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IAC-22-C3.3.8 Six years of spaceflight results from the AlSat-1N Thin-Film Solar Cell (TFSC) experiment

Craig Underwood [a,*], Dan Lamb [b], Stuart Irvine [b], Simran Mardhani [a], Abdelmadjid Lassakeur [c]

[a] Surrey Space Centre, BA Building, University of Surrey, Guildford, Surrey, GU2 7XH, UK
[b] Centre for Solar Energy Research, Swansea University, OpTIC Centre, Ffordd William Morgan, St. Asaph Business Park, LL17 0JD, UK
[c] Satellite Development Center, Algerian Space Agency, BP 4065, Ibn Rochd USTO, 31130, Oran, Algeria

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ABSTRACT

The increasing power demands of spacecraft payloads and the realistic prospect of space based solar power (SBSP) stations as a means of providing zero carbon electricity in the 2030s, means that there is an emerging requirement for large area, yet lightweight, solar photovoltaic (PV) arrays that will provide far greater power (kW_{peak}) than is currently available. To be practical, such arrays will need to use solar cells which have a much higher specific power (i.e., power per unit mass) and a much lower cost per watt than current space-rated solar PV technologies. To this end, the Centre for Solar Energy Research (CSER) at Swansea University have been working on a new solar cell technology, based on thin-film cadmium telluride (CdTe), deposited directly onto ultra-thin space qualified cover glass material. This offers a potentially high specific power and when adopting the conventional CdTe manufacturing process, a low-cost technology. The ultra-thin glass can produce a solar cell which is sufficiently flexible to allow "roll-out" deployment strategies. Four prototype cells were flown as part of the Thin-Film Solar Cell (TFSC) experimental payload, developed by CSER and the Surrey Space Centre (SSC), on the joint Algerian Space Agency (ASAL) – UK Space Agency AlSAT-1N Technology Demonstration CubeSat, launched into a 661 km × 700 km, 98.20° Sun Synchronous orbit, on September 26, 2016. The experiment has provided the first in-orbit current/voltage (I/V) measurements of this novel technology, and more than five years of flight results have now yielded new insights into its longer-term performance and inherent radiation hardness, which makes them particularly attractive for maintaining high end-of-life (EOL) performance for long duration space missions. The results help to strengthen the argument for further development of this technology for space application. The data, collected over ~30,000 orbits, show no signs of cell delamination (a potential risk for such technologies), no deterioration in short circuit current or in series resistance. However, all four cell's fill factors were observed to decrease over the duration of the mission, caused primarily by a decrease in their shunt resistance. This has been attributed to the diffusion of gold atoms from the back electrical contacts. We conclude therefore that further development of this technology should utilize more stable back contacting methodologies more commonly employed for terrestrial CdTe modules. However, this flight has proven the basic soundness of the technology for use in space.

1. Introduction

The ever increasing electrical power demands of large space systems (>50 kW_{peak}) and the prospect of deploying massive space based solar power (SBSP) systems (potentially in the few GW range) [1] in the next decade to provide "zero-carbon" baseload electrical power, mean that there is a pressing need to develop large area solar photovoltaic (PV) arrays that will provide far greater power (kW_{peak}) than is available currently for use in space.

To be practical, and cost-effective, such arrays will need to employ solar cells which provide much higher specific powers (i.e., power per unit mass – $W \cdot kg^{-1}$), at much lower cost per watt, than those based on current space-rated solar photovoltaic (PV) technologies. The new cell technologies would also need to be able to withstand the rigours of the space environment, including the extremes of temperature and the high levels of ionising radiation typically encountered there. Indeed, it would be advantageous if such cells were *more* robust against the deleterious

* Corresponding author.
E-mail addresses: c.underwood@surrey.ac.uk (C. Underwood), d.a.lamb@swansea.ac.uk (D. Lamb), S.J.C.Irvine@swansea.ac.uk (S. Irvine), simran.mardhani@gmail.com (S. Mardhani), alassakeur@cds.asal.dz (A. Lassakeur).

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Nomenclature

FF	Fill Factor
I_{sc}	Short-Circuit Current (A)
I–V	Current *vs.* Voltage
J_{sc}	Short-Circuit Current Density (A·cm^{-2})
J-V	Current Density *vs.* Voltage
P_{mp}	Maximum Power Point Power (mW)
R_s	Series Resistance (Ω·cm^2)
R_{sh}	Shunt Resistance (Ω·cm^2)
V_{oc}	Open Circuit Voltage (mV)
η	Efficiency

Acronyms/Abbreviations

ADC	Analogue-to-Digital Converter
ADCS	Attitude Determination and Control
AM0	Air Mass Zero (Space Vacuum)
ASAL	Agence Spatiale Algerienne
AZO	Aluminium doped Zinc Oxide
CAN	Controller-Area-Network
CSER	Centre for Solar Energy Research
EM	Engineering Model
EOL	End of Life
EPSRC	Engineering and Physical Science Research Council (UK)
EQE	External Quantum Efficiency
FM	Flight Model
HRT	High Resistive Transparent
ISRO	Indian Space Research Organisation
LEO	Low-Earth Orbit
MOCVD	Metal Organic Chemical Vapour Deposition
OBC	On-Board Computer
PCB	Printed circuit Board
PSLV	Polar Satellite Launch Vehicle
PV	Photo-Voltaic
QST	Qioptiq Space Technology
SBSP	Space Based Solar Power
SSC	Surrey Space Centre
TCE	Transparent Conducting Electrode
TCO	Transparent Conducting Oxide
TFSC	Thin-Film Solar Cell
UKSA	United Kingdom Space Agency

effects of space radiation than those based on silicon or current *III-V* semiconductor compounds, in order that they could support greatly extended mission lifetimes, as it will be very expensive to replace such large space infrastructure once it is deployed.

To this end, the Centre for Solar Energy Research (CSER) at Swansea University, in collaboration with the University of Surrey, has developed a space qualified thin-film cadmium telluride (CdTe) solar PV cell technology that has the potential to meet all these requirements.

