Characterization of MOCVD Thin-Film CdTe Photovoltaics on Space-Qualified Cover Glass

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***Abstract*—This paper details the AM0 conversion efficiency of a metal–organic chemical vapor phase deposition thin-film cadmium telluride (CdTe) solar cell deposited onto a cerium-doped cover glass (100 μm). An AM0 best cell conversion efficiency of 12.4% (0.25-cm^2 contact area) is reported. An AM0 mean efficiency of 12.1% over eight cells demonstrated good spatial uniformity. Excellent adhesion of the cell structure to the cover glass was observed with an adhesive strength of 38 MPa being measured before cohesive failure of the test adhesive. The device structure on cover glass was also subject to severe thermal shock cycling of +80 °C to −196 °C, showing no signs of delamination and no deterioration of the photovoltaic (PV) performance.**

***Index Terms*—Cadmium telluride (CdTe), metal–organic chemical vapor deposition (MOCVD), photovoltaic (PV) cells, transparent conductive oxide (TCO).**

I. Introduction

THERE is an increasing interest, in extraterrestrial photovoltaics (PV), for far higher power arrays than are currently in operation. The current industry standard triple-junction PV technology plays a crucial role in powering, for example, communication and global positioning satellites, Martian rovers, and space probes. However, emerging applications will demand high power coupled with low weight (high specific power kW/kg) and a lower production cost technology. These emerging demands include solar electric propulsion (SEP) through the use of ion thrusters [1], [2], space-based solar power (SBSP) arrays transmitting their power to earth-based receivers [3]–[6], and Lunar and Martian bases [7]. SEP is a replacement to conventional chemical propulsion systems that offer significant weight savings. SEP uses electricity generated by solar arrays to produce ions of gases such as Xenon and accelerates these ions via thrusters, thus producing momentum in the opposing direction. SBSP is a method of collecting solar power in space for use on Earth, other planets, or Moons, and exploits the higher (than terrestrial) solar irradiance. Any potential Lunar or Martian base will require a lightweight and robust PV solar array for both transportation and deployment. Alternative space-qualified solar cell technologies are needed to meet the demands of these advances in propulsion, energy harvesting, and space exploration.

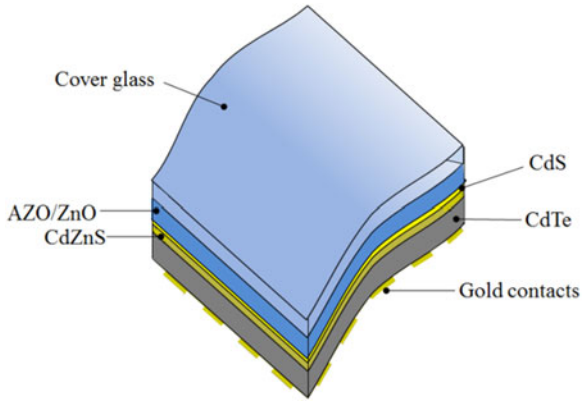

Fig. 1. Cross section of a flexible CdTe thin-film superstrate structure (layer thicknesses not to scale).

This paper describes the AM0 (zero air mass) measurements of a high specific power (0.57 kW/kg for the 12.4% best cell), potentially low-cost and radiation hard CdTe PV technology. An atmospheric-pressure metal–organic chemical vapor deposition (MOCVD) process was used to produce all of the semiconductor layers, which provided the processing temperature and materials composition flexibility required for this structure. The PV superstrate structure shown in Fig. 1 was achieved by depositing an aluminum-doped zinc oxide (AZO) transparent conducting oxide (TCO) and thin-film cadmium telluride (CdTe)-based solar cell onto Qioptiq Space Technology's (QST) flexible and radiation hardened cerium-doped cover glass. Previous work reported on the development of the TCO layer and feasibility of device structure on cover glass leading to best cell (0.25 cm^2) efficiency under AM1.5G of 15.3% [8]–[10].

