metal organic chemical vapour deposition (MOCVD) is used to produce the CdTe PV device.

Experimental

The device structure follows the superstrate configuration with all layers deposited by atmospheric pressure metal organic chemical vapour deposition (MOCVD) (figure 1). Two different thicknesses of QST's uncoated cerium-doped micro-sheet cover glass were used as substrates for this research. In all cases the cover glass was first coated with 800 nm of aluminium-doped zinc oxide (AZO) to form a transparent conductive front contact. Sample A was deposited on a 50 µm cover glass and sample B a 100 µm cover glass. The results of both of these samples have both been reported elsewhere but are reiterated here to demonstrate the progress made [13, 14]. Samples C and D were deposited onto a chemically toughened 100 µm cover glass which is now the substrate of choice for further development of this device structure. Oxygen plasma cleaning of the bare cover glass was introduced for samples B, C and D. The cover glass was subject to 5 minutes exposure to oxygen plasma generated in a 40 kHz/200 W plasma chamber at 90 % power and using 60 standard cubic centimetres per minute high purity oxygen flow. Samples C and D included a 90 nm zinc oxide buffer (ZnO) as shown in figure 1. Samples A and B did not include the ZnO buffer layer.

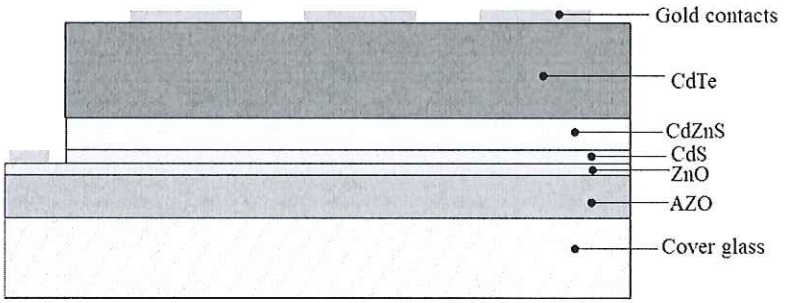

Fig.1. Schematic cross-section of a flexible CdTe thin film solar cell

The window layer (n-type) consisted of a thin cadmium sulphide (CdS) layer (50 nm) followed by a thicker cadmium zinc sulphide (CdZnS) layer (200 nm). The former acts as a seed layer for the wider band gap CdZnS which forms the bulk of the window layer. The absorber was achieved using an arsenic-doped cadmium telluride (CdTe:As) layer 2250 nm thick. Finally, a cadmium chloride ($CdCl_2$) layer of 1000 nm thickness was deposited before an annealing step promoted the diffusion of the

chlorine into the absorber layer. For further details of the fabrication process see [15-17]. The thickness of the window layer for sample D was reduced to improve blue-response (the CdS layer was thinned to 25 nm and the CdZnS layer to 125 nm).

In all cases the as-grown device structure was treated with a deionized water rinse and nitrogen blow off to remove any surface remnants of the $CdCl_2$. Samples C and D benefited from an additional air anneal at 170 °C for 30 and 60 minutes respectively before back contacting. The back contact was achieved by evaporating 0.25 cm^2 gold squares onto the CdTe (see figure 2). Front contacting for sample A was first realized by embedding a gold wire into silver paint applied to the revealed AZO. Samples B, C and D were front contacted by evaporating gold directly onto the AZO/ZnO then using a silver ink to adhere a copper ribbon to the gold and finally securing the copper ribbon contact in place using an adhesive Kapton tape. Figure 2 also serves to illustrate the sample area over which the 0.25 cm^2 cells are produced (~ 4 x 4 cm).

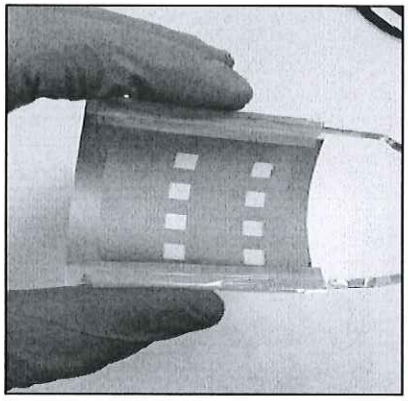

Fig. 2. Thin film CdTe on QST cover glass. Gold squares represent 0.25 cm^2 cells.

