High-Efficiency Silicon-perovskite Tandem Cells and Modules: Demonstration and Commercial Evaluation

Project results and lessons learnt

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Executive Summary

The motivation of the project is to develop tandem solar cell technology with efficiencies (e.g., >30% for silicon-perovskite tandem) surpassing the theoretical limit of single junction solar cell (e.g., 29% is the practical limit for Si single junction cell). The aim is to conduct R&D for premium high-efficiency product that will be more attractive than a new low-efficiency, thin-film product.

Several strategies for integrating perovskite solar cell with silicon solar cell for high power conversion efficiency have been trialled and were successful. These include spectrum splitting using optical elements to divert high photon-energy-sunlight onto the perovskite cell and low-photo-energy sunlight onto the silicon cell. Another strategy is the use of perovskite cell itself as a spectrum splitter by reflecting low photo energy sunlight onto the silicon cell while absorbing high photon energy sunlight itself for power conversion. The third strategy is by mechanically stacking a perovskite cell on top of a silicon cell while independently wiring the cells to produce power output equalling the sum of the outputs of the individual cells. The last strategy is by directly fabricating a perovskite solar cell on top of a silicon cell. The boost in performance is thus a result of the boost in output voltage equalling the sum of the voltages of the individual cells. The last approach which is also called monolithic integration is most elegant reducing complexity associated with wiring and packaging. However, this approach requires careful cell design to achieve low loss interface and to match output currents of the individual cells as they are electrically connected in series. In addition, fabrication processes and architectures of the individual cells need to be compatible with each other.

At the start of the project, only a very few mechanically stacked 4-terminal perovskite tandem cell demonstrations were reported. Throughout the project, we have been able to demonstrate 4-terminal silicon-perovskite tandem-cells with efficiencies >26%.

At the start of the project, monolithic silicon-perovskite tandem cell demonstrations were non-existent. Throughout the project, monolithic silicon-perovskite tandem cell reports began to emerge around the world. In these demonstrations, silicon hetero-junction cells were used as the bottom cells. However, silicon homo-junction cells dominate ~90% of the world photovoltaic market with a well-established industry process. In this project, we have focussed on the silicon-perovskite tandem cell demonstrations that use silicon homo-junction cells as the bottom cells. We have been able to produce many innovative and cost effective tandem cell designs, in particularly, for interfacing between the perovskite cell and heavily-doped silicon surface. At the end of the project, we have demonstrated high efficiency monolithic silicon-perovskite tandems with efficiencies exceeding 22% reported in high impact journal articles. We have also been able to demonstrate tandems on larger areas such as 4cm2 and 16cm2 with efficiencies of 23% and 22%, respectively.

At the start of the project, stability testings of perovskite cells were rudimentary. Some of the organic light emitting diode encapsulation schemes have been adapted for packaging perovskite cells. However, low cost module encapsulation schemes relevant to photovoltaic industry cost structure needed to be developed. In this project, low cost polyisobutylene(PIB)-based encapsulation methods have been developed that are shown to be very effective in limiting environmental exposure of perovskite cells. Encapsulated cells were able to pass the IEC61215:2016 (Terrestrial Photovoltaic (PV) Modules) specified Thermal Cycling; Damp Heat and Humidity Freeze accelerated test. Preliminary outdoor testing of PIB-encapsulated tandem cells also shows promising results. UV down-shifting material has also been demonstrated to be effective in improving both UV response and therefore cell performance and UV stability of tandem cells.

This project also facilitated techno economic analyses on perovskite solar cell on glass, perovskite solar cell on flexible substrate by roll-to-roll process and silicon-perovskite tandem for the first time. For the purpose of the analyses, a methodology has been developed that is most suitable for evaluating early stage technologies accounting for uncertainty in cost input data. The studies highlighted high cost material items requiring research into lower cost alternatives without sacrificing cell performance. The studies also highlighted the need to develop scalable deposition processes that have lower material utilisations. The higher the cost improvements, the lower the tandem cell efficiency targets need to be for the technology to match the incumbent in cost terms. The importance of on-going work to improve the durability and lifetime of perovskite PV technology is paramount for perovskite-silicon tandem's levelised cost of energy to match that of the incumbent.

Project Overview

Project summary

In this project, the following were achieved:

1. Demonstrate >26% efficient silicon-perovskite tandem-cells;
2. Fabricate tandem-cells with form and function compatible with present commercial silicon cells (e.g., by monolithic integration and using homo-junction silicon solar cells as bottom cells);
3. Encapsulate perovskite cells for accelerated tests (industry-standard regimes) to investigate effectiveness of cell level strategies to address documented perovskite stability issues accessing capabilities of solar cell manufacturer (e.g., Trina Solar).
1. Industrially cost promising processes, relative to present commercial product.

Project scope

The motivation of the project is to develop tandem solar cell technology with efficiencies (e.g., >30% for silicon-perovskite tandem) surpassing the theoretical limit of single junction solar cell (e.g., 29% is the practical limit for Si single junction cell). The aim is to conduct R&D for premium high-efficiency product that will be more attractive than a new low-efficiency, thin-film product.