This innovative step of depositing the thin-film solar cell directly onto the cover glass has a number of potential benefits including a reduction of weight and potential cost saving by dispensing with the normal substrate such as germanium or gallium arsenide for multijunction solar cells. Due to QST's chemical toughening process, the glass has a high degree of flexibility, allowing for development of new space and weight saving

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stowage and deployment technologies. The radiation hard cover glass is ordinarily laminated to the front of all PV destined for space application.

PV deployed in space must be resilient and stable to high-energy particles such as protons and electrons, as well as high levels of ultraviolet radiation. These high-energy particles are known to cause damage in solids through ionization and displacement, producing electron traps within the irradiated material and altering the electronic properties of the semiconductor layers [11]–[14]. Further, when the particles are incident on the transparent environmental barrier (i.e., glass), ionization causes a perturbation of the electrical neutrality, resulting in an electric field that acts as a color center, darkening the glass and, thus, reducing transmission of photons through the PV material. This darkening of the glass is a fast process rapidly reducing the photocurrent of the PV device. The cerium-doped cover glass provides protection from protons and electrons with stopping distances shorter than the thickness of the glass and avoids darkening due to UV irradiation through a mechanism, whereby cerium Ce^{3+} ions are oxidized to Ce^{4+} [15].

The theoretical limit for a single junction of this thin-film PV material is determined by the Shockley–Queisser limit of around 30%. The world-record efficiency for terrestrial CdTe solar cells is 21.5% set by First Solar [16]. In [17], the highest efficiency CdTe device deposited onto a flexible glass designed for terrestrial use has been reported. Using a combination of chemical bath deposition (window layer) and close space sublimation (absorber layer), the best cell on 100-μm Corning Willow glass achieved a 16.2% AM1.5 efficiency. While this glass superstrate would be incompatible for space application, the results highlight that the work presented in this paper on cover glass is readily transferable to the terrestrial flexible glass, thus providing an exploitation route to high specific power terrestrial applications.

CdTe is well documented as a suitable material for space applications such as detectors due to its inherent radiation hardness [18], [19]. Its use as a PV absorber material for space has been studied using soda-lime glass as the substrate [20], [21]. Romeo *et al.* [20] showed that for proton fluence as high as 10^{13} cm^{-2}, there was no notable damage to the CdTe cell and that a CdTe cell exposed to electron energy of 8 MeV did not lead to an increase in deep level traps.

Extraterrestrial PV is also subject to high levels of thermal stress due to large temperature variations. PV arrays deployed in Low Earth Orbit will experience temperatures of up to $+140$ °C in sunlight, while as low as -100 °C in eclipse for 5000 cycles per year. A Geostationary Earth Orbit array will experience eclipses increasing in duration of up to 72 min for two six-week seasons per year, in which the lower temperature of the array can dramatically drop down to -180 °C before rapidly increasing to the sunlight temperature of $+60$ °C.

Previous research into a thin-film solar technology for space application included a program conducted by Dutch Space B.V., investigating copper indium gallium diselenide (CIGS) deposited onto 25-μm-thick titanium foil [22]. This structure suffered from severe degradation when subject to thermal cycling through -175 °C to $+100$ °C. Thus, thorough investigation of the thermal stability is deemed essential for any proposed thin-film PV technology for space applications.

II. Materials and Methods

A. Substrate and Transparent Conducting Oxide

Chemically toughened, 100-μm-thick, cover glass of 60×60 mm dimension was supplied by QST. The AZO front contact and high-resistivity zinc oxide (ZnO) buffer layers were deposited by MOCVD using a nitrogen carrier gas and the chemical precursors: diethylzinc (DEZn), *tert*-Butyl alcohol (TBA), and trimethylaluminum (TMA). The ratio of the precursors was set at 1:3:0.1 for the AZO and 1:3:0 for the ZnO (DEZn:TBA:TMA). The substrate deposition temperature was 400 °C for the AZO TCO, and a thickness of 800 nm yielded a sheet resistance of 8 Ω/square. For the ZnO buffer layer, a temperature of 400 °C and thickness of 100 nm were used. The AZO deposition conditions and thickness were previously established on the cover glass to optimize for a high transparency, low haze, and high conductivity [8]–[10].