Whilst this work was in progress, an opportunity to fly test cells on the joint Algerian Space Agency (ASAL) – UK Space Agency (UKSA) AlSat-1N CubeSat arose, and a successful bid was made to fly a payload capable of characterising the cells in orbit, via an automatic Current-Voltage (*I–V*) measurement circuit. The resulting Thin Film Solar Cell (TFSC) payload, comprising four test cells, was integrated onto the AlSat-1N 3U CubeSat at Surrey, and launched from India into a 661 km × 700 km, 98.20° inclination Sun Synchronous orbit on September 26, 2016.

Six years' worth of in-orbit solar cell performance data has now been obtained, and as of September 2022, AlSAT-1N and the TFSC payload continue to operate.

In this paper, we present our findings on the long-term performance of the cells in orbit.

2. Development & testing of the CdTe space cells

Between 2013 and 2016, such cells were developed and tested under a three-year UK Engineering and Physical Science Research Council (EPSRC) funded project (Grant Ref. EP/K019597/1).

The prototype CSER CdTe solar PV space cells comprised layers of thin-film semiconductor materials deposited directly onto ultra-thin space qualified cerium-doped alumino-silicate cover-glass, developed by Qioptiq Space Technology (QST) Ltd. based in Rhyl, Wales. The cerium doping resists the darkening effect that would otherwise occur when high intensity ionising radiation acts on un-doped glass [2].

CSER used an atmospheric-pressure metal organic chemical vapour deposition (MOCVD) process to deposit the transparent conducting oxide (TCO) and thin-film cadmium telluride (CdTe) layers directly onto this ultra-thin, flexible, glass.

The industry leader then and now, for CdTe manufacturing, is First Solar Inc. who utilize High-Rate Vapour Transport Deposition (HR VTD). It is assumed, by the authors, that any future large-scale adoption of CdTe directly on cover-glass would employ this HR VTD mature manufacturing process with its inherently lower production cost than MOCVD.

The resultant PV cell structure (Fig. 1) follows the superstrate configuration, where an aluminium doped zinc oxide (AZO) front contact and zinc oxide high resistive transparent (HRT) layer is followed by a cadmium zinc sulphide ($Cd_{0.3}Zn_{0.7}S$) *n*-type window layer and a arsenic-doped cadmium telluride (CdTe:As) *p*-type absorber layer, deposited sequentially onto the 100 μm thick QST glass, which is the standard protective layer normally laminated to the front side of space-qualified solar cells.

The cell is illuminated from the cover-glass side.

For the first batches of prototype cells, the oxygen plasma cleaned, chemically toughened glass was coated with 800 nm of AZO and 90 nm of zinc oxide (ZnO), followed by 50 nm of cadmium sulphide (CdS) and 200 nm of cadmium zinc sulphide ($Cd_{0.3}Zn_{0.7}S$) to form the window layer, and finally 2250 nm of arsenic-doped CdTe and 1000 nm of cadmium chloride ($CdCl_2$) to form the absorber layer. An annealing step was then used to promote the diffusion of chlorine into the CdTe.

Later, it was found that the blue response and the efficiency of the cells could be improved by depositing a thinner window layer of just 25 nm CdS and 125 nm CdZnS, and this was used for the later batches of cells.

The flexibility of the 100 μm thick cells is well illustrated in Fig. 2.

References [3–6] give more details on the fabrication process, and also on the mechanical testing undertaken, the results of which are summarized here.

Laboratory measurements of the prototype (i.e., non-flight) cells demonstrated that this unique CdTe-on-cover-glass approach was able to achieve an air mass zero (AM0) conversion efficiency of 12.4%,

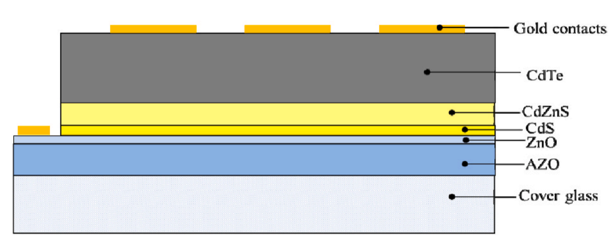

Fig. 1. Thin-film CdTe cell device structure.

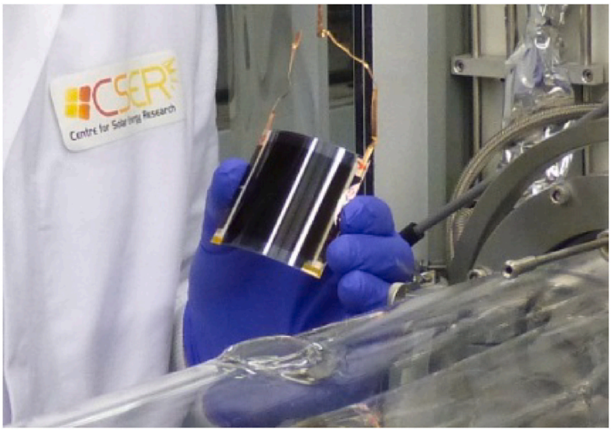

Fig. 2. Demonstration of the flexibility of the thin-film CdTe cell structure.

yielding a cell level specific power of 600 W kg^{-1} [3]. The AM1.5 world record cell efficiency for arsenic doped CdTe is held by First Solar Inc. at 22.3% [7]. There is no technological barrier, with the right market incentive, for First Solar's deposition techniques and device structure to be applied directly to cover-glass. The authors found, in previous work, that there is a relative 15% decrease in maximum efficiency when considering the change in spectral distribution between AM0 and AM1.5 illumination [3]. Applying this factor to First Solar's AM1.5, 22.3% could then deliver a potential AM0 cell efficiency of 19.2%. With an analogous device stack and 100 μm cover glass, the mass would be comparable with the work presented here, making a cell specific power of 900 W·kg^{-1} possible.

The prototype cell properties are summarized in Table 1 for a batch of 8 test cells, singling out the best cell and presenting the means and standard deviations for the properties of the entire batch of 8.