At the start of the project, monolithic silicon-perovskite tandem cell demonstrations were non-existent while only a very few mechanically stacked 4-terminal perovskite tandem cell demonstrations were reported. Throughout the project, we have been able to demonstrate 4-terminal silicon-perovskite tandem-cells with efficiencies at

- 23.4% in 2015 via spectrum splitting (J. Phys. Chem. Lett. 2015, 6, 3931–3934);
- 24.5% in 2016 via mechanical stacking (Adv. Energy Mater. 2016, 1601768);
- 26.4% in 2017 via mechanical stacking (Adv. Energy Mater, DOI: 10.1002/aenm.201700228)
- 26.7% (26.9% with anti-reflection coating) in 2018 via mechanical stacking (J. Mater. Chem. A, 2018, DOI:10.1039/C7TA10945H)

While progress was being made to increase perovskite cell efficiency, integration approaches needed to be developed in this project for monolithic tandems that avoid the complexity in wiring and packaging. New tandem cell designs were developed that are compatible with the use of silicon homo-junction cells that dominate ~90% of the world photovoltaic market with a well-established industry process. The low cost and effective interfacing approaches between the perovskite cell and heavily-doped silicon surface developed include:

1. metal grid interfacing with indium tin oxide (ITO), then compact titanium dioxide (c-TiO_2) for a mesoporous perovskite cell. The demonstrated monolithic tandem produced an efficiency of 22.5% on 1 cm^2 (Energy Environ. Sci., 2017,10, 2472-2479)
2. direct full area contacting with tin oxide (SnO_2) (without the use of any interface layer, or ITO or metal grid) for a planar perovskite cell. This low-cost approach is also suitable for large area resulting in a few successful demonstrations producing 20.5% on 4cm^2 (Energy Environ. Sci.,

2018,11, 2432-2443); 21.8% on 16cm2 (ACS Energy Lett.2018,3,9.2299-2300). A 23.0% cell on 4cm2 using this approach will be reported in 2019.

3. heavily doped poly-silicon (without the use of interfacial ITO), contacting c-TiO_2 for a mesoporous perovskite cell. The demonstrated monolithic tandem produced an efficiency of 22.9% on 1 cm2 (Sci. Adv. 2018;4: eaau9711).

At the start of the project, stability testings of perovskite cells were rudimentary. Some of the organic light emitting diode encapsulation schemes have been adapted for packaging perovskite cells. However, low cost module encapsulation schemes relevant to photovoltaic industry cost structure (typically lower for PV than display industry) needed to be developed.

In this project, low cost polyisobutylene(PIB)-based encapsulation methods have been developed and have been adopted by the participating institutes in Australia in this project and other researchers around the world. The schemes are shown to be very effective in limiting environmental exposure of perovskite cells. Encapsulated cells were able to pass the

1. IEC61215:2016 (Terrestrial Photovoltaic (PV) Modules) specified thermal cycling accelerated test (200 cycles between -40 °C and 85°C with less than 5% efficiency loss)
2. IEC61215:2016 accelerated damp heat test (1000 hours at 85% relative humidity (RH) and 85°C)
3. IEC61215:2016 accelerated humidity freeze test (50 thermal cycles as a pre-requisite followed by 10 cycles between 40 °C and 20 hours of 85% RH and 85°C)

In facts, some encapsulated cells exceeded the requirements for damp heat and humidity freeze accelerated tests by 800 hours (of damp heat) and 20 cycles (of humidity freeze), respectively. Further work is currently being undertaken to adapt PIB encapsulations for tandem solar cells for outdoor testing. UV down-shifting material has also been demonstrated to be effective in improving both UV response and therefore cell performance and UV stability of tandem cells. Results will be published in 2019.

Preliminary cost analysis has been conducted on our lab-demonstrated cell processing sequences with the aim of providing useful guidelines for cost and efficiency trade-offs required for commercial viability. Few key findings include

- Reducing total cost by scalable manufacturing that has a lower rate of material utilisation (e.g., blading, or spraying, rather than spin coating).
- Replacement of high cost hole transport layer (e.g., 2,2',7,7'-Tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene (spiro-OMeTAD)) in the perovskite cell with a cheaper alternative
- Costs of [6,6]-phenyl-C61-butyric acid methyl ester (PCBM), lead Iodide and TiO_2 paste for mesoporous TiO_2 are high compared to the use of SnO_2 only.

At this early stage of technology development, tandem cell efficiency targets over 35% are required for the processing sequences analysed, much higher than the highest efficiency demonstrated. That is why cost improvements will be essential in order to lower these targets to more achievable levels. It must be emphasised that these targets are for 6” square wafer cell efficiencies, which have not yet been demonstrated in the lab. Scaling up to this size whilst maintaining efficiency is not trivial, and this presents another area of work for the commercialisation of this technology. Also, the levelised cost of energy analysis assumes that the lifetime of the modules and their degradation rates match those of crystalline silicon modules. This demonstrates the importance of on-going work of increasing the durability and lifetime of perovskite PV technology. As the technology especially, packaging approach for tandem cell matures and lower cost cell designs are developed, more accurate cost models will be developed.

Outcomes

This project has put Australian researchers on the map of world leading perovskite research and silicon perovskite tandem research extending Australia's world-class research position in photovoltaics.

Throughout the project, we have

- Given 78 presentations in domestic and international conferences – 19 of which are plenary, keynote or invited
- published 68 scientific journal articles. Some of which
  - have been featured in Nature Energy Research Highlights,
    - G. Tregnago, " Easing tandem up-scaling ", Nature Energy Vol. 3, August 2018, 615
    - E. Coudrec, "Perovskite Photovoltaics - Manufacturing Costs", Nature Energy 2, 17080 (2017)
  - has been 2018 Energy and Environmental Science HOT Article (Energy Environ. Sci., 2018,11, 2432-2443)
  - have received high citations to be placed in the top 1% in their respective field (ACS Energy Lett., 2018, 3 (3), pp 647–654; J. Mater. Chem. A, 2018, 6, 3583-3592; Solar Energy Materials and Solar Cells, Volume 174, January 2018, Pages 314-324)
- generated 20 new stories
- filed 5 patent applications.
- contributed to the training of 30 higher degree research students and postdoctoral fellows.