Current density versus voltage (J–V) measurements were made using a Keithley 2400 source meter and an ABET Technologies Sun 2000 solar simulator calibrated to AM1.5G (1000 W/m^2) using a Fraunhofer Institute for Solar Energy Systems silicon reference solar cell. Thermal shock testing of the TCO structure, on toughened cover glass 100 µm, was conducted at QST. The sample was first held at 80 °C for 1 minute then lowered until completely immersed in liquid nitrogen (–)196 °C and again held for 1 minute. This cycle was repeated 10 times. A Scotch Tape Test was performed to evaluate the adhesion of the coating before and after thermal shock testing. The Scotch Tape test was carried out using L-T-90 cellophane tape. The methodology followed adhered to MIL-C-675C 3.8.52. where 2 cm of tape was pressed firmly against the surface of the sample and then quickly

removed at an angle perpendicular to the surface. The sample was deemed to have passed the test if there was no visible sign of delaminated coating on the tape or removed from the sample surface. The TCO structure was also evaluated for a deterioration of sheet resistance using a CMT-SR2000N mapping four-point-probe with 300 μm diameter tips.

Results and Discussion

The four samples discussed in this paper (A-D) were deposited over a 12-month period and each represents a step change in performance that can be attributed to intentional changes in the fabrication process.

Figure 3 is a plot of current density (mA/cm^2) versus voltage (V) under AM1.5G illumination and shows the incremental improvements in conversion efficiency (η). The J/V curves show an increase of open-circuit voltage (V_{oc}), and decrease of series resistance (the gradient of the straight portion of the line in forward bias).

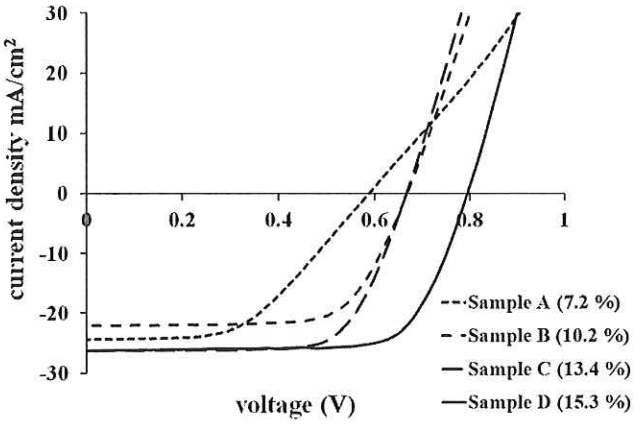

Fig. 3. Plot of current density (mA/cm^2) versus voltage (V) under AM1.5G illumination of 0.25 cm^2 thin film CdTe cells, on QST cover glass, efficiency was incrementally improved over a 12 month time frame.

Table 2 displays the J-V parameters of samples A-D showing the incremental improvements in η. The improved surface preparation of the cover glass substrate through oxygen plasma cleaning is known to remove organic contaminants and induce a hydrophilic character by increasing the surface energy. Pinholes and macro-defects, previously observed in the AZO, were reduced to a minimum after the oxygen plasma cleaning process was introduced. This improvement in film coverage and

quality has been reported by other authors researching CdTe photovoltaics [18, 19]. The short-circuit current density (J_{sc}) varies between samples A-D but shows no significant trend although the highest Jsc value (26.3 mA/cm^2) was seen for sample D which benefited from a reduction in window layer thickness from 240 nm to 150 nm.

Step change in device η (%)	Sample A	Sample B	Sample C	Sample D
η (%)	7.2	10.2	13.4	15.3
J_{sc} (mA/cm^2)	24.3	22.1	25.1	26.3
V_{oc} (mV)	586	667	707	788
FF (%)	50.6	69.4	75.3	74.0
R_s (Ω·cm^2)	11.2	4.2	3.6	3.3
Oxygen Plasma Clean before AZO	No	Yes	Yes	Yes
Gold contact to TCO	No	Yes	Yes	Yes
Post-growth air anneal	No	No	30 mins	60 mins
ZnO buffer	No	No	Yes	Yes
Thinner window layer	No	No	No	Yes

Tab. 2. J-V parameters quantising incremental improvements with process changes identified.

The R_s was significantly reduced from 11.2 to 3.3 Ω·cm^2 between sample A and sample D. The most significant decrease in R_s was observed between sample A and sample B, both of which did not benefit from the high-resistivity ZnO layer or indeed the post-growth anneal in air. For this decrease in R_s no change was made to the back contacting, and was attributed to an improvement of the front contact resistance in a previous publication [14]. The authors described how sample A had one front contact made to the AZO along one side of the 60 x 60 mm substrate using a gold wire embedded in a silver paint. This geometry and type of contacting to the AZO was suspected to be the major contribution to the high R_s 11.2 Ω·cm^2 of sample A. It was suggested that some interaction between the solvent of the silver paint and the AZO before curing could not be ruled out and for sample B the geometry and type of contact was changed. For sample B and indeed the previously reported on samples C and D the AZO front contact was revealed along both sides of the substrate and a 100 nm thickness gold film evaporated directly onto the AZO followed by coating with a silver ink. Both the gold and silver ink aid the uniform contact of the electrical connections of the characterisation equipment.

