Interim Project Dissemination Report

(including Lessons Learnt)

Tandem Silicon - Durable Silicon Perovskite Tandem Photovoltaics

Lead organization:	University of Sydney
Project Partners:	Australian National University, Macquarie University, University of New South Wales, AGP America S.A
Project commencement date: 18 Sept 2020	**Completion date:** 10 April 2023
Date of report:	7 October 2021
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Executive Summary

This Project aims to improve the durability of perovskites for silicon (Si)-perovskite-tandem photovoltaics (PV) which is critical for this technology to be truly cost effective. Long lifetime is critical to guarantee the same or lower levelized-cost-of-energy to incentivise manufacturers to invest in tandem-cell technology, which may be seeking the additional power generated by Si-perovskite tandem PV with high efficiency.

To improve the durability of Si-perovskite tandem, this project, will

(a) Carry out chemical analyses of perovskite and Si-perovskite test structures and cells by gas chromatography in conjunction with mass spectrometry (GC-MS) to identify degradation products and thereby underlying degradation mechanisms caused by i) moisture; ii) light; and iii) thermal.

(b) Carry out spatial and temporal characterisation of perovskite and Si-perovskite test structures and cells before and after encapsulation by i) luminescence imaging and ii) high-throughput in-situ light intensity dependent and thermal dependent measurements to elucidate degradation pathways

(c) Develop low cost glass-glass bonding encapsulations and electrical feedthroughs that are compatible with Si-perovskite tandem to eliminate degradation.

(d) Explore chemically- or phase-stable perovskite alternatives such as perovskite quantum dots (QD) as light absorbers for the perovskite sub cells in the tandem.

Project Overview

The four work packages will involve the following tasks:

Work-package 1: Gas chromatography – mass spectrometry (GC-MS)

Automated headspace GC-MS analysis will be performed to investigate the moisture, temperature and light induced decomposition of perovskite precursors, un-encapsulated test-structures and perovskite cells, in order to rank the effectiveness of competing packaging schemes and stability of different cell designs.

Work-package 2: Advanced characterisations for evaluating cell stability

The spatial variation and evolution of the luminescence intensity, sub-bandgap absorptivity and optical bandgap will be compared among the fresh and degraded cells that have been subjected to environmental stimuli. The team will explore statistical correlations between optical parameters and degradation behaviours and establish methodologies to predict and improve the performance of solar cells.

Measurement and data analysis protocols for the high-throughput stability testing will be developed.

Data will be used to rapidly identify encapsulation and contacting issues, as well as to pinpoint localised faults or defects in different layers of the cells that may trigger or accelerate degradation or cell failure.

Work-package 3: Hermetic glass-glass-sealing

To develop hermetic polymer-free low-temperature glass-glass bonding technologies as a potential low-cost encapsulation approach for perovskite solar cells via water-glass bonding and anodic bonding. Effect of processing conditions on bond strength, hermeticity and impact on solar cells will be studied.

Work-package 4: single-junction and Si-perovskite QD tandem cell demonstrations for stability evaluation. Work will commence with proven cell structure and proven processes (e.g., the use of tin oxide (SnO_2) for electron-transport-layer (ETL) for the purpose of stability evaluation. Hole transport layer other than spiro-OMeTAD to be explored for better stability and lower parasitic optical absorption.

Project Update

Progress against outcomes

A. Establish measurement protocols for
   (i) GC-MS of perovskites, single junction and tandem solar cell test structures, unencapsulated and encapsulated cells after environmental stresses, **Protocols established for GC-MS sample preparation, light and thermal stress tests, and GC-MS measurement**
   (ii) statistical analyses of current-voltage (I-V) data of perovskite-top-cells and perovskite-QD top-cells during thermal and light stresses; **Current-voltage measurement protocols established and demonstrated. Several small batches of cells have been tested. Larger testing batches are planned for Sept – Dec 2021, COVID-permitting.**
   (iii) optical-bandgap, luminescent-intensity and absorptivity imaging before and after these stresses. **Measurement protocols and data analysis techniques established and demonstrated on individual cells. Larger testing batches are planned for Sept-Dec 2021, COVID permitting.**

B. Increase knowledge of perovskite cell degradation mechanisms by:
   (i) decomposition products and reactions from GC-MS. Decomposition products and reactions from **methyl ammonium (CH_3NH_3)-containing perovskite and formamidinium ($HC(NH_2)_2$)-containing perovskite identified. Measurement and analysis resuming from Oct 2021 will focus on the effect of encapsulant and electron transport layer on the decomposition products and reactions.**

(ii) key drivers for electrical performance drop (e.g., current and/or voltage and/or fill factor) from I-V data analyses; **Preliminary work in 2021 reveals all parameters contribute to electrical performance drop. Batch testing of cells in late 2021 will feed into this outcome and will be used to design targeted investigations into 2022.**

(iii) weak spots in cell design and encapsulations revealed by imaging. **Localised imperfections and defects imaged for un-encapsulated cells. Testing on encapsulated cells will commence in 2022.**

C. Establish research capability and capacity to:

(i) develop cell design and encapsulation strategies for maximising Si-perovskite-tandem durability.

(ii) develop polymer free glass-glass bonding with hermetic electric feedthrough for encapsulating single junction and Si-perovskite tandem cells scalable for large area devices.

(iii) verify phase stability and optical stability of single junction QD and Si-perovskite-QD tandem cells; and

(iv) demonstrate operational perovskite Si-perovskite-QD tandem cell.