We have made contributions to the technology to bring it to the stage where industry can make informed decisions about large-scale investments required for market-introduction of premium products exploiting these developments. Start-ups formed for commercialising silicon-perovskite tandem include Oxford PV in the UK, and Tandem PV in the US.

Presentations

1. Plenary talk in 29th Europan PV Solar Energy Conference and Exhibition 2014, Amsterdam, The Netherlands, 22-26 Sep 2014 by Martin A. Green, "Perovskite Single-Junction and Silicon- or CIGS-Based Tandem Solar Cells: Hype or Hope?"
2. Oral presentation in 6th World Conference on Photovoltaic Energy Conversion, Nov 23-27, 2014. Kyoto, Japan by Jae Yun, "Kelvin Probe Force Microscopy Study of Perovskite-Based Solar Cells"
3. M. A. Green, "Mainstream Photovoltaics: Where Can Perovskites Make Impact?" Hybrid and Organic Photovoltaic Conference 2015, Rome, Italy, 10-13 May 2015 (Plenary)
4. M. Green, "Challenges Facing Commercialisation of Si-based Tandem Cells", 2015 MRS Spring Meeting, San Francisco, USA, 6-10 April 2015 (Invited Talk)
5. X Deng, X Wen, R Sheng, S Huang, T Harada, TW Kee, MA Green, A. Ho-Baillie (2015), "Ultrafast Charge Generation and Relaxation Dynamics in Methylammonium Lead Bromide Perovskites",

Proc. SPIE 9668, Micro+Nano Materials, Devices, and Systems, 966848 (December 22, 2015); doi:10.1117/12.2202330. (Oral)

6. S Chen, X Wen, S Huang, R Sheng, MA Green, A Ho-Baillie (2015), “Illumination dependent carrier dynamics of CH3NH3PbBr3 perovskite”, Proc. SPIE 9668, Micro+Nano Materials, Devices, and Systems, 96681R (December 22, 2015); doi:10.1117/12.2202176
7. M. M. Lunardi, R. Corkish, S. Moore, A. Ho-Baillie (2015), “Perovskite/silicon Tandem Solar Cells: A Life Cycle (LCA) Perspective”, Asia-Pacific Solar Research Conference, 8-10 Dec 2015, Brisbane, Queensland. (Oral)
8. T. Duong et al., “Efficient inv-Transparent PerovskiteSolar Cell for Four-Terminal Tandem Structure”, Oral Presentation at Asia-pacific Solar Research Conference, Brisbane Convention And Exhibition Centre, Queensland, 8 Dec - 10 Dec 2015. (Oral)
9. X. Wen; A. Ho-Baillie; S. Huang; R. Sheng; S. Chen; Y. Feng; and M. A. Green (2015), "Density Dependent Carrier Dynamics in Organic-inorganic Metal Halide Perovsktite", International Conference and Exhibition on Mesoscopic & Condensed Matter Physics, June 22-24, 2015, Boston, USA. (Invited)
10. U Bach, “Recent Progress in Dye-Sensitized and Perovskite Solar Cells”, IUPAC-2015 Bexco, Busan, Korea, August 6-13, 2015
11. U Bach, “Inorganic Complexes for Solar Energy Harvesting”, Pacifichem Hawaii, 15-20 Dec., 2015
12. Y.-B. Cheng, F. Huang, M. Xiao, Y. Zhu, J. Etheridge, U. Bach, L. Spiccia, “Nucleation and Grain Growth in Methylammonium Lead Iodide Perovskite Films”, 2015 MRS Spring Meeting, San Francisco, California, April 6-10, 2015
13. Y.-B. Cheng, F. Huang, M. Xiao, U. Bach, L. Spiccia, “Microstructural Control for High Efficiency Planar Perovskite Solar Cells”, 3rd Intern. Conf. on Advanced Complex Inorganic Nanomaterials, Namur, Belgium 13-16 July, 2015
14. Y.-B. Cheng, “Microstructural Development for Perovskite Solar Cells”, 1st Intern. Symp. on Energy Chemistry and Materials, Shanghai, China 29-31 Oct., 2015
15. Y.-B. Cheng, “Perovskite Solar Cells and Their Stability” OSA 2015 Light, Energy and the Environment Congress, Suzhou, China 2-5 Nov., 2015
16. H. Mulmudi and D. Grant, “Overview of perovskite activities@ANU: Fundamentals & Devices”., presentation at IIT, Milan, Italy on 6th October
18. Mulmudi Hemant Kumar, The Duong, Yiliang Wu, Chog Barugkin, Heping Shen, Thomas White, Kylie Catchpole, Klaus Weber, “Investigating phase segregation in Rubidium based mixed cation perovskite solar cells using cathodoluminescence” Asia-Pacific Research Conference, Canberra, Australia (Nov 2016)
19. Mulmudi Hemant Kumar, The Duong, Yiliang Wu, Chog Barugkin, Heping Shen, Thomas White, Kylie Catchpole, Klaus Weber, “Investigating phase segregation in Rubidium based mixed cation perovskite solar cells using cathodoluminescence” 2nd International Conference on Perovskite Solar Cells and Optoelectronics, Genova, Sept. 2016
20. Heping Shen, Yiliang Wu, Jun Peng, The Duong, Tom White, Klaus Weber, Kylie Catchpole. Fabrication of highly efficient large-area perovskite solar cell (PSC) by spin-coating method, International Conference on Hybrid and Organic Photovoltaics (HOPV16), Swansea, United Kingdom, 28th June - 1st July.
21. Heping Shen, Daniel Jacobs, Yiliang Wu, The Duong, Jun Peng, Tom White, Klaus Weber, Kylie Catchpole. Understanding hysteresis and slow response time of transient behavior in perovskite solar cell, Asia-Pacific Solar Research Conference, 29 Nov. - 1 Dec., 2016, Canberra, Australia.

