Public 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:	31 March 2023
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Content

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Executive Summary

This Project fulfilled its aim 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. This project completed the tasks as set out in the 4 Work Packages as outlined in the Project Overview.

All milestones were achieved with valuable insights provided for developing durable perovskite-silicon. In this project, we have successful elucidate the differences between light and thermal induced degradation mechanisms through chemical analysis, and examination of performance drop using advanced characterizations. We have demonstrated effective and novel encapsulation methods for single and multiple junction perovskite devices. We have introduced alternative tandem structures using perovskite quantum dots (QD). An encapsulated Si-perovskite tandem solar cell passed the IEC61215 Thermal Cycling accelerated test. At the time of reporting, we are one of the 3 groups in the world to be able to do so. The knowledge gained in this project will be leveraged and translated for future projects on other types of multi-junction solar cells such as triple junction tandems and other tandems that involve other types of thin film photovoltaic technologies such as CIGS ($Cu(In,Ga)(S,Se)_2$) and organic-PV.

Project Overview

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

Chemical analyses of perovskite and Si-perovskite test structures and cells by gas chromatography in conjunction with mass spectrometry (GC-MS) have been carried out to identify degradation products and thereby underlying degradation mechanisms caused by i) thermal, ii) light and iii) the combination of thermal and light stress. Stability of devices with different electron transport layers were also compared.

Work-package 2: Advanced characterizations for evaluating cell stability

Spatial and temporal characterisation of perovskite, perovskite quantum dot, and Si-perovskite test structures and cells have been carried out by i) luminescence imaging and ii) high-throughput in-situ light intensity dependent and thermal dependent measurements to elucidate degradation pathways. Statistical analysis of Current-Voltage data was completed to identify the key drivers for performance drop.

Work-package 3: Hermetic glass-glass-sealing

Low-cost glass-glass bonding with electrical feedthrough encapsulations have been developed for single junction perovskite solar cells and Si-perovskite tandem solar cells with negligible efficiency change before and after encapsulation. Our encapsulated Si-perovskite tandem solar cells passed the IEC 61215 passed the Thermal Cycling test.

Work-package 4: single-junction and Si-perovskite QD tandem cell demonstrations for stability evaluation.

We have explored chemically- or phase-stable perovskite quantum dots (QD) as light absorbers for the perovskite sub cells in the tandem. We have demonstrated operational perovskite QD-silicon tandem solar cell and their stabilities were assessed in this project.

Project Outcomes

In this multi-discipline collaborative project, the University of Sydney (USyd), University of New South Wales (UNSW), Australian National University (ANU) and Macquarie University (MQ) have established new and increased existing research capability and capability including measurement protocols for assessing the stability of Si-perovskite solar cells. We have increased our knowledge on perovskite cell degradation mechanisms which was then used to develop new cell designs and new encapsulating strategies for improving durability of Si-perovskite solar cells involving new patent application. Not only did we engage with the researchers in our own field, but our achievements were also disseminated in the wider scientific community. We also engaged with other stakeholders such as high school students, industry partners (including AGP Glass) and our achievements have been recognized by the general public.

Key Highlights

In this project, we have extended our perovskite degradation chemical analysis capability from GC-MS to depth profile X-ray photoelectron spectroscopy and revealed the differences and synergies of thermal and light stresses on perovskite solar cells with different types of carrier selective materials. We discovered thermal-induced-degradation occurs at certain perovskite/carrier-selective-contact interfaces that does not happen under light stress only. Likewise, we discovered certain light-induced-degradation that does not occur under thermal stress. Under a combination of thermal and light stresses, both types of degradations occur. This may motivate development of future strategies of lengthening operation lifetime of perovskite cells that involves reduction or elimination of thermal or light stress in the field. We have also identified the types of carrier-selective-contacts that are more prone to light or thermal stresses. Details of these findings will be published in a scientific journal in year 2023.

In terms of cell encapsulations, we have been successful in developing a method that does not use polymer material for the lamination, but rather a direct glass-glass bonding method for encapsulating perovskite cells suitable for both n-i-p and p-i-n polarities, resulting in one patent application filed.

In terms of durability demonstrations, we have successfully encapsulated a perovskite-silicon tandem cell using polymer-based method which become one of the first few cells to pass the industry standard IEC 61215 Thermal Cycling test retaining 98.8% of initial PCE.