Fig. 3 shows the test structure that was used for measuring the *J-V* characteristics of the 8 prototype cells under a laboratory AM0 solar illumination source.

Fig. 4 shows the best prototype cell's current-density versus voltage (*J-V*) curve under AM0 solar illumination, and Fig. 5 shows the external quantum efficiency (EQE) of the cell.

For spaceflight applications, the cells could be laid down on a surface to form a conventional solar panel, however, for a "rolled out" deployed array, the cells would need an additional protective layer for the exposed gold back contacts and CdTe semiconductor material on the opposite side to the cover glass superstrate. This could be a second ultra-thin glass layer to form a glass-semiconductor-glass sandwich, or it could be a polymer layer.

Although 100 μm QST cover glass was chosen for the developmental prototype cells, thinner glass is potentially available. We could, for example, envisage using two 50 μm glass layers – one as the superstrate (as above), and one as a substrate to cover the back contacts, thus forming a completely encapsulated cell.

This would still have the same degree of flexibility (10 cm bend radius) as the prototype cells. Alternatively, the cells could be mounted onto a flexible Kapton® film substrate to form such a deployable "roll-out" array.

Table 1
J-V parameters for 8 × 0.25 cm^2 prototype (non-flight) cells measured under AM0 illumination.

J/V parameter	Best Cell	Mean	Std. Dev.
η % (±0.5)	12.4	12.1	0.2
J_{sc} mA·cm^{-2}	28.0	28.0	0.4
V_{oc} mV	788	774	13
FF[a] %	76.8	76.4	1.0
R_s Ω·cm^2	2.3	2.6	0.2
R_{sh} Ω·cm^2	2050	1428	400

[a] Fill Factor.

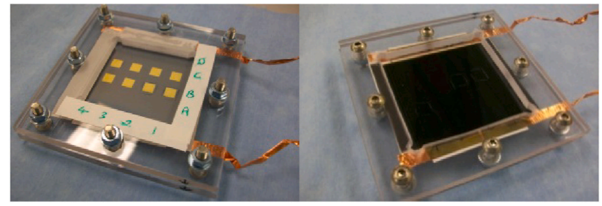

Fig. 3. CdTe cell test structure: 8 × 0.25 cm^2 cells: left hand image shows the gold contacts; right hand image shows the glass superstrate illuminated side.

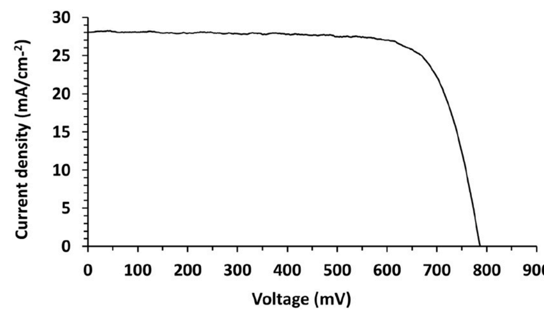

Fig. 4. *Best prototype (non-flight) cell* J-V *curve under AM0 illumination (12.4% efficiency).*

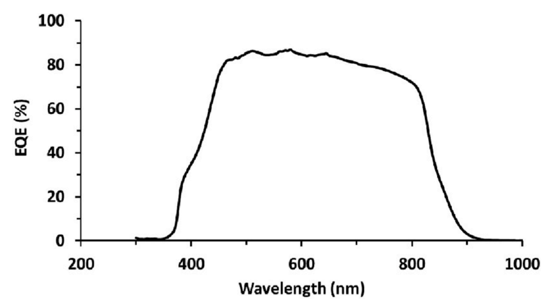

Fig. 5. Best prototype (non-flight) cell external quantum efficiency (EQE) curve under AM0 illumination (12.4% efficiency).

One of the key concerns for thin-film CdTe solar cell technology is its mechanical robustness. The adhesion between the glass, encapsulant, active layers, and back layers can be compromised for many reasons, e.g., moisture ingress or lack of adequate cleaning of the glass, and a particular concern is that the TCO layer may delaminate from an adjacent glass layer [8].

This potential failure mode has tended to suppress interest in the development of thin-film CdTe solar cells for space application. Thus, in this development work, careful attention was paid to the mechanical robustness of the technology.

We therefore carried out an extensive programme of mechanical and thermal stress testing, including bond adhesion pull-testing and minimum roll-radius testing.

It was found that the cells could withstand between 15 and 39 MPa pull forces and, with the 100 μm QST glass, a bend radius of 10 cm could be sustained without damage. Reference [6] gives details of the electrical properties before and after the tests.

The AZO on cover glass structure was found to be robust and did not delaminate under the standard "Scotch Tape Test" before or after extreme thermal shock testing of ten cycles of +80 °C to −196 °C (liquid nitrogen plunge). No change in sheet resistance was found from before to after these tests.

Thermal cycle testing was conducted in air using a Vötsch VCL 7010 chamber, with test structures cycled between +140 °C and −70 °C. The ramp rate was set at 3 °C/min. The device test structures passed all tests.

Similar cycling tests were applied to other test cells made in preparation for spaceflight on the AlSat-1N mission. These were found to survive temperature cycling between +85 °C and −40 °C without any significant change in performance.

All cells showed a decrease in series resistance with temperature cycling (~15 Ωcm^2 to ~10 Ωcm^2). It should be noted, however, that these were early production experimental cells.

Another concern for space solar PV cells is the effects of exposure to intense ionising radiation.

In proton beam irradiation tests carried out at the University of Surrey, the CdTe thin-film cells were found to exhibit excellent radiation hardness characteristics. The cells showed little degradation up to a proton fluence of 1×10^{13} cm^{-2} for 0.5 MeV protons [9]. The energy was selected so as to cause the protons to deposit the maximum energy (and stop) in the region of the solar cell junction, and thus produce the greatest effect.