22. Yiliang Wu, Hemant Mulmudi, Xiao Fu, Kylie Catchpole, Tom White, and Klaus Weber, Grain boundary characterization using Cathodoluminescence and Photoluminescence mapping of large grained perovskite films, Asia-Pacific Solar Research Conference, 29 Nov. - 1 Dec., 2016, Canberra, Australia
23. Dale Grant, Kylie Catchpole, Klaus Weber and Thomas White, Material Selection Criteria For Perovskite/Silicon 2-Terminal Tandem Solar Cells: An Optical Perspective, 2nd International Conference on Perovskite Solar Cells and Optoelectronics, Genova, Sept. 2016
24. Dale Grant, Kylie Catchpole, Klaus Weber and Thomas White, Material Selection Criteria, An Optical Study On Material Selection For Perovskite/Silicon 2-Terminal Tandem Solar Cells, Asia-Pacific Solar Research Conference, 29 Nov. - 1 Dec., 2016, Canberra, Australia
25. White, T. Duong, D. Grant, D. A. Jacobs, K. J. Weber and K. R. Catchpole, "Light Management and Optical Design for High Efficiency Perovskite-Silicon Tandem Solar Cells, European Materials Research Society (EMRS) Fall Meeting, Warsaw, Poland, Sept 2016.
26. The Duong, Jun Peng, Andrew Blakers, Klaus J. Weber, Kylie R. Catchpole: High efficiency perovskite-silicon tandem: roadmap to 26%, Asia-Pacific Solar Research Conference, Canberra 2016, November 29 – December 1, 2016.
27. The Duong, Dale Grant, Shakir Rahman, Andrew Blakers, Klaus J. Weber, Kylie R. Catchpole: Efficient Semi-Transparent Perovskite Solar Cell For Four-Terminal Tandem Structure, MRS Spring meeting, Phoenix, Arizona, March 28- April 1, 2016.
28. Bach, "Recent Advances in Perovskite Solar Cell Research: Semitransparent and flexible CH3NH3PbI3 solar cells and their stability", 12th Workshop on the Future Direction of Photovoltaics, Tokyo, Japan, January 28-29, 2016
29. Bach, "Dye-sensitized and Perovskite Solar Cells", 5th International SolTech Conference, Munich, Germany, April 5 – 8, 2016
30. U. Bach, "Perovskite Solar Cells", 3rd Asia Pacific Solar Research Conference, Canberra, 29 Nov - 1 Dec 2016
31. U. Bach, "Dye-sensitized and Perovskite solar cells", Emerging Energy Technologies Summit and Exhibition, Melbourne, Australia, December 5 –7, 2016
32. Y.-B Cheng, "Microstructural Development and Characterisation for Perovksite Solar Cells", 12th Workshop on the Future Direction of Photovoltaics, Tokyo, Japan, January 28-29, 2016
33. Y.-B Cheng, "Stability of Perovskite Solar Cells under Static and Dynamic Illumination Conditions", The 5th Sungkyun International Solar Forum, Seoul, Korea, May 25-27, 2016
34. Y.-B Cheng, "Electron Microscopy Characterisation of CH3NH3PbI3", 10th Aseanian Conference on Nano-Hybrid Solar Cells, Beijing, China, September 20-23, 2016
35. Y.-B Cheng, "Control of nucleation and growth in organic–inorganic hybrid perovskite solutions", International Symposium on Next Generation Solar Cells and Solar Energy Conversion, Hsinchu, Taiwan, November 21-24, 2016
36. Y.-B Cheng, "Stability Issues of Perovskite Solar Cells", 3rd Asia Pacific Solar Research Conference, Canberra, 29 Nov - 1 Dec 2016
37. Ho-Baillie, I. Almansouri, M. Green (2016), "The Ultimate Efficiency of Organolead Halide Perovskite Solar Cells Limited by Auger Processes", 2016 MRS Spring Meeting and Exhibit, Mar 28- Apr 01, 2016, Phoenix, Arizona, USA (Oral)
38. Q. Ma, S. Huang, M. A. Green, A. Ho-Baillie, "Inorganic CsPbIBr2 Perovskite Solar Cell", International Conference on Hybrid and Organic Photovoltaics (HOPV16), Swansea, United Kingdom, from 28th June - 1st July 2016 (Oral).