In this project, a perovskite cell stability testing system has been established at ANU that can simultaneously measure up to 32 perovskite cells in a N_2 filled environment at the same time.

This system is designed to perform a range of ISOS-I testing protocols developed for organic solar cells. In this project, a total of 171 perovskite solar cells, including low and high bandgap absorber materials, have been tested using the ISOS-I protocols. The testing revealed several concurrent degradation mechanisms under light and elevated temperature. Higher temperatures resulted in a higher degree of degradation in the perovskite film and interface layers. Imaging results also uncover defects as a result of non-optimized fabrication process and electrode-misalignment causing low cell performance. This highlights the usefulness of the imaging capability as a non-intrusive defect-diagnostic as part of new cell-design and process development tool. Also, preliminary tests (light soaking protocol ISOS-I at 25°C) were performed on ten quantum dot (QD) perovskite cells. Again, imaging results revealed defects from non-optimized processes affecting QD film surface morphology and subsequently QD cell performance. This informs future optimization of substrate preparation and precursor preparation steps to eliminate defects (caused by particle aggregation, cross-contamination for example) observed.

Operational Si- perovskite QD tandem solar cell has also been demonstrated for the first time, achieving an open-circuit voltage of 1.6 V and a respectable power conversion efficiency (PCE) surpassing that of the single junction QD solar cell. Preliminary stability tests showed that unencapsulated tandem cells retained 70% of the initial efficiency after 7 days of storage in ambient. The source of instability has been identified, namely the interfacing between the Si cell and the QD cell. More work will be performed to improve both the performance and stability of the tandem solar cells for publication in a scientific journal in due course.

Throughout the project, AGP Glass has engaged in project reporting; sample exchanges for durability testing; technology transfer for some of the glass bonding developed; and provision of materials such as glass, encapsulant and edge sealing materials. AGP sees potentials in the development of new hermetic encapsulation methods and advanced characterization techniques (e.g., GC-MS, and hyperspectral imaging) that can be extended for other types of devices prone to degradation such as displays, lighting, and sensors, that are also part of AGP's R&D.

Impact Report

35 Presentations in domestic and international conferences

25 of which are plenary, keynote or invited talks

13 Scientific journal articles published to date

2 National Science Week Events

2 Lectures for the Harry Messel International Science School

9 Prestigious awards

6 Interviews and news articles

> 50 Lab tours

1 patent application filed

10 postdoctoral fellows, higher degree research students and undergraduate trained

Increased knowledge and new capability for understanding and for assessing perovskite cell stability

Improved durability of Si-perovskite tandem solar cells

Subsequent spin-off projects and funding success leveraging capability and capacity established from this project

Outreach

- Anita Ho-Baillie participated in "Lines of Best Fit" Event National Science Event (2022) where Scientists meet Improvisational comedy, https://www.scienceweek.net.au/event/lines-of-best-fit/the-university-of-sydney/, 15 Aug 2022
- Anita Ho-Baillie was part of the International Women's Day Panel and Q&A organised by ARC Centre of Exciton in Exciton Science, March 2022.
- Anita Ho-Baillie was part of the "Live from the Lab" Event for the National Science Week. Musician Setwan who wrote a piece of new music composition based on Ho-Baillie's research broadcast on FBi Radio, 16 August 2021
- A. Ho-Baillie, "Next Generation Photovoltaics", Harry Messel International Science School, 07/2022 (Invited talk and Lab Tour)
- A. Ho-Baillie, "Status of Photovoltaics: Role of Research and Development", Harry Messel International Science School, 07/2021 (Invited talk and Lab Tour)

- Project team has given over 50 lab tours for government departments, companies, university executives, academics, and students during the course of this project

Publicities

- Anita Ho-Baillie interviewed by Paul Looyen for Physics High podcast, 3 Sep 2021
- Article by Engineering Australia for Create Magazine on Solar Future, July-Aug 2021
- Article by Michael Mazengarb, "Poking holes" in solar cells the secret to Aussie perovskite world record, Renew Economy, 25 May 2021
- Anita Ho-Baillie interviewed by Robyn Williams (2021), https://www.abc.net.au/radionational/programs/scienceshow/perovskitespromise- new-ways-of-generating-solar-power/13173086, ABC Radio National the Science Show at 12:05 pm on 20 Feb.
- Article by David Carroll, "Australian researchers to set solar PV pace following $4.5 million funding boost", January 14, 2021
- Anita Ho-Baillie interviewed by Joe O'Brien, Live, ABC News Mornings, "Energy Revolution - IEA report predicts solar will overtake coal and gas", 09:16 AEST, 14 Oct 2020.

