

Australian Centre for Advanced Photovoltaics

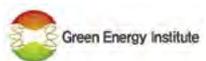
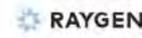
Annual Report 2020



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Acknowledgements

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Courtesy of Centre staff, students and others

Cover image
A/Prof Xiaojing Hao, ACAP researcher and recipient of the
2020 Malcolm McIntosh Prize for Physical Scientist of the Year

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ACAP

DIRECTOR'S REPORT

Solar photovoltaics involves the generation of electricity directly from sunlight when this light shines upon solar cells packaged into a solar module. Silicon is the most common material used to make these photovoltaic cells, similarly to its predominant role in microelectronics, although several other photovoltaic materials are being actively investigated.

With the devastating Australian bushfires followed by the coronavirus pandemic, 2020 was a difficult and often tragic year for many. Photovoltaics, however, continued on a positive trajectory with record levels installed globally.

Highlights were a marked change in attitude by the International Energy Agency (IEA), billing itself as “the world’s authority on energy” but with an appallingly poor past record in understanding solar’s likely impact. In the 2020 issue of the IEA’s flagship publication, the World Energy Outlook 2020, a marked change in emphasis is noted including the statement: “With sharp cost reductions over the past decade, solar PV is consistently cheaper than new coal- or gas-fired power plants in most countries, and solar projects now offer some of the lowest cost electricity ever seen.” Under the banner of “Solar becomes the new king of electricity”, solar is projected to account for most new electricity generation out to 2040, despite the IEA still underestimating likely installation rates by a huge margin.

Another 2020 highlight has been the global manufacturing industry’s almost complete adoption of UNSW PERC cell technology, where PERC stands for “passivated emitter and rear cell”, conceived and perfected at UNSW in the 1980s and 1990s. Over 90% of global production in 2020 was PERC-based, up from almost zero per cent in 2015. ACAP played a key role in this transition, the most significant in the industry over the last 40 years, through the hydrogenation work initiated and led by the late Professor Stuart Wenham. PERC has led to a new surge in solar cost reductions not only through the increased energy conversion efficiency it offers but also through its increased functionality. This includes bifacial operation at low cost, boosting system output by 5–20% via light incident on the rear of solar modules, and large-wafer compatibility, due to the rear patterning required with PERC allowing cutting into smaller cells after fabrication. Larger wafers have led to a push to larger module sizes over the past few years, reducing assembly, transportation and installation costs.

Australia leads the world in rooftop solar installations. The lead in small systems (<100 kW) was increased during 2020 with an additional 3 gigawatts installed during the year, a 40% increase over 2019, the previous record year, with a similar increase in large commercial systems. Solar’s contribution to electricity generation in the Australian National Electricity Market increased to 9.7% averaged over 2020, likely to exceed 12% average in 2021. Even more importantly, this strong solar contribution has significantly improved the power network’s ability to meet peaks in electricity demand during summer heatwaves, where solar is proving much more reliable than conventional coal generators, whether new or aging.

Also, on the international front, annual global photovoltaic installations increased to a new record of 145 gigawatts installed in 2020, according to market analysts. Photovoltaics also reinforced its position as one of the lowest cost options for electricity production yet developed, with wholesale module selling prices dropping 16% from 2019 averaged over the year. The lowest bid for the long-term supply of solar via a power purchase agreement decreased to US\$13.12/MWh in August 2020. In breaking news as this report goes to press, this figure was reduced to US\$10.40/MWh in early 2021, or an incredible US 1 cent/kWh, in normal household units!

Australia has played a major role in achieving these very low costs and is expected to play a key role in future cost reductions through the ongoing activities of the Australian Centre for Advanced Photovoltaics (ACAP), documented in this 2020 Annual Report.

This is the eighth annual ACAP report, with ACAP activities supported by the Australian Government through the Australian Renewable Energy Agency (ARENA). ACAP aims to significantly accelerate photovoltaic development by leveraging development of “over the horizon” photovoltaic technology, providing a pipeline of improved technology for increased performance and ongoing cost reduction. A second aim is to provide high quality training opportunities for the next generation of photovoltaic researchers, with one targeted outcome being to consolidate Australia’s position as the photovoltaic research and educational hub of the Asia-Pacific manufacturing region. In achieving these aims, ACAP works with a wide range of both local and international partners.

ACAP came into being on 1 February 2013 after the signing of a Head Agreement between the University of New South Wales (UNSW) and ARENA. During 2013, related Collaboration Agreements were signed between UNSW and the other ACAP nodes, Australian National University (ANU), University of Melbourne (UoM), Monash University, University of Queensland (UQ) and CSIRO (Materials Science and Engineering, Melbourne) and, additionally, with the ACAP industrial partners, Suntech Research and Development, Australia (SRDA) (partnership now transferred to Wuxi Suntech Power Co., Ltd), Trina Solar Ltd, BlueScope Steel and BT Imaging, and subsequently with PV Lighthouse, Greatcell Pty Ltd and RayGen Resources Pty Ltd