With the R_s optimised for samples B, C and D it is a steady increase in V_{oc} thereafter from 667 to 788 mV which is driving the improvement in efficiency. The introduction of the intrinsic ZnO buffer layer (90 nm thick) for samples C and D can be expected to improve V_{oc}. A high-resistivity transparent layer is commonly used for CdTe PV to reduce micro-shunts due to pin-holes in the window layer [20]. The major increase in V_{oc} is attributed to the introduction of first the 30 and then the 60 minute post-growth air anneal for samples C and D respectively. This post-growth air anneal creates a back surface oxide layer increasing V_{oc} [21].

Results have been presented based on the best single 0.25 cm^2 cells taken from a 4 × 4 cm section of the cover glass/CdTe structure. Such tracking of best cell performance is useful to highlight trends in J-V parameters and to demonstrate the progression of research; however consideration of multiple cells from each cover glass/CdTe structure is also important to investigate cell variance and therefore deposition uniformity. Table 3 displays the mean J-V parameters of all cells measured (denoted by the best samples B, C and D).

Sample	Best η (%)	No. cells	Mean J-V parameters η (%)	(σ)	J_{sc}(mA/cm^2)	V_{oc} (mV)	FF (%)	R_s (Ω·cm^2)	R_{sh} (Ω·cm^2)
Sample B	10.2	4	9.5	0.7	21.8	662	65.9	4.4	1106
Sample C	13.4	8	11.9	0.5	24.4	682	71.8	3.7	3698
Sample D	15.3	8	13.5	0.9	23.4	803	71.7	4.5	1406

Tab. 3. J-V parameters for three different cover glass/CdTe depositions. The second column indicates the best device efficiency whilst all other data is taken from the mean values of a number of cells from the same deposition as each sample in the first column.

A standard deviation of no greater than σ 0.9, for all three sample mean efficiencies, indicates a robustness of the deposition process over the whole measured area of the substrate deposition (4 x 4 cm). The increase in mean device efficiency of both sample C and D is consistent with the optimisation of the post-growth anneal. The significant parameter leading to an increase of mean device efficiency for sample D is the V_{oc} of 803 mV achieved by increasing the post growth air anneal time from 30 to 60 minutes.

Any solar array deployed in Space can anticipate very large and sudden thermal gradients. These temperature gradients can be as large as 140 °C to (-) 200 and occur in a matter of minutes.

Delamination of any part of the thin film structure, under these conditions, is of real concern and can be mitigated for by thermal shock testing and thermal cycling under vacuum. Initial thermal shock tests at atmospheric pressure were trialled on the AZO coated cover glass. Samples were first heated (+80 °C) for 1 minute then lowered until completely immersed in liquid nitrogen (–196 °C) and again held for 1 minute. This cycle was repeated 10 times and the samples removed. All of the AZO coated cover glass samples were subject to the Scotch Tape Test after the thermal shock cycling with no residue on the tape or delamination of the thin film observed. The sheet resistance was measured at 15 points across the AZO on cover glass yielding an average of 8 Ω/□. No change of average sheet resistance was observed after the thermal shock cycling. These initial results are promising and future work will look at thermal shock testing a working device to measure J/V parameters before and after and cycling over with a controlled ramp rate and under vacuum.

Conclusions

This research further demonstrates the feasibility of a thin film CdTe photovoltaic structure deposited directly onto the industry standard Space cover glass. A predicted 14% module efficiency thin film CdTe solar cell on cover glass can compete with current more efficient triple junction Space solar cells in terms of higher specific power. The progress in developing this new thin film photovoltaic structure has been described with conversion efficiency increasing from 7.2 to 15.3 % over a 12 month time frame. The newly reported improvements in device conversion efficiency from sample C (13.4%) to sample D (15.3 %) were attributed to the introduction of a high resistive ZnO buffer layer reducing micro-shunts and the introduction and optimisation of a post-growth anneal in air increasing V_{oc}. The mean J/V parameters presented demonstrate that the "best cell" results reported within this paper are supported by a strong foundation of photovoltaic performance across up to 8 x 0.25 cm^2 cells deposited over an area of 4 x 4 cm. As well as photovoltaic performance, the durability of the first layer, the thin film transparent conducting oxide/cover glass interface, has been considered. The AZO on cover glass structure did not delaminate under the Scotch Tape Test before or after extreme thermal shock of 10 cycles of + 80 to -196 °C. Further testing will take place to establish robustness in a Space environment in terms of radiation hardness.

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