Awards

- Project Student Guoliang Wang won the Wal Read Memorial Award for Best Student Poster at poster award at Asia-pacific Solar Research Conference, Newcastle 12/2022.
- Anita Ho-Baillie won the Royal Society of NSW Warren Prize in 2022. Link: https://www.sydney.edu.au/news-opinion/news/2022/12/08/royal-society-of-nsw-winners.html
- Anita Ho-Baillie named Clarivate Highly Cited Researcher in 2022. Link:: https://www.sydney.edu.au/news-opinion/news/2022/11/16/sydney-researchers-ranked-among-global-elite.html
- Hieu Nguyen received the 2021 Vietnam Golden Globe Awards in Science & Technology for Young Scientists, by the Vietnamese Ministry of Science and Technology. Link: https://en.vietnamplus.vn/vietnamese-scientist-in-australia-honoured-with-sciencetechnology-prize/218283.vnp
- Hieu Nguyen named as one of the Ten Outstanding Young Faces of Vietnam 2021, by the Prime Minister of Vietnam. Link: https://en.vietnamplus.vn/ten-outstanding-young-faces-of-vietnam-announced/223025.vnp
  Anita Ho-Baillie named Clarivate Highly Cited Researcher in 2021, https://www.sydney.edu.au/news-opinion/news/2021/11/17/sydney-academics-recognised-in-highly-cited-researchers-list.html.
- Anita Ho-Baillie won an University of Sydney Vice Chancellor’s Award for Outstanding Research Engagement & Innovation 2021
- Anita Ho-Baillie and Martin Bucknall announced as Australian Museum Eureka Prize finalists, https://australian.museum/get-involved/eureka-prizes/2021-eureka-prizes-finalists/, 2-Sep-21
- Anita Ho-Baillie named Australian Research Council Future Fellow, https://rms.arc.gov.au/RMS/Report/Download/Report/1b0c8b2e-7bb0-4f2d-8f52-ad207cfbb41d/229, Aug 2021
- Anita Ho-Baillie named Clarivate Highly Cited Researcher in 2020, https://recognition.webofscience.com/awards/highly-cited/2020/, November 2020.