B. Window and Absorber Layer Structure

An initial 25-nm CdS nucleation layer was deposited onto the ZnO/AZO/cover glass at 315 °C followed by a 125-nm $Cd_{0.3}Zn_{0.7}S$ (n-type) window layer deposited at 360 °C [23]. For all cells, the CdTe (p-type) absorber layer was deposited at 390 °C with two stages of arsenic doping: the first 3000 nm of CdTe receiving a doping concentration of $2 \times 10^{18} cm^{-3}$ with a final 250-nm CdTe layer receiving a higher concentration of $>1 \times 10^{19} cm^{-3}$ (lowering the back contact resistance) [24]. Finally, a 1000-nm $CdCl_2$ layer was deposited at 200 °C, and the structure was annealed at 420 °C for 10 min for cell activation [25]. All these processes were carried out consecutively in the same MOCVD chamber using hydrogen as the carrier gas.

C. Postgrowth Cell Preparation

Due to the intentionally increased arsenic doping concentration, at the back surface of the CdTe, no postgrowth etching of the surface was required. The as-grown cell structure was treated with a deionized water rinse and nitrogen blow off to remove any surface remnants of the $CdCl_2$ treatment. An additional air anneal at 170 °C and for 60 min was carried out to improve the open-circuit voltage (V_{oc}) and fill factor (FF) [26]. Cells of 0.25-cm^2 were made by evaporating 160 nm of gold onto the CdTe surface using a mask. The TCO (ZnO/AZO) front contact was revealed on either side of the eight cells.

D. Cell Characterization

AM0 current density versus voltage (V) (*J*–*V*) measurements were made using an ABET Technologies, Sun 2000, solar simulator along with a Keithley 2400 source-meter. An ABET 11054 AM0 filter was used, but without access to an AM0 calibrated CdTe reference cell, the solar simulator was calibrated for the CdTe cells by the following methodology.

1) External quantum efficiency (EQE) measurement of one of the 0.25-cm^2 cells was made using a Bentham PV300 spectrometer itself calibrated using a certified silicon photodetector.
2) The $J_{\rm sc}$ of the cell was then calculated from the area under the EQE curve as

$$J_{\rm sc} = \int_{\lambda_A}^{\lambda_B} \mathrm{SR}\,(\lambda)\,.I_{e\lambda}\,(\lambda)\,d\lambda \qquad (1)$$

where $I_{e\lambda}$ is the spectral irradiance (under ASTM-E490 AM0 conditions) of the solar spectrum (W·m^{-2}·nm^{-1}) at a particular wavelength, and SR(λ) is the spectral response (A·W^{-1}), which can be calculated as

$$\mathrm{SR}(\lambda) = \frac{q\lambda}{hc}.\mathrm{EQE}(\lambda) \qquad (2)$$

where q is the elementary charge, h is Planck's constant, c is the speed of light in vacuum, and EQE(λ) is the EQE of the device at a particular wavelength.
3) With the cell then placed under the solar simulator, the lamp intensity was adjusted until the AMO EQE-derived $J_{\rm sc}$ value for the cell was reached. The stability of the lamp intensity, yielding this calibrated $J_{\rm sc}$, was ensured with a 30-min stabilization period.

The values for $V_{\rm oc}$ and FF will be partially dependent on the intensity of the incident light. By using EQE, which is an essentially intensity-independent measure of wavelength-dependent performance (i.e., the percentage of photons incident to the device that generate extracted carriers) as a reference point, it allows real values of the other cell parameters under AM0 conditions to be measured.