Progress:

i)&ii) Encapsulation process and infrastructure needed for Si-perovskite-tandem defined. Preliminary work completed for polymer glass-glass bonding with electric feedthrough for large area Si-perovskite tandem cells. Polymer-free bonding for perovskite films has commenced.

iii)&iv) Phase and optical stability of single junction QD with different compositions examined. Various Si-perovskite-QD tandem cell architectures have been simulated. Development of phase stable QD and operational tandem cells are in progress

Key Highlights

- 13 domestic and international conferences
- 5 relevant journal publications
- At least 12 high profile outreach activities, publicity or public announcements and industry engagement. Highlights include:
  - Interview with Joe O'Brien on live TV - ABC News Mornings,
  - Thomas White's perovskite cell world record announcement,
  - Solar cell lab tour for company Maoeng Group;

  - Anita Ho-Baillie named Clarivate Highly Cited Researcher and Australian Research Council Future Fellow,
  - Anita Ho-Baillie and Martin Bucknall named Australian Museum Eureka Prize finalists
- Number of jobs created = 3.25 FTE for 2 years.
- Research training of at least 1 PhD student.

Engagement with industry partner - AGP Glass

Activities include the following

- Participation in project reporting meetings
- Samples exchange for durability testing with USYD
- Technology transfer for anodic and water glass bonding from USYD to AGP
- Raw materials provided to USYD including glass, encapsulant and edge sealing materials

AGP sees high potentials in 1) the development of advanced characterization techniques to study durability of hybrid organic-inorganic optoelectronic devices, such as perovskite and perovskite tandem photovoltaics, 2) the development of new device structures that could potentially improve durability or performance, and 3) the development of new hermetic encapsulation methods. In particular, the use of GC-MS could be extended to study other devices prone to degradation such as displays, lighting, and sensors, that are also part of AGP's R&D. High throughput stability testing and hyperspectral imaging are also of high value to AGP to characterize, evaluate and select devices/materials and technologies from different suppliers as part of the technology scouting activities. The development of low-cost techniques (including low raw material cost and low capex investment) for hermetic encapsulation are industrially relevant as current commercial techniques are very limited. There is a high potential for licensing and/or commercialization.

Lessons Learnt

Lessons Learnt Report:

Project Name: *Durable Silicon Perovskite Tandem Photovoltaics*

Knowledge Category:	Financial
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

GC-MS measurement is highly resource intensive. Budget on equipment usage in UNSW was underestimated in the project proposal.

Implications for future projects

Increase budget on GC-MS equipment usage for next R&D project

Lessons Learnt

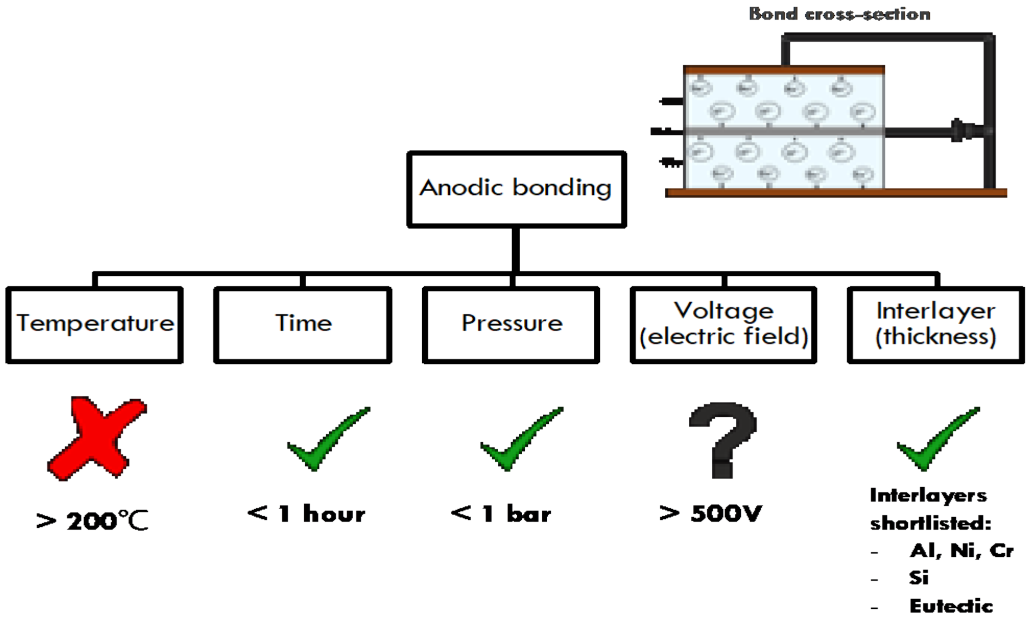
Lessons Learnt Report:

Project Name: *Durable Silicon Perovskite Tandem Photovoltaics*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

After a comprehensive literature review of various low-temperature glass-to-glass bonding techniques, it is found that anodic bonding can be used for bonding glasses with low thermal expansion coefficient within 1-hour, at bonding pressure below 1 bar using interlayers such as Al, Ni, Cr and Si. However, the bonding process requires temperatures > 200°C. Additionally, high direct current voltage needed has been identified as a possible drawback.



Implications for future projects

Due to the bonding temperature required to be above 200°C, anodic bonding is less desirable for encapsulating perovskite solar cells but possibly suitable for forming electrical feedthrough for the purpose of extracting power from the encapsulated solar cells. Focus of future project should be on the examination of the effectiveness of anodic bonding for electrical feedthrough by considering: i) type of interlayer used; ii) cleaning method and iii) bonding strength with respect to voltage, pressure, time and temperature.