Journal publications

1. Takamure, N., Caro, L. G., Fukata, N., Ho-Baillie, A., & McKenzie, D. R. (2022). Structural study of hermetic seal formed by water glass at low temperature when trapped between glass plates. Japanese Journal of Applied Physics, 61(9), 095505. 10.35848/1347-4065/ac825e
2. Takamure, N., Sun, X., Nagata, T., Ho-Baillie, A., Fukata, N., & McKenzie, D. R. (2022). Thermodynamic Interpretation of the Meyer-Neldel Rule Explains Temperature Dependence of Ion Diffusion in Silicate Glass. Physical Review Letters, 129(17), 175901.
3. A. D. Bui, N. Mozaffari, T. N. Truong, T. Duong, K. J. Weber, T. P. White, K. R. Catchpole, D. Macdonald, H. T. Nguyen, Electrical properties of perovskite solar cells by illumination intensity and temperature dependent photoluminescence imaging, Progress in Photovoltaics: Research and Applications, 2022 (30) 1038-1044.
4. Hu, L., Duan, L., Yao, Y., Chen, W., Zhou, Z., Cazorla, C., ... & Huang, S. (2022). Quantum dot passivation of halide perovskite films with reduced defects, suppressed phase segregation, and enhanced stability. Advanced Science, 9(2), 2102258.
5. Wang, Y., Duan, C., Zhang, X., Sun, J., Ling, X., Shi, J., ... & Ma, W. (2022). Electroluminescent solar cells based on CsPbI3 perovskite quantum dots. Advanced Functional Materials, 32(6), 2108615.
6. Hu, L., Li, Q., Yao, Y., Zeng, Q., Zhou, Z., Cazorla, C., ... & Liu, F. (2021). Perovskite Quantum Dot Solar Cells Fabricated from Recycled Lead-Acid Battery Waste. ACS Materials Letters, 4(1), 120-127.
7. Bui, A. D., Mahmud, M. A., Mozaffari, N., Basnet, R., Duong, T., Bartholazzi, G., ... & Nguyen, H. T. (2021). Contactless and Spatially Resolved Determination of Current− Voltage Curves in Perovskite Solar Cells via Photoluminescence. Solar RRL, 5(8), 2100348.
8. Granados, L., Morena, R., Takamure, N., Suga, T., Huang, S., McKenzie, D. R., & Ho-Baillie, A. (2021). Silicate glass-to-glass hermetic bonding for encapsulation of next-generation optoelectronics: A review. Materials Today, 47, 131-155.
9. Almora, O., Baran, D., Bazan, G. C., Cabrera, C. I., Erten-Ela, S., Forberich, K., Guo, F., Hauch, J., Ho-Baillie, A. W. Y., Jacobsson, T. J., Janssen, R. A. J., Kirchartz, T., Kopidakis, N., Loi, M. A., Lunt, R. R., Mathew, X., McGehee, M. D., Min, J., Mitzi, D. B., Nazeeruddin, M. K., Nelson, J., Nogueira, A. F., Paetzold, U. W., Rand, B. P., Rau, U., Snaith, H. J., Unger, E., Vaillant-Roca, L., Yang, C., Yip, H.-L., Brabec, C. J., Device Performance of Emerging Photovoltaic Materials (Version 3). Adv. Energy Mater. 2023, 13, 2203313. https://doi.org/10.1002/aenm.202203313
10. Almora, O., Baran, D., Bazan, G. C., Berger, C., Cabrera, C. I., Catchpole, K. R., Erten-Ela, S., Guo, F., Hauch, J., Ho-Baillie, A. W. Y., Jacobsson, T. J., Janssen, R. A. J., Kirchartz, T., Kopidakis, N., Li, Y., Loi, M. A., Lunt, R. R., Mathew, X., McGehee, M. D., Min, J., Mitzi, D. B., Nazeeruddin, M. K., Nelson, J., Nogueira, A. F., Paetzold, U. W., Park, N.-G., Rand, B. P., Rau, U., Snaith, H. J., Unger, E., Vaillant-Roca, L., Yip, H.-L., Brabec, C. J., Device Performance of Emerging Photovoltaic Materials (Version 2). Adv. Energy Mater. 2021, 11, 2102526. https://doi.org/10.1002/aenm.202102526
11. Almora, O., Baran, D., Bazan, G. C., Berger, C., Cabrera, C. I., Catchpole, K. R., Erten-Ela, S., Guo, F., Hauch, J., Ho-Baillie, A. W. Y., Jacobsson, T. J., Janssen, R. A. J., Kirchartz, T., Kopidakis, N., Li, Y., Loi, M. A., Lunt, R. R., Mathew, X., McGehee, M. D., Min, J., Mitzi, D. B., Nazeeruddin, M. K., Nelson, J., Nogueira, A. F., Paetzold, U. W., Park, N.-G., Rand, B. P., Rau, U., Snaith, H. J., Unger, E., Vaillant-Roca, L., Yip, H.-L., Brabec, C. J., Device Performance of Emerging Photovoltaic Materials (Version 1). Adv. Energy Mater. 2021, 11, 2002774. https://doi.org/10.1002/aenm.202002774
12. Tang, S., Bing, J., Zheng, J., Tang, J., Li, Y., Mayyas, M., ... & Ho-Baillie, A. W. (2021).

Complementary bulk and surface passivations for highly efficient perovskite solar cells by gas quenching. Cell Reports Physical Science, 2(8), 100511.
13. Cho, Y., Bing, J., Kim, H. D., Li, Y., Zheng, J., Tang, S., ... & Ho-Baillie, A. W. (2021). Immediate and temporal enhancement of power conversion efficiency in surface-passivated perovskite solar cells. ACS Applied Materials & Interfaces, 13(33), 39178-39185.