E. Mechanical and Environmental Testing

The adhesion strength of the full device structure on cover glass was determined via a pull-test, using an Instron 5500R tensile test machine with Bluehill 2 software to control the test and acquire the data. The bottom surface of the dolly had a diameter of 5 mm, giving an area of 19.6 mm^2. A 5-kN load cell was fitted to the frame and the crosshead movement was at 0.1 mm/min. The glue was a cyanoacrylate-based Loctite Super Glue. The failure surfaces were analyzed for their chemical composition using X-ray photoelectron spectroscopy (XPS) using a Thermo Scientific Thetaprobe XPS instrument employing a monochromatic Al Kα X-ray source with a photon energy of 1486.6 eV. The diameter of the X-ray beam spot was 400 μm. Broad scan spectra were recorded at a pass energy of 300 eV. Spectra were charge referenced to the C 1 s peak at 285.0 eV.

The full device structure, on toughened 100-μm cover glass, was placed in a thermal shock tester located at QST. The sample was first held at +80 °C for 1 min and then quickly lowered until completely immersed in liquid nitrogen at –196 °C and again held for 1 min. This cycle was repeated 20 times. A Scotch Tape Test was performed (MIL-C-675C 3.8.5) to evaluate the adhesion of the coatings, before and after the thermal shock test (TST), using L-T-90 cellophane tape and pressing 2 cm of the tape firmly against the surface of the sample before quickly removing it at an angle perpendicular to the surface. The tape was then examined for sample residue and the sample itself examined for delamination using an optical microscope at 10 × magnification.

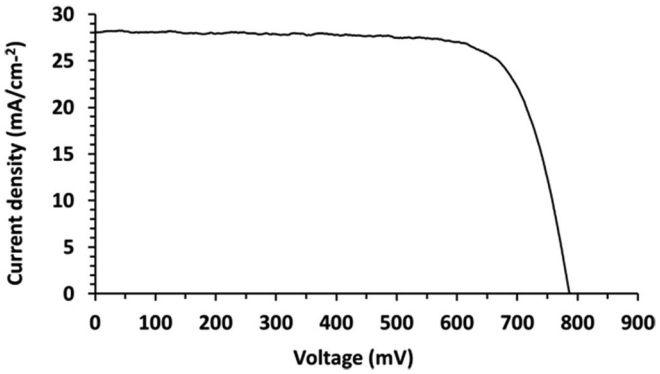

Fig. 2. Plot of *J–V* under AM0 illumination of the best thin-film CdTe cell on cover glass.

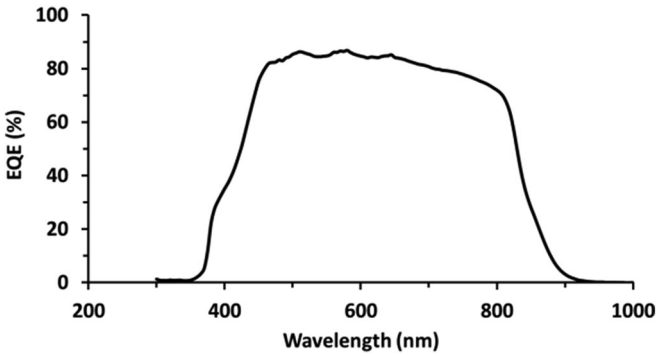

Fig. 3. EQE spectrum of the highest η AM0 12.4% cell.

III. Results and Discussion

A. Cell Performance

Cells of 8 × 0.25 cm^2 located within a 40 × 40 mm^2 area of the deposited thin-film device were measured for AM0 conversion efficiency using the methodology described previously. A plot of current density versus voltage for the highest efficiency cell is shown in Fig. 2. This is measured to have an AM0 conversion efficiency (η) of 12.4%, for a device deposited onto 100-μm cover glass, which equates to a cell specific power of 0.57 kW/kg.