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40. J. Kim, J. S. Yun, X. Wen, A. M. Soufiani, C. F. J. Lau, B. Wilkinson, J. Seidel, M. A. Green, S. Huang, and A. W. Y. Ho-Baillie (2016), “Nucleation and Growth Control of HC(NH2)2PbI3 for Planar Perovskite Solar Cell”, E-MRS Fall Meeting and Exhibit, Warsaw University of Technology, Poland, September 19 to 22, 2016. (Oral)
41. X. Deng, X. Wen, C. F. J. Lau, T. Young, J. Yun, M. A. Green, S. Huang and A. W. Y. Ho-Baillie (2016). “Ion Migration and Decomposition of Methyl-ammonium Lead Iodide Perovskite Induced by an Electric Field”, The International Conference on Solution Processed Innovative Solar Cells, 8th - 9th September 2016, Berlin, Germany.
42. Mahboubi Soufiani, Z. Hameiri, S. Meyer, S. Lim, M. J. Y. Tayebjee, J. S. Yun, A. Ho-Baillie, L. Spiccia and M. A. Green (2016), “Lessons Learnt from Spatially-resolved Electro- and Photo-luminescence Imaging: Interfacial Delamination in CH3NH3PbI3 Planar Perovskite Solar Cells upon Illumination”, Asia-pacific Solar Research Conference and the 4th Australian Centre for Advanced Photovoltaics Conference, 28 Nov to 2 December 2016 (Oral)
43. Q. Ma, S. Huang, C. F. J. Lau, X. Deng, M. Zhang, M. Green, A. Ho-Baillie (2016), “Inorganic CsPbI2Br Perovskite Solar Cells”, Asia-pacific Solar Research Conference and the 4th Australian Centre for Advanced Photovoltaics Conference, 28 Nov to 2 December 2016 (Oral)
44. Shi, T. Young, J. Kim, Y. Sheng, L. Wang, Y. Chen, Z. Feng, P. J. Verlinden, M. Keevers, M. Green, A. Ho-Baillie (2016), “Accelerated Lifetime Testing of Organic-Inorganic Perovskite Solar Cells Encapsulated by Poly-isobutylene”, Asia-pacific Solar Research Conference and the 4th Australian Centre for Advanced Photovoltaics Conference, 28 Nov to 2 December 2016 (Oral)
45. F. J. Lau, X. Deng, Q. Ma, J. Zheng, J. S. Yun, M. A. Green, S. Huang, A. W. Y. Ho-Baillie (2016), “CsPbIBr2 Perovskite Solar Cell by Spray Assisted Deposition”, Asia-pacific Solar Research Conference and the 4th Australian Centre for Advanced Photovoltaics Conference, 28 Nov to 2 December 2016 (Oral)
46. N. Chang, A. Ho-Baillie, P. A. Basore, T. Young, R. Evans, R. J. Egan (2016), “A Manufacturing Cost Analysis Method for Early Stage Technologies”, Asia-pacific Solar Research Conference and the 4th Australian Centre for Advanced Photovoltaics Conference, 28 Nov to 2 December 2016 (Oral)
47. J. Kim, J. S. Yun, B. Wilkinson, X. Deng, Y. Cho, A. Mahboubi Soufiani, D. Lee, M. A. Green, S. Huang, A. Ho-Baillie, “Towards Large Area and High Efficiency Perovskite Solar Device by Modified Spin-Coating Process”, Asia-pacific Solar Research Conference and the 4th Australian Centre for Advanced Photovoltaics Conference, 28 Nov to 2 December 2016 (Oral)
48. M. M. Lunardi, A. Ho-Baillie. S. Moore, J. P. Alvarez-Gaitan, and R. Corkish (2016), “Life Cycle Assessment and Energy Payback Time of Perovskite/Si Tandem Solar Cells”, Asia-pacific Solar Research Conference and the 4th Australian Centre for Advanced Photovoltaics Conference, 28 Nov to 2 December 2016 (Oral)
49. Ho-Baillie (2016), “Perovskite Solar Cell Research under Australian Centre of Advanced Photovoltaics”, Asia-pacific Solar Research Conference and the 4th Australian Centre for Advanced Photovoltaics Conference, 28 Nov to 2 December 2016 (Oral)