Subsequently, an opportunity arose to irradiate test cells with electrons, using a facility at TUDelft in the Netherlands. The cells were subject to a mean fluence of 1×10^{15} cm^{-2} of 1 MeV electrons, and it was found that the cells' efficiencies were only reduced by 4% (i.e., dropping from ~12% to ~11.5%).

3. Development of the AlSat-1N Thin-Film Solar Cell (TFSC) experiment

Given the potential benefits of CdTe thin-film technology for use in space, gaining space flight experience of them was a priority, and so we were extremely grateful to both the Algerian and the UK space agencies for accepting our proposal for a Thin-Film Solar Cell (TFSC) experiment to fly on the AlSat-1N mission. It had to be a very rapid production, with just 7 months allocated from project kick-off to delivery (March 16th to September 14th' 2015).

The work of preparing the TFSC payload was split between CSER, University of Swansea, based in St. Asaph (Wales), and the Surrey Space Centre (SSC), University of Surrey, based in Guildford (England). CSER was responsible for manufacturing the test cells, and SSC was responsible for developing the payload flight electronics and measurement system.

CSER manufactured a new batch of test cell structures, with each test structure comprising four 1 cm^2 area thin-film CdTe cells. One of these 4-cell structures was selected for flight, and the others were used as flight spares/engineering models or were retained for future ground characterization testing.

The CdTe device structure was deposited directly onto a 60 mm × 60 mm × 100 μm QST cover-glass, so that the glass acted as the protective cover-glass superstrate in flight.

Metal organic chemical vapour deposition (MOCVD) was used to deposit all the semi-conductor layers onto the cover glass as described above. Aluminium-doped zinc oxide (AZO) was the first layer deposited, and this formed an extremely well adhered common transparent conducting electrode (TCE) layer.

This was followed by a very thin, high resistance, layer of zinc oxide (ZnO) to reduce micro-shunts. Both these initial layers were deposited at atmospheric pressure, using a nitrogen carrier gas.

The glass/TCE structure was then transferred to another atmospheric pressure MOCVD reactor, which used hydrogen carrier gas to deposit the *n*-type cadmium-zinc-sulfide (CdZnS) layer and the *p*-type arsenic-doped cadmium-telluride (CdTe) layer. Finally, a chlorine heat treatment was used to passivate grain boundaries [4]. The surface was then rinsed with deionized water and the structure annealed in air for 90 min at 170 °C before revealing the TCE bus bars by mechanical scraping.

Gold contacts of 200 nm thickness were evaporated onto both the bus bars and the CdTe back surface defining four separate 1 cm^2 rectangular cells, as shown in Fig. 6. These four cells share a common front TCE.

External electrical contacting was then made possible through the use of a second piece of cover glass with evaporated gold tracks, which were offset by 5 mm and secured using a space qualified double-sided adhesive polyimide (Kapton®) film to make a glass-semiconductor-glass sandwich (Fig. 7).

The polyimide had 5 mm diameter holes punched over each of the contact points, and these were filled with a conductive silver epoxy to make contact with the gold tracks (Fig. 8).

Indium tin (InSn) metallic pads were then soldered onto the exposed ends of the backing cover glass gold strips, before embedding gold wire into them, to facilitate electrical contact with the FR4 glass-epoxy External Board, produced by SSC (Fig. 9).

Unfortunately, the silver-loaded epoxy introduced a relatively large increase in series resistance from ~2 Ω cm^2 for the cells themselves, to a total of ~8 Ω cm^2, however, in the short time frame given to prepare the payload, it was decided that this approach offered the most durable electrical connection between the cells and the TFSC External Board circuit. Further details can be found in Ref. [10].

The TFSC External Board also housed an LM35 temperature sensor, configured to measure in the range of −56 °C to +148 °C, mounted centrally in intimate contact with the back of the cells. This sensor allowed the temperature of the cells to be measured each time they were surveyed.

The External Board was mounted at the base of one of the CubeSat's solar panels (Fig. 10) and was connected to the TFSC Internal Board via a wire harness and printed circuit board (PCB) tracks on the rear of the solar panel.

The Internal Board (Fig. 11) houses the majority of the TFSC's payload electronics which are designed to measure the current *vs.* voltage (*I–V*) curves and temperature response of the 4 experimental thin-film CdTe solar cells (labelled Cells 0 to 3) when illuminated by the Sun on orbit.

It comprises an MSP430 micro-controller with a controller area network (CAN) interface and integrated 12-bit analogue-to-digital converters (ADCs), which digitize the temperature, current and voltage signals from the four test solar cells.

The cells are each controlled by an 8-bit digital programmable precision current sink circuit, which is switched to each cell in turn.

The programmed current demand is swept from zero (i.e., open circuit conditions), to a maximum, beyond the short circuit current capability of the cells, so that the voltage across the cell moves from V_{oc} (open circuit voltage) to zero at I_{sc} (short circuit current) – thus generating the *I–V* curve. The cells are protected against reverse bias by a diode strap.

The current, voltage and temperature signals are measured via precision instrumentation amplifiers. The maximum V_{oc} the circuit can measure is set to 1.024V, as from ground tests we expected V_{oc} to be around 0.7–0.8V, and the maximum current sink available is set to 51.2 mA, as we did not expect more than ~30 mA from the 1 cm^2 area cells under full (AM0) solar illumination.

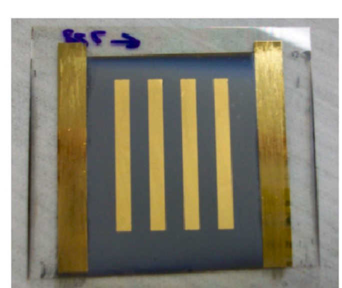

Fig. 6. AlSat-1N TFSC payload 4 cell test structure (back gold contacts for 4 × 1cm2 rectangular cells).