The EQE spectrum for this cell is shown in Fig. 3. The above band gap (< 850 nm) spectral response is very respectable for a CdTe cell without an antireflection coating, ranging between 80% and 90%. The reduction in EQE at the longer wavelengths range (i.e., 700–850 nm) is indicative of a short minority carrier diffusion length either from recombination within the CdTe layer or at the back surface. This offers an opportunity for further improvement in efficiency for this cell structure. The blue response is limited by the $Cd_{0.3}Zn_{0.7}S$ window layer whose optical band gap is 3.0 eV with a cutoff below 410 nm. However, due to the very thin nature of the CdZnS layer, not all energy is absorbed by this layer, and a second cutoff is evident

TABLE I
J–V PARAMETERS FOR $8 \times 0.25\,\text{CM}^2$ CELLS MEASURED UNDER AM0 ILLUMINATION

J/V parameter	Best	Mean	SD
$\eta\%$ (± 0.5)	12.4	12.1	0.2
J_{sc} mA $\cdot$ cm^{-2}	28.0	28.0	0.4
V_{oc} mV	788	774	13
FF%	76.8	76.4	1.0

The first column indicates the best cell efficiency, while the second is the mean data from eight cells fabricated over $40 \times 40\,\text{mm}^2$ deposition area.

at 360 nm, corresponding to the absorption by the AZO TCO with an optical band gap of 3.3 eV.

B. Uniformity of Cell Performance

Tracking the best cell performance in each array of cells is useful to highlight trends in *J–V* parameters and to demonstrate the potential of this structure toward space application; however, consideration of multiple cells from a larger area over the cover glass/CdTe structure is also important to investigate cell variance and, therefore, deposition uniformity. Table I displays the mean *J–V* parameters for $8 \times 0.25\,\text{cm}^2$ AM0 measured cells. For completeness, the standard deviation for each set of mean data is also presented. The mean AM0 cell efficiency of 12.1% with a standard deviation 0.2 shows a degree of material uniformity across the $40 \times 40\,\text{mm}^2$ area where the eight cells are fabricated. The average FF of 76.4% indicates good lateral AZO conductivity and a back "Ohmic" contact, as well as minimal contact resistance losses throughout the structure.

C. Adhesion Testing of Cell Structure

The adhesion of the cell structure becomes more important when considering that the final application may require the flexible nature of the cover glass to be exploited. A minimum adhesive strength has been determined via a quantitative pull test. In the first instance, a simple Scotch Tape Test was first used demonstrating that no delamination of the CdTe cell material from the cover glass occurs. The results of the pull test, which is more stringent than the Scotch Tape Test, are shown in Fig. 4, where load (N) versus extension (mm) is annotated with the failure load for each test point. When tested at five separate positions, a minimum adhesive strength of 15.6 MPa (load/adhesion area) was measured. In each case, XPS analysis of the failed surfaces on both the dolly and glass substrate showed that a cohesive failure had occurred within the Loctite Super Glue rather than at the adhesive cell structure interface. Although absolute adhesive strength was not possible to determine, due to the failure within the cyanoacrylate Superglue, the PV layers survived loads of up to 764 N equivalent to an adhesive strength of 38 MPa. These minimum adhesion strengths compare well to similar pull tests performed on other PV materials such as AZO deposited on polyethylene terephthalate flexible substrate by RF reactive magnetron sputtering. This structure showed an adhesion strength of 12.7 MPa, increasing to

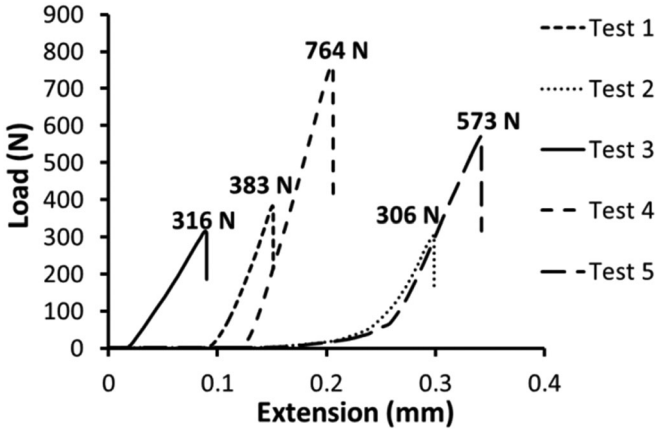

Fig. 4. Load (N) versus extension (mm) annotated with the failure load for each test point on the CdTe back surface.