50. Ho-Baillie (2016), "Opportunities and Challenges of Perovskite Solar Cells", The 13th International Conference on Optoelectronic and Microelectronic Materials and Devices, 12-14 DECEMBER, 2016, The University of New South Wales, Sydney, Australia (Invited)
51. Cho Fai Jonathan Lau, Meng Zhang, Xiaofan Deng, Jianghui Zheng, Jueming Bing, Qingshan Ma, Jincheol Kim, Long Hu, Martin A. Green, Shujuan Huang, and Anita Ho-Baillie (2017), "Highly Efficient Strontium Doped Low Temperature Processed CsPbI2Br Perovskite Solar Cells", 2017 International Symposium on Energy Conversion and Storage Materials, Brisbane, 31th July 2017 – 3rd Aug 2017. (Oral)
52. M Zhang, JS Yun, Q Ma, J Zheng, CFJ Lau, X Deng, J Kim, D Kim, J. Seidel , M. A. Green, S. Huang, and A. W. Y. Ho-Baillie (2017), "High-Efficiency Rubidium-Incorporated Perovskite Solar Cells by Gas Quenching", 3rd International Conference on Perovskite Solar Cells and Optoelectronics, Oxford, United Kingdom from 18th – 20th September 2017. (Oral).
53. Jae S. Yun, Jincheol Kim, Trevor Young, Rob Patterson, Hongze Xia, Dohyung Kim, Jan Seidel, Sean Lim, Sheng Chen, Martin A. Green, Shujuan Huang, and Anita Ho-Baillie (2017), "Humidity Induced Degradation via Grain Boundaries of HC(NH2)2PbI3 Planar Perovskite Solar Cells", Asia-pacific Solar Research Conference, Melbourne, 5 to 7 December 2017 (Oral)
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55. Jianghui Zheng, Long Hu, Jae S. Yun, Meng Zhang, Cho Fai Jonathan Lau, Jueming Bing, Xiaofan Deng, Qinshan Ma, Yongyoon Cho, Weifei Fu, Chao Chen, Martin A. Green, Shujuan Huang and Anita W. Y. Ho-Baillie (2017), "Solution-processed, silver-doped NiOx as hole transporting layer for high efficiency inverted perovskite solar cells", Asia-pacific Solar Research Conference, 5 to 7 December 2017 (Oral)
56. Ho-Baillie (2017), "Opportunities and Challenges of Perovskite Solar Cells", 2017 International Conference on BioNano Innovation, Brisbane, 24-27 September, 2017 (Keynote)
57. Ho-Baillie (2017), "Opportunities and Challenges of Perovskite Solar Cells", 4th International Conference on Advanced Electromaterials (ICAE 2017), 21 to 24 November 2017, Korea (Invited).
58. U Bach, "Back-Contact Perovskite Solar Cells", CAMS Wollongong, November 2018 (Invited)
59. U Bach, "Back-Contact and Dipole-Field Concepts and their Application to Perovskite Solar Cells", IPEROP Kyoto, January 2018
60. U Bach, "Towards Single-Crystalline Perovskite Devices", HOPV Rome May 2019 (Invited)
61. U Bach "Towards Single-Crystalline and Back-Contact Perovskite Devices", ICMAT Singapore June 2019 (Invited)
62. J. Lu, U. Bach. "Changelings in the stability of Perovskite Solar Cell". The 7th International Forum of Huazhong University of Science and Technology For Outstanding Young Talent. Wuhan, China, 2018
63. J. Lu, U. Bach. The stability of Perovskite Solar Cell. NPU 5th Aoxiang Forum for Distinguished Young Scholars. Xi'an, China, 2019
64. Tan, S. R. Raga, A. S.R. Chesman, S. O. Fürer, F. Zheng, D. P. McMeekin, L. Jiang, W. Mao, X. Lin, X. Wen, J. Lu, Y.-B. Cheng, J. Bach, LiTFSI-Free Spiro-OMeTAD-based Perovskite Solar Cells with Power Conversion Efficiencies Excedding 19%, MRS Fall Meeting, Boston, the U.S. (2018).
65. T. White, "Perovskite-silicon tandem solar cells: progress, challenges and opportunities," Keynote presentation, OSA Light, Energy and the Environment Congress, Singapore, November 2018.

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69. Ho-Baillie, "Encapsulating Perovskite Solar Cells to Withstand Environmental Stress", 2019 Materials Research Society (MRS) Spring Meeting APR 22 –26, 2019, PHOENIX, ARIZONA Symposium ES16, "Perovskite Photovoltaics and Optoelectronics" (Invited)
70. K. Catchpole, "Perovskite-Based Tandems—Approaches to High Efficiency", 2019 Materials Research Society (MRS) Spring Meeting APR 22 –26, 2019, PHOENIX, ARIZONA Symposium ES16, "Perovskite Photovoltaics and Optoelectronics" (Invited)
71. Ho-Baillie, "Perovskite Solar Cells", 2019 Australian Research Council Centre of Excellence in Exciton Science Seminar Series MAR 29, 2019, Monash University (Keynote)
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74. K. Catchpole, "High Efficiency Perovskite/Silicon Tandem Solar Cells", 2018 Materials Research Society (MRS) Fall Meeting NOV 25 –30, 2018, BOSTON, MASSACHUSETTS Symposium ET04, "Perovskite Solar Cells—Challenges and Opportunities" & ET02, "Silicon for Photovoltaics" (Invited)
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Patent Applications

1. "A high efficiency stacked solar cell" Application No. 2013902948
2. "Improved precipitation process for producing perovskite-based solar cells", Application No. 2014900910
3. "Interconnection arrangements for solar cells", Australian Provisional Patent Application No. 2015903675.
4. "Encapsulation and sealing method for perovskite solar cells", Australian Provisional Patent Application 2017902609
5. "Self-assembled surface passivation via lead displacement for perovskite solar cells" Provisional Application 2018901203