Fig. 7. *AlSat-1N TFSC payload 4 cell test structure contact plate (gold on* 100 μm *thick QST glass).*

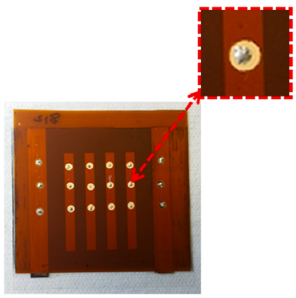

Fig. 8. AlSat-1N TFSC payload 4 cell test structure contact points (Silver-epoxy filled, with InSn pads).

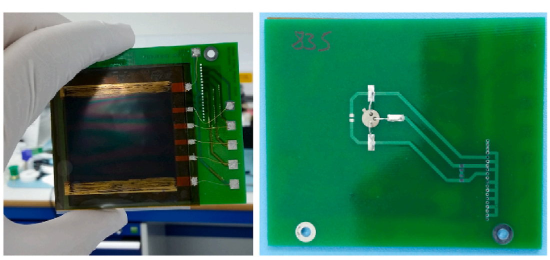

Fig. 9. *AlSat-1N TFSC payload External Board: (left) front surface showing the contacts to the four 1 cm2 rectangular cells and two gold bus bars through the 100 μm thick QST glass superstrate; (right) back surface, showing the LM35 temperature sensor.*

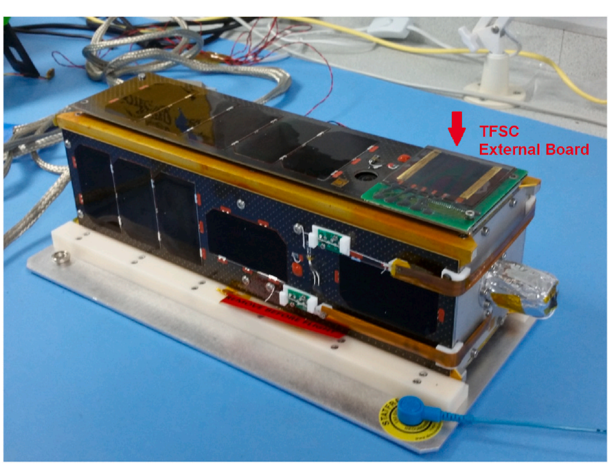

Fig. 10. AlSat-1N 3U (30 cm × 10 cm × 10 cm) CubeSat flight model (FM) showing the mounting of the TFSC payload External Board.

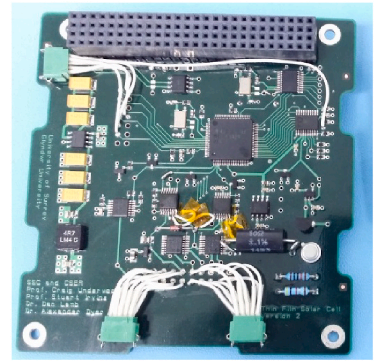

Fig. 11. *AlSat-1N TFSC payload internal board (*96 mm × 90 mm, *CubeSat PC104 standard).*

All measurements are made to 12-bit precision (i.e., 0.5 mV for cell voltage and 25 μA for cell current) and the system accuracy was established by cross-checking the readings with precision multi-meters and digital oscilloscope measurements and was found to be better than 0.1%. Temperatures are measured to 0.1 °C precision via the LM35 sensor.

Once triggered, the system measures the *I–V* curve of each cell in turn – i.e., 256 measurements of current and 256 measurements of voltage per cell, along with 4 temperature readings, one taken at the start of each cell survey – 2052 readings in total.

The programmed currents are independently measured over a precision 10-Ω resistor. This allows any variation in measurement accuracy due to degradation of components to be detected. Fig. 12 shows a schematic of the cell measurement circuit.

The entire survey of 4 cells completes in just over 1 s – i.e., a deliberate 1 ms delay was programmed between each of the 4 × 256 *I–V* measurement pairs, as this was found allow enough time for the amplifiers and driving circuits to settle between individual measurements. If necessary, this time delay could be re-programmed in flight by telecommand.

The power consumption of the TFSC payload was measured to be ~1–1.5W during operation.

The measurement data are stored locally, and then are transferred by request as telemetry over the CAN bus to the spacecraft's on-board computer (OBC) and the payload is switched off to save power. The OBC downloads the TFSC data later, when the spacecraft is within range

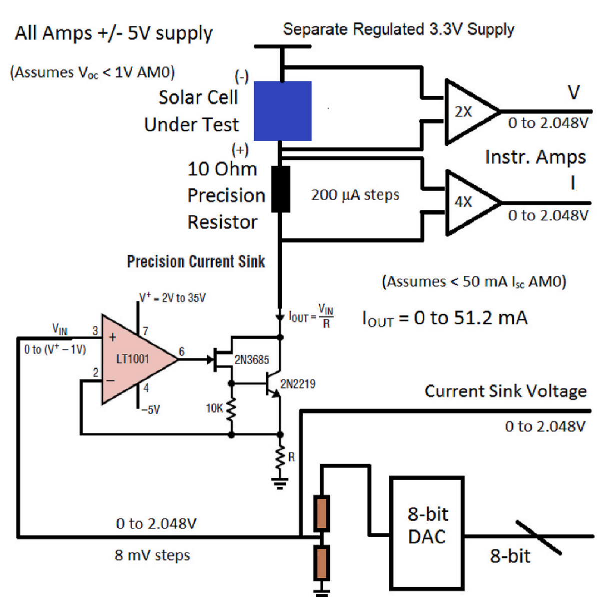

Fig. 12. *AlSat-1N TFSC payload precision* I–V *curve measurement schematic.*

of the ASAL mission operations control centre ground-station in Oran, Algeria.

We did consider building in a collimated photodiode ("Sun Overhead") trigger sensor into the External Board, so that the survey would be made only when the Sun was directly "overhead" the cells – i.e., with the light at vertical incidence or "normal" illumination. However, given the nature of the Sun-synchronous orbit and some uncertainty about the precision of the spacecraft's attitude determination and control system (ADCS), we opted instead to just take surveys by pre-programmed command and use the satellite's own sun sensor readings to determine the orientation of the TFSC External Board with respect to the Sun at the time each survey was taken.