Conference presentations

1. A. Ho-Baillie, "Perovskite Tandem Solar Cells". Asia-Pacific International Conference on Perovskite, Organic Photovoltaics and Optoelectronics (IPEROP23) Kobe, Japan Jan 24, 2023 (Invited talk)
2. A. Ho-Baillie, "Perovskite Tandem Solar Cells" Emerging PV online workshop, Next Generation Solar Energy (NGSE) conference (https://www.ngse.info/) December 8, 2022 (Invited talk)
3. A. Ho-Baillie, "Perovskite tandem solar cells" International Conference on "Materials for Humanity (MH22), Materials Research Society of Singapore, 19-21 Sep, 2022 (Invited talk)
4. A. Ho-Baillie, "Recent progress and future prospects of perovskite tandem solar cells", International Symposium on Clean Energy Materials (ISCEM) 2022, 30th June-2nd July 2022 on Gold Coast (Keynote talk)
5. A. Ho-Baillie, "Perovskite single junction and multi-junction solar cells", Internatinoal Conference on the Physics of Semiconductors (ICPS) 2022, 27-30 June (Invited talk)
6. A. Ho-Baillie, "Future prospects of perovskite tandem solar cells"., Advanced PV 2030 Symposium Online, Tuesday 14 June 2022 (Keynote).
7. A. Ho-Baillie, Panel discussion, Advanced PV 2030 Symposium Online, Tuesday 14 – Friday 17 June 2022, https://webcast.csiro.au/sharevideo/f2475af5-267b-4f82-8ee8-5ecdf9ae9173.
8. A. Ho-Baillie, "New interface design for large area perovskite-Si tandem", Helmholtz Xentrum Berlin 2022 Tandem PV workshop, May 30 – June 1, 2022 in Freiburg, Germany (Invited talk)
9. A. Ho-Baillie, "Intrinsic stability of perovskites and meta-stability of perovskite solar cells", Towards Stable Perovskite Photovoltaics TSPV22 symposium, nanoGe Spring Meeting 2022 Mar 07-11, 2022 (Invited talk)
10. H. Nguyen, "Optical and electrical properties of photovoltaic materials via luminescence", International Conference on Materials Science and Engineering, Gold Coast, 12/2022 (Invited talk).
11. A. D. Bui, "Imaging Electrical Properties of Perovskite Solar Cells by Illumination Intensity and Temperature Dependent Photoluminescence", 8th WCPEC 2022, Milan, 09/2022.
12. N. D. K. Nguyen, "Correlative imaging of optical properties for perovskite materials in single-junction and tandem solar cells", 8th WCPEC 2022, Milan, 09/2022.
13. H. Nguyen, "Optical spectroscopy and imaging characterization for photovoltaics, Research methods for Solar PV", SUPERGEN SuperSolar Hub, UK, 04/2022 (Invited public seminar).
14. H. Nguyen, "The multi efforts behind solar cell efficiencies: the fundamentals, characterisation and materials engineering", The 4th Energy Future Conference, Sydney, 10/2021 (Invited talk).
15. H. Nguyen, "Behind efficiencies: the multi-pronged approach to improved solar photovoltaics", International Conference on Materials Science and Engineering, Brisbane 10/2021 (inviG. Wang, A. Ho-Baillie, "Hole selective contact engineering for efficient high bandgap perovskite single junction and perovskite double junction tandem solar cells". Asia-pacific Solar Research Conference, Newcastle 12/2022 (Invited talk).
16. G. Wang, A. Ho-Baillie, "Hole selective contact engineering for efficient high bandgap