Transferability

- Transparent or semi-transparent electrodes necessary for the tandem demonstrations can be used for
    - bi-facial perovskite modules and
    - building or vehicle integrated photovoltaics
- Encapsulation techniques developed can be used for
    - photovoltaic glazing whether opaque, semitransparent or transparent,
    - perovskite or other types of photovoltaic technologies,
    - display technologies such as perovskite light emitting diodes.
- Interfacing approaches developed can be used for
    - double junction perovskite - perovskite tandem
    - triple junction perovskite - perovskite -silicon tandem
- Through the project, knowledge sharing has been conducted participating institutes via research exchanges and visits amongst including hands-on training and advice on
    - perovskite cell processing,
    - ITO sputtering,
    - PIB encapsulation,
    - External quantum efficiency measurement of tandem cells,
    - Maximum power point tracking measurement of solar cells.
- Knowledge sharing more broadly relative to what was originally planned:
    - Presentation to researchers: 78 (exceeded 4 / year x 4 years as planned)
    - Reports to ARENA: in 2016, 2017 and 2018 (match number planned)
    - Media and journal articles: 98 (exceeded 6 as planned)
    - Presentations at major industry conference: 2 in 2014; 2 in 2015; 2 in 2016; 1 in 2017; 5 in 2018; 2 in 2019 (exceeded planned presentations in 2016 and 2017 only)
    - Presentations to potential investors: Suzhou GCL Nanotechnology Co., Ltd, China; Jinko Solar, China; Shenzhen Heiking PV Technology, China; Dyesol now Greatcell Materials (exceeded 3 as planned)
    - Public dissemination report (as planned)
- Other projects/tools in this area by CI's in this project that contribute to the same field
    - CONTRACT RESEARCH for a Chinese Start-up, 2019-2020, "High Efficiency Monolithic Perovskite/Si Tandem Solar Cell", UNSW
    - ARENA 2017/RND012, 2017-2021, "Manufacturing of Printed Perovskite PV Modules", UNSW, CSIRO, Cambridge, Monash
    - ARC LINKAGE PROJECT LP160101322, 2016-2019, "Hermetic Encapsulated Perovskite Solar Cells for Energy Harvesting Glazings", UNSW
    - ARENA AUSTRALIAN CENTRE FOR ADVANCED PHOTOVOLTAICS, 2016-2021, "Perovskite Solar Cell Research", UNSW, ANU, Monash, UQ, CSIRO, UMel
    - ARC DISCOVERY PROJECT DP160102955, 2016-2018, "Stable Non-toxic Organic-inorganic Halide Perovskite Solar Cells", UNSW
    - ARC DP180100835, 2018-2020, "Stable and efficient perovskite solar cells", ANU
    - ARC Discovery Early Career Researcher Award DE190101501, 2019-2021, "Perovskite solar cells with printed back electrodes", Monash
    - ARC Future Fellowship FT180100302, "Perovskite-silicon tandem solar cells", ANU

Conclusion and next steps

The project has delivered "an increase in skills, capacity and knowledge" in silicon-perovskite tandem solar cell research and perovskite solar cell research through strong involvement of PhD students, postdoctoral and early career researchers, mentored by internationally prominent key researchers, with opportunities enhanced through multi-institutional academic and pre-commercialisation industrial involvement.

This project has put Australian researchers on the map of world leading perovskite research and silicon perovskite tandem research extending Australia's world-class research position in photovoltaics. Spin off projects have come out of this as a result.

We have made contributions to the technology to bring it to the stage where industry can make informed decisions about large-scale investments required for market-introduction of premium products exploiting these developments. Start-ups formed for commercialising silicon-perovskite tandem include Oxford PV in the UK, and Tandem PV in the US.

On-going work of increasing the durability and lifetime of perovskite PV technology is important. Low cost materials and scalable methods need to be developed for driving the cost down. Due to the uniqueness of perovskite technology which is in the form of thin film that allows it to be applied on different kinds of substrates, niche application of perovskites should be explored allowing the technology to compete in markets (e.g., integrated photovoltaics) different to that (e.g., roof-tops and solar farms) of traditional PV technology. The advances made can be translated to other types of PV applications and next generation multi-junction tandem technologies.

Figure 1: Tandem cell being tested outdoor

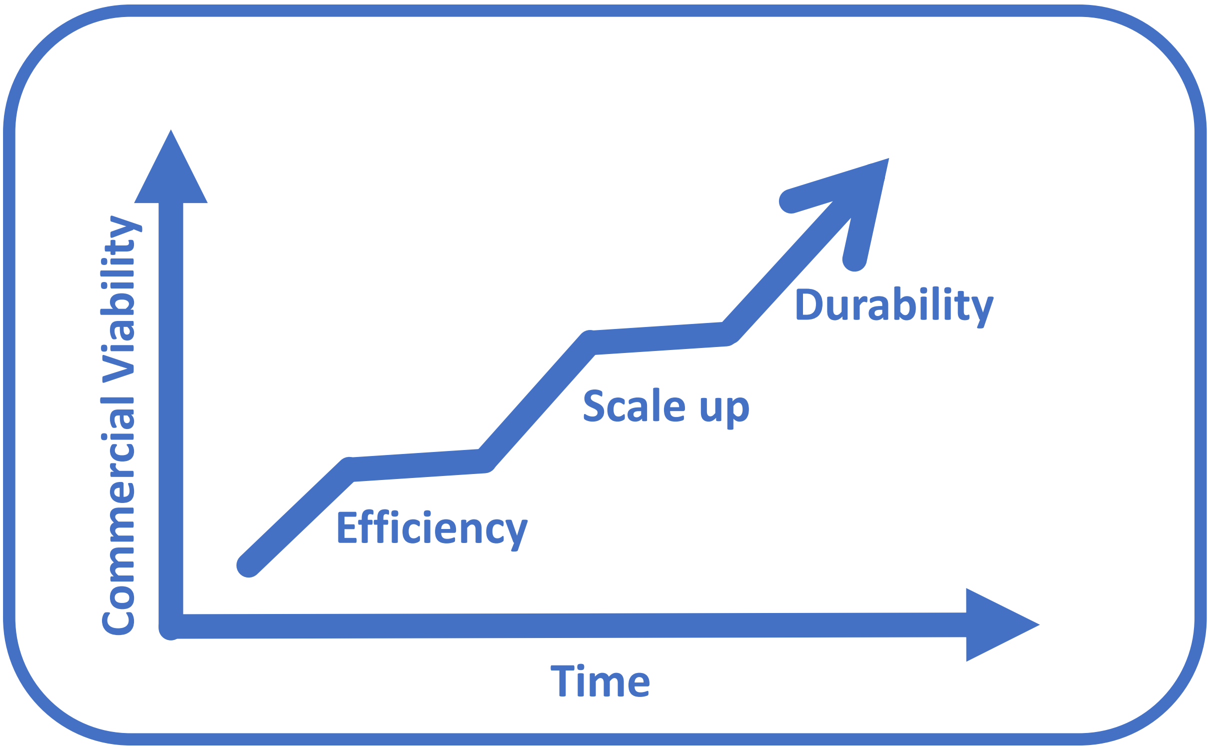

Figure 2: Pathway towards commercialisation

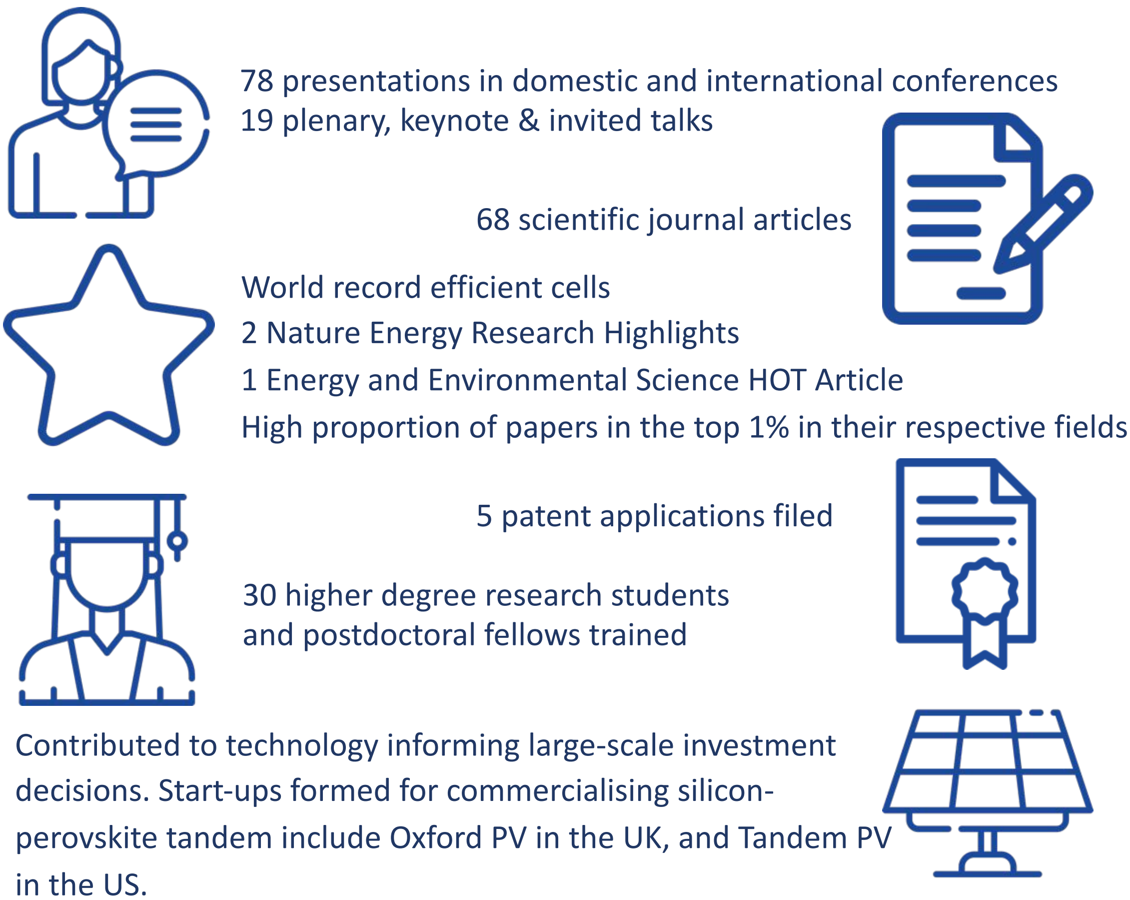

Figure 3: Project outcome info-graphics

Lessons Learnt

Lessons Learnt Report: High-Efficiency Silicon-perovskite Tandem Cells and Modules: Demonstration and Commercial Evaluation

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

Key learning

R&D is highly material intensive. Budget on materials was underestimated in the project proposal

Implications for future projects

Increase budget on materials for next R&D project

Lessons Learnt

Lessons Learnt Report: High-Efficiency Silicon-perovskite Tandem Cells and Modules: Demonstration and Commercial Evaluation

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

Key learning

The techno-economic analyses based on lab-based fabrication processes showed that, at this early stage of technology development, tandem cell efficiency targets over 35% – on commercial 6” square silicon wafers – are required, much higher than the highest efficiency demonstrated anywhere worldwide to date.

Implications for future projects

While silicon-perovskite tandem technology is a promising candidate for future high-efficiency PV cells and modules, and efficiency over 35% is not impossible for double junction tandem, focus of future projects should also be on driving cost down such as

- *The use of low cost materials*
- *The development of scalable methods suitable for volume manufacturing processing sequences, e.g., with lower material utilisation rate*

Note that scaling up to commercial cell size (e.g., 6” square) whilst maintaining efficiency is not trivial and presents another area of work for the commercialisation of this technology.

While the encapsulation schemes developed during this project are shown to be very effective in limiting environmental exposure of perovskite cells, on-going work of increasing the durability and lifetime of perovskite PV technology is important as the techno-economic analysis assumed that the lifetime of the modules and their degradation rates match those of standard crystalline silicon modules