We recognised that, in some cases, this might mean that surveys would be made when the solar incidence angle was very oblique, or indeed when the cells were pointing away from the Sun, however, given that we could request multiple surveys to be made, we knew that there would be at least some which would occur under good illumination and that this would be sufficient for determination of the cells' performance.

This turned out to be a good decision, as the operational attitude of the spacecraft meant that in practice, the External Board was never *exactly* under normal solar illumination.

Before flight, the performance of the flight cells was evaluated under AM0 and AM1.5 lighting conditions at CSER. Table 2 shows the key parameters of the 4 Cells under AM0 illumination post encapsulation as measured on November 19, 2015.

However, once delivered to Surrey (SSC), we noted an apparent and unexpected shift in V_{oc} for all the cells – with V_{oc} now measured to be around 850 mV at room temperature, when illuminated by a 25W quartz-halogen lamp (Fig. 13). Due to time and resource constraints, we were not able to investigate this phenomenon any further at the time. Thus, this change remains unexplained. The electrical measurement accuracy of both the engineering model (EM) and flight model (FM) TFSC were carefully checked and calibrated during production, and so we were confident that we were measuring a real effect. To make sure, we later checked the measurement accuracy of the EM TFSC payload against the experimental set-up at CSER and found them to be in complete agreement under controlled solar spectrum illumination. We saw further increases in V_{oc} in orbit, however, these changes were consistent with our expectations based on known light soaking and ambient temperature effects within the CdTe materials system [11].

AlSat-1N was shipped out from SSC to the Indian launch site, arriving there on September 6, 2016. The TFSC was checked out (in 42 °C heat) and showed consistent *I–V* curves for all four cells, with V_{oc} readings between 850 and 870 mV. The spacecraft was launched on an Indian Space Research Organisation (ISRO) Polar Satellite Launch Vehicle (PSLV) on September 26, 2016 and the first in-orbit operations of the TFSC payload occurred on the 8th and October 9, 2016 during spacecraft commissioning.

4. AlSat-1N TFSC flight results and discussion

Following spacecraft commissioning, on January 5, 2017, the first survey was made with the cells well illuminated by the Sun, and all four cells produced excellent *I–V* curves (see Fig. 13). The behaviour of all four cells was consistent, with measured open-circuit voltages (V_{oc}) between 938 mV and 945 mV and with short circuit currents (I_{sc}) around 30 mA. The temperature of the cells was 10 °C.

The power at the maximum power point (P_{mp}) was measured as ~16 mW at 124.2 mW cm^{-2} solar flux, giving an efficiency of 12.8% at a fill factor of 63.9%.

Table 2
Cells pre-flight characterisation at CSER.

Cell number	0	1	2	3
V_{oc} (mV)	761	760	756	745
I_{sc} (mA)	27.6	28.2	27.8	27.4
Cell Temp (°C)	28	28	28	28

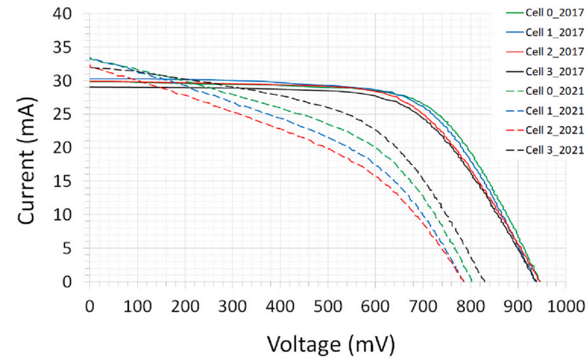

Fig. 13. AlSat-1N TFSC payload in-orbit *I–V* results for January 5, 2017 compared with those from the February 8, 2021.

This is to be contrasted with the survey taken much later, on February 8, 2021, where under 112 mW cm^{-2} solar flux, at a temperature of 19 °C, the mean V_{oc} had dropped to 801 mV (closer to their value at manufacture, prior to delivery to SSC) and the mean I_{sc} had *increased* to 33 mA.

However, the shape of the curve was much poorer, with a fill factor of just 44%, giving an overall efficiency of 8.4%. These effects we primarily ascribe to a large fall in shunt resistance. The reasons for this are discussed below.

The TFSC was designed for a nominal mission lifetime of 1 year, and we hoped that we might perhaps get 18 months to 2 years' worth of flight data before the spacecraft battery began to fail – this being the usual life-limiting factor of a small CubeSat.

It is, therefore, a tribute to the Surrey and Algerian team who built the spacecraft, and to the ASAL mission controllers who have monitored, operated, and looked after it in orbit, that AlSat-1N is *still* operational and producing useful data after more than *six years* in orbit.

Over the last six years, the TFSC has been commanded to take around 150 surveys over ~30,000 orbits under varying solar illumination levels. The LM35 temperature sensor has measured TFSC cell temperatures varying from −3.8 °C to +51 °C during this time. Note: not all surveys are made under good solar illumination as the cells may sometimes be pointing away from the Sun.

As noted previously, TFSC surveys are commanded according to a schedule uploaded into the spacecraft's OBC as part of the mission operation plan, rather than being triggered by a "Sun Overhead" sensor.

We took the decision not to put a Sun Overhead Trigger sensor on the External Board due to the concern that the attitude of the spacecraft might be such that the Sun would never come to be *exactly* normal to the External Board, and thus the TFSC might never be triggered.

We instead decided to obtain what cell measurement data we could and derive the solar incidence angle retrospectively from the spacecraft's attitude determination system – principally the analogue sun-sensor mounted on the same facet as the test cells. This provides our solar incidence angle reference.

In order to compute the incident solar flux on the TFSC cells, the corresponding solar irradiance values have been obtained from NASA's SORCE (Solar Radiation and Climate Experiment) mission data [12].

Due to Earth's varying distance from the Sun, the total solar irradiance fluctuates by about 6.9% throughout a year (from about 140 mW cm^{-2} in early January to about 132 mW cm^{-2} in early July). The sun sensor on-board AlSat-1N is a simple planar photodiode which gives a 10-bit binary output, which would correspond to readings ranging from 0 (for zero illumination) to 1023 (for full illumination) without calibration.