perovskite single junction and perovskite double junction tandem solar cells”. Asia-pacific Solar Research Conference, Newcastle 12/2022 (Poster)
17. M. P. Bucknell, J. Bing, A. Ho-Baillie, “Headspace GC-MS analysis as a new tool in the development of stable perovskite solar cells” MWAC Reconnection Day Workshop, Radisson Blu Hotel, Sydney, 17th Nov 2022
18. S. Huang, L. Hu, Surface Passivation Strategies for Colloidal Quantum Dot Solar Cells, 2022 International Symposium on Clean Energy Materials, Gold Coast, June 2022 (Invited talk).
19. L. Hu, S. Huang, Bandgap engineering of halide perovskite quantum dots for solar cell application, 2022 International Symposium on Clean Energy Materials, Gold Coast, June 2022 (Poster).
20. S. Huang, Surface Passivation Strategies for Flexible Perovskite Quantum Dot Solar Cells, 10th International Conference on Advanced Materials and Nanotechnology, Rotorua, February 2023. (Poster)
21. Hu, L., Huang, S., Optical Bandgap Engineering of Halide Perovskite Quantum Dots for Solar Cell Applications, 8th World Conference on Photovoltaic Energy Conversion, September Milano 2022. (Oral)
22. L. Hu, S. Huang, Optical Bandgap Engineering of Halide Perovskite Quantum Dots for Solar Cell Applications, 8th World Conference on Photovoltaic Energy Conversion, September Milano 2022. (Oral)
23. L. Hu, S. Huang, "Flexible Inorganic CsPbI3 quantum dot solar cell", PVSEC-31 December 3021
24. H. Nguyen, "Recent progress in the characterization of photovoltaic materials (silicon, perovskite, tandem, and 2D materials)", the 8th Australian Centre for Advanced Photovoltaics (ACAP) Conference, Melbourne, 12/2020 (Invited talk).
25. H. Nguyen, "Optical spectroscopy for photovoltaics, Research Methods for Solar PV", SUPERGEN SuperSolar Hub, UK, 04/2021 (Invited public seminar)
26. A. D. Bui, D. MacDonald, H. Nguyen, "Contactless and Spatially Resolved Determination of Current− Voltage Curves in Perovskite Solar Cells via Photoluminescence", the 48th IEEE Photovoltaic Specialists Conference, 06/2021.
27. T. White, "High efficiency perovskite-silicon tandem solar cells", the 13th International Symposium on Modern Optics and its Application, 08/2021 (Invited talk).
28. A. Ho-Baillie, “By passing wires - Monolithic Integrated Devices for Solar Driven Hydrogen Production and Solar Batteries”, 4th Energy Future Conference (EF4), 18-20 October 2021 (Plenary talk)
29. A. Ho-Baillie, “Meta-stability and Durability of Perovskite Solar Cells”, ACS Fall 2021, 08/2021 (Invited talk)
30. A. Ho-Baillie, "Perovskite solar cells", SPIE Optics and Photonics, 08/2021 (Plenary talk)
31. A. Ho-Baillie, "Next Generation Solar Cells for Solar City, Smart City: Transforming the urban energy landscape“, Melbourne Energy Institute Public Lecture, 05/2021 (Keynote talk)
32. A. Ho-Baillie, "Next Generation solar Cells ", Australian Research Council Centre of Excellence in Exciton Science Workshop, 02/2021 (Keynote talk)
33. A. Ho-Baillie, "Perovskite solar cells", International Conference on Hierarchical Green Energy Materials, National Cheng Kung University, Taiwan, 01/2021 (Keynote talk)
34. A. Ho-Baillie, "Perovskite solar cells", The Electrochemical Society Webinar Series, 12/2020 (Invited talk)
35. A. Ho-Baillie, "Durable Perovskite Solar Cells", Materials Research Society (MRS) Fall Meeting, Symposium EN01 Next Steps for Perovskite Photovoltaics and Beyond, 11/2020. (Invited talk)

Patent application

Anita Wing Yi Ho-Baillie, Laura Granados Caro, David Robert McKenzie, Jueming Bing, Shi Tang. 2022-010-PRO-0 - Encapsulated optoelectronic device – 2022903527

Lessons Learnt

Project Name: *Durable Silicon Perovskite Tandem Photovoltaics*

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

Key learning

Setting up high throughput in-situ IV testing is challenging inside an inert environment that causes degradation of the LED-based light source in the absence of oxygen. Degradation of LED is reversible upon re-exposure to oxygen.

Implications for future projects

Set up separate compartments for the solar simulator (with the presence of oxygen) and for the solar cells under test (in the absence of oxygen)

Project Name: *Durable Silicon Perovskite Tandem Photovoltaics*

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

Key learnings

As we attempt to reduce our reliance on the use polymer for glass to glass lamination for cell encapsulation, but rather a direct glass-glass bonding method, we found that we needed to introduce capping layer/stack, edge seal and those with desiccating capabilities were preferred. Care must therefore be taken when choosing these materials to ensure they do not react with the perovskite absorber, carrier-selective materials and metal electrode. The choice of cover glass is also important for encapsulating tandem cells to ensure high ultra-violet light transmission to maximize the benefit of tandem solar cells.