TABLE II
J–V PARAMETERS FOR $8 \times 0.25\,\text{CM}^2$ CELLS FABRICATED OVER $40 \times 40\,\text{MM}^2$ DEPOSITION AREA AND MEASURED UNDER AM1.5 ILLUMINATION

J/V parameter	Before TST	Post TST	21 days post TST
$\eta\%$ (± 0.5)	14.8	14.8	14.9
J_{sc} mA $\cdot$ cm^{-2}	25.2	25.5	25.9
V_{oc} mV	788	788	788
FF%	74.6	73.7	73.1

The first column shows the average cell parameters. The second column the average cell parameters 3 h after the TST, while the third column the average cell parameters 21 days after the TST.

23.6 MPa when employing a 15-nm aluminum buffer layer [27]. An ITO coating reported in [28] and again deposited by magnetron sputtering yielded an adhesion strength as high as 17.9 MPa when depositing directly onto a glass substrate.

D. Thermal Shock Testing

The QST cover glass used for this research is optimized to match the coefficient of thermal expansion (CTE) of gallium-arsenide-based space solar cells with a CTE of $6.0 \pm 0.75 \times 10^{-6}$ °C^{-1}. CdTe has a CTE of between 4.96×10^{-6} and 5.7×10^{-6} °C^{-1} for temperatures between 20 °C and 420 °C [29]. This close CTE match will minimize strain under the severe thermal gradients to which space PV cells are exposed. To investigate this failure mode, a TST of the completed device structure was conducted. The device structure was subject to 20 cycles of thermal shock, as described in Section II-E. Following the TST cycling, the device was visually unchanged, and the Scotch Tape Test did not result in delamination.

For the $8 \times 0.25\,\text{cm}^2$ solar cells located again over a $40 \times 40\,\text{mm}^2$ area, the AM1.5 *J–V* parameters were measured before, after, and 21 days after the TST. The data presented in Table II show no significant changes within experimental error.

These TST test parameters are considered to be severe and indeed are very similar to those used by Dutch Space B.V., which resulted in delamination of the CIGS [23]. Therefore, these initial results appear promising, and future work will look

further at the TST, as well as the effect of thermal cycling over a narrower range of temperatures, but with a controlled ramp rate and under vacuum.

IV. Conclusion

This paper has demonstrated the feasibility of a thin-film CdTe PV structure deposited directly onto the industry standard space cover glass. A thin-film CdTe solar cell on cover glass technology could compete with higher efficiency but heavier triple-junction space solar cells in terms of higher specific power. The calibrated AM0 measurement yielded a best conversion efficiency of 12.4%, which equates to a cell-specific power of 0.57 kW/kg. The mean cell performance over a device deposition area of $40 \times 40\,\text{mm}^2$ of 12.1% with standard deviation 0.2 shows good uniformity of the device material. In addition to PV performance, the durability of this type of structure has been considered. The CdTe cell structure is well adhered to the cover glass with applied pull test tensile stresses of up to 38 MPa, all failing within the adhesive layer. There was no sign of delamination of the cell structure from the cover glass substrate or within the PV solar cell multilayer structure. Further indication of the suitability of this cell structure for space applications was its resistance to extreme thermal shock of 20 cycles of $+80$ to $-196\ ^\circ\text{C}$ with no delamination evident visually before or after a Scotch Tape Test and no significant change in the cells performance. Further testing is required to fully establish performance under space qualified conditions. Contemporary reports on CdTe PV demonstrate that there is a realistic scope for further increase in AM0 cell efficiency toward 20% by optimization of the semiconductor layers. Monolithic integration needs to be demonstrated, and a cost analysis provided to enable direct comparison of this technology to the next generation of high-efficiency multijunction solar cells for large-scale space PV solar energy applications.

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