By making multiple observations of raw sun sensor readings over time, we determined that a calibration scale factor of 0.8 should be applied to the raw sun-sensor output (i.e., a raw value of 818 = 140 mW cm^{-2}).

Applying these principles, it was then possible to calculate the calibrated solar flux for any one data acquisition.

To extract the maximum science value from the results, the survey data were carefully filtered to ensure that they represented surveys taken when the cells were well illuminated by the Sun, with no interference from Earth albedo effects or Earth's own thermal infra-red emissions. We found that 66% of the surveys had to be removed from the analysis.

Fig. 14 shows a plot of short circuit current (I_{sc}) for all four cells plotted against the solar flux for multiple surveys.

As expected, the plot shows a linear relationship, giving confidence that the calibration procedure has been effective.

Fig. 15 shows the effect of temperature on open circuit voltage (V_{oc}), again taken from multiple surveys.

The negative slope is again as expected, and the measured value of 0.19% per °C is in line with laboratory measurements of light-soaked cells.

Table 3 shows the derived solar flux incident on the cells and the cell temperatures (at the time of the solar illuminated measurements) for the best illuminated survey in the given month.

As Table 3 and the *I–V* curves plotted in Fig. 13 show, whilst all the cells continue to behave similarly (at least until February 2021), there has been a significant degradation in fill factor (Fig. 16) over the period, resulting in a drop in efficiency (Fig. 17).

Fig. 18 shows the individual cell *I–V* curves for March 2022, and from this it is clear that the cells have degraded further, and now only cell 3 is showing a distinct "knee" in the curve.

Table 4 shows the mean solar cell parameters (V_{oc}, I_{sc} (normalised to 140 mW cm^{-2} incident solar flux) fill-factor (FF), efficiency, series resistance and shunt resistance) for the surveys in Table 3.

A close inspection of the derived shunt and series resistances (Figs. 19 and 20) shows that, although the series resistance has remained more-or-less constant (possibly a small increase), there has been a notable exponential drop in the shunt resistance. This explains the degradation effects observed.

We believe that this drop in shunt resistance is due to the in-diffusion of the gold from the back contact into the CdTe absorber, along the grain boundaries and down to the TCE. Such metal in-diffusion has been observed to cause this type of effect in laboratory tests – especially at the elevated temperatures known to have been experienced by the TFSC cells. A detailed analysis, based on the first 3 years of TFSC flight data is presented in Ref. [13]. The data presented here is an extension of this work.

The TFSC Payload was designed to last for a one-year mission lifetime, and it was not within the remit of the payload build to develop an alternative back contact to the cells. This is something that would need to be addressed for future flights.

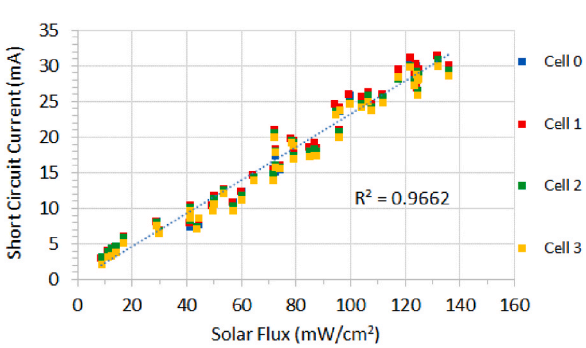

Fig. 14. AlSat-1N TFSC short circuit current (I_{sc}) *vs.* sun sensor/SOURCE derived solar flux.

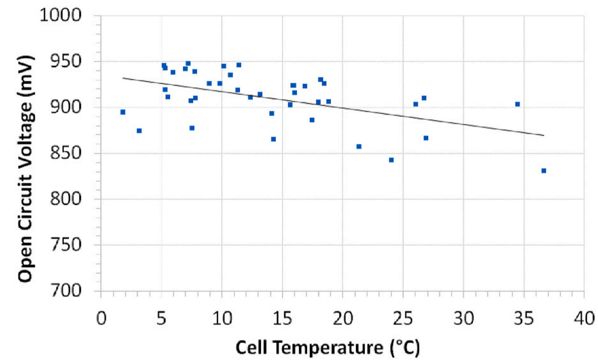

Fig. 15. AlSat-1N TFSC open circuit voltage (V_{oc}) *vs.* measured cell temperature.

Table 3
TFSC survey solar flux and temperature data.

Survey Month/Year	Solar Flux (mW·cm^{-2})	Derived Cell Incident Flux (mW·cm^{-2})	Cell Temp (°C)
Jan-17	140.7	124.3	10.1
Mar-17	137.6	135.9	10.7
Apr-17	135.1	124.9	18.1
May-17	134.0	131.8	18.4
Jun-18	131.7	121.6	17.4
Mar-19	138.4	123.9	1.8
Sep-19	134.9	117.3	21.3
Sep-20	134.6	91.8	11.3
Feb-21	139.8	112.0	19.3
Mar-22	138.4	99.2	3.2

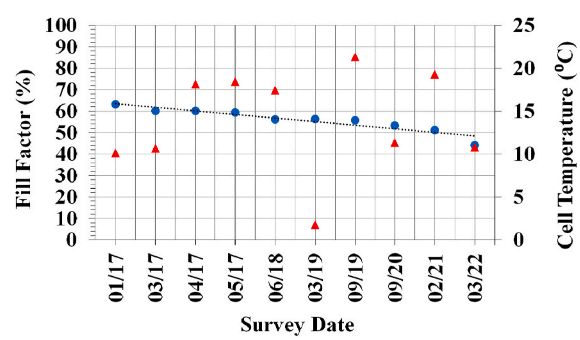

Fig. 16. AlSat-1N TFSC mean fill factor (FF) *vs.* time (2017–2022) and trend line [● = FF; ▲ = Temperature].

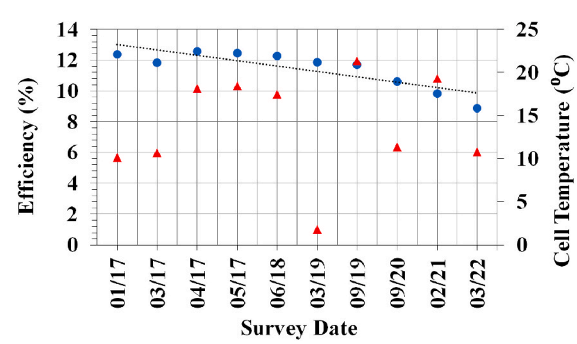

Fig. 17. AlSat-1N TFSC mean efficiency (η) *vs.* time (2017–2022) and trend line [● = η; ▲ = Temperature].

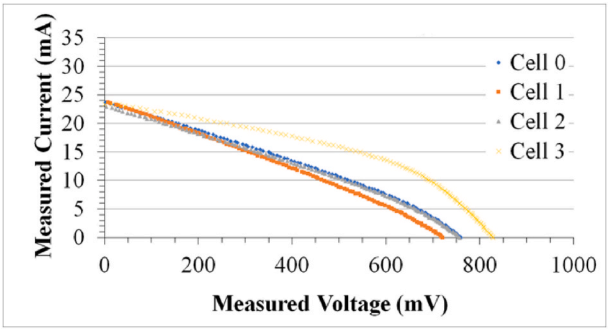

Fig. 18. AlSat-1N TFSC cell I–V curves for March 4th' 2022 (survey id15).

Table 4
TFSC mean cell performance data.

	V_{oc} (mV)	I_{sc}[a] (mA)	FF (%)	Eff. (%)	R_s ($\Omega \cdot cm^2$)	R_{sh} ($\Omega \cdot cm^2$)
Jan-17	942.0	29.6	63.9	12.8	8.6	589.6
Mar-17	932.9	29.9	60.7	12.3	8.6	347.7
Apr-17	924.9	31.1	60.6	13.0	8.7	338.9
May-17	921.5	31.3	59.7	12.9	8.5	322.7
Jun-18	880.5	32.8	55.4	12.2	8.7	156.3
Mar-19	890.4	32.8	52.9	11.3	9.0	119.7
Sep-19	849.2	32.7	51.6	10.8	9.1	105.6
Sep-20	815.8	29.6	45.7	9.1	12.7	93.5
Sep-21	800.5	31.7	44.3	8.4	11.1	66.5
Mar-22	766.5	30.4	32.8	6.1	13.0[b]	63.8[b]

[a] I_{sc} has been normalised to 140 mW cm^{-2} AM0 solar flux.
[b] Cell 3 only – cells 0, 1 and 2 are too degraded to derive these values for cells 0, 1 and 2.

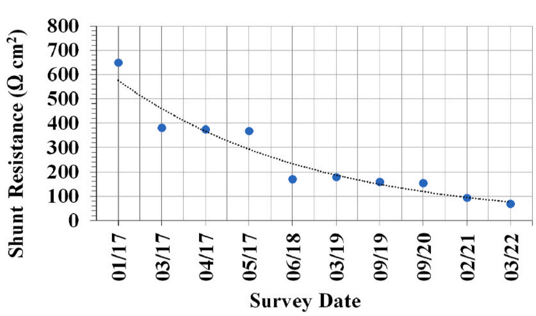

Fig. 19. AlSat-1N TFSC shunt resistance (R_{sh}) *vs.* time (2017–2022) – note near exponential decline.

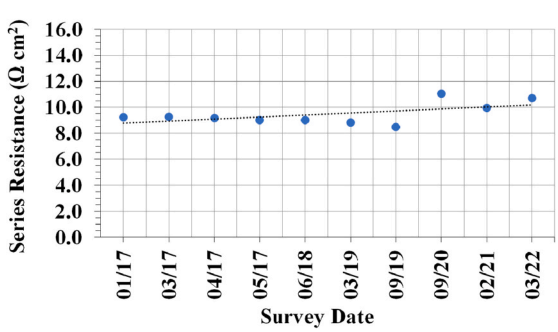

Fig. 20. AlSat-1N TFSC series resistance (R_s) *vs.* time (2017–2021) – possibly a small increase.

5. Conclusions

This paper has presented a CdTe thin-film solar cell technology developed for spaceflight, where the semiconductor materials are deposited directly onto a 100 μm thick cover glass. An extensive campaign of ground measurements showed that the cells are mechanically robust (addressing a major concern for this technology) and highly flexible, leading to the prospect of new deployment strategies for exceptionally large solar PV arrays.

Through proton and electron beam testing, the cells were found to be exceptionally resilient to ionising radiation damage. This means that fewer cells would be needed to mitigate the degradation typically seen between cells' beginning-of-life and end-of-life performance. Also, thinner cover glasses may be used, leading to mass savings.

Currently, cell efficiencies (AM0) of the order of 12–13% are being achieved. Although this is small compared to conventional space cells this work, using MOCVD and with a suitable market, is replicable using the latest CdTe large-scale manufacturing technologies and higher performance device structure.

Four test cells were flown on the joint ASAL/UKSA AlSat-1N technology testbed 3U CubeSat launched in September 2016. These are monitored by the TFSC Payload which gives accurate, detailed *I–V* curves for each of the cells, enabling the effects of solar illumination, temperature, and ionising radiation exposure to be observed. The spacecraft and TFSC payload remain operational as of September 2022.

The TFSC Payload, originally designed for a one year of in-orbit data acquisition, has provided more than six years of *I–V* measurements. The cells remain fully operational and have survived the space environment well, showing no signs of delamination. However, we do see significant degradation (decrease) of the shunt resistance which has been exponential in time. We ascribe this to the diffusion of gold from the back contact into the CdTe layer forming micro-shunts along the grain boundaries. Any future demonstration of the CdTe TFSC technology will require a new back contact architecture to be developed to realise the true potential of these cells for spaceflight.

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.

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