Implications for future projects

There is still a lot of work that needs to be done for optimizing the choice of capping layer/stack, and edge seal and their implications on the encapsulation process steps that do not harm the cell. We anticipate to publish details in scientific journal(s) in due course.

Reduced reliance on reactive dopants in carrier-selective materials, volatile organic components in the perovskite absorber and reactive metal electrodes will also help improve the durability of perovskite single junction and tandem solar cells rather than sole reliance on improving cell encapsulation methods.

Project Name: *Durable Silicon Perovskite Tandem Photovoltaics*

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

Key learning

Interfacing layers used in Si-perovskite and Si-perovskite QD tandems can be the source of instability as observed during the course of this project.

Implication for future projects

Alternative materials have been identified and will be trialed in future work. We anticipate to publish success and details in scientific journal(s) due course.

Project Name: *Durable Silicon Perovskite Tandem Photovoltaics*

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

Key learning

The hyperspectral imaging tool was a microscope-based version specifically designed for capturing high-resolution images of small-area samples. Therefore, in order to image multiple solar cells in a sample testing jig, mapping is required. Additionally, the working distance between the microscope objective lens and the sample is less than 1 cm, which greatly limits the design flexibility of the sample testing jig for a large number of cells.

Implications for future projects

To capture a large number of cells over a wide area and allow maximum flexibility in sample testing jig design, an ideal imaging system would be a free-space coupling model. With this model, the field of view can be easily controlled over a broad range of physical dimensions by using an appropriate imaging lens. While spatial resolution may be sacrificed, a free-space coupling system is preferred for statistical analysis and uniformity monitoring purposes.

Project Name: *Durable Silicon Perovskite Tandem Photovoltaics*

Knowledge Category:	Technical
Knowledge Type:	Operation and Maintenance
Technology Type:	Solar PV
State/Territory:	ACT

Key learning

In a university IT environment, using the option to pause Windows Updates on a desktop Windows operating system typically seems not to work reliably on recent versions of Windows, so the computer can reboot during long experiments. If any laboratory equipment requires Windows -based software to be running in order to collect measurement data, this leads to failed experiments.

Implications for future projects

Where possible, for long-term experiments avoid choosing laboratory equipment that requires software that runs on Windows desktop operating systems. Instead choose equipment that works with a server operating system such as Linux or a server version of Windows, to avoid data loss resulting from Windows Updates.

Project Name: *Durable Silicon Perovskite Tandem Photovoltaics*

Knowledge Category:	Technical
Knowledge Type:	Operation and Maintenance
Technology Type:	Solar PV
State/Territory:	ACT

Key learning

Laboratory instruments that come with computer software frequently have bugs in the software. The user base of laboratory products is so small that bugs can remain un-fixed by the manufacturer for several years. Also where features are missing in the software (such as maximum-power-point tracking in the equipment used to measure solar cells, or the ability for the software to be controlled automatically overnight without a human clicking a mouse button), once the instrument has been purchased there is no certainty that the instrument vendor will add the feature, nor make available the necessary interfaces or source code for researchers to add the feature themselves. Open-source software lacks these restrictions and therefore may increase the usefulness and value of the instrument.

Implications for future projects

Where possible it is better to choose laboratory instruments which use software for which the source code is available so that missing features are possible to add regardless of the preferences of the instrument vendor. Alternatively, instruments with documented hardware interfaces and protocols should be chosen so that the supplied software can be replaced with alternative software that provides the missing features. If purchasing laboratory instruments, prior to agreeing to a purchase it is worth asking for the source code to the control software (perhaps under a non-disclosure agreement if required by the vendor) so that if any additional features later become required, it is possible to add the missing features without first convincing the vendor that doing this work is in their interest.

Project Name: *Durable Silicon Perovskite Tandem Photovoltaics*

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

Key learning

Sometimes devices are masked (via the use of taping) for area definition during the fabrication of carrier-selective layer which can happen in low pH environment. The masking tape if chosen inappropriately can degrade in the acidic environment.

Likewise, the synthesize of perovskite QD precursors can create an acidic environment causing laboratory glassware seals to degrade if chosen inappropriately.

Implications for future projects

Choose chemical stable masking tape and lab wear seals or remove the reliance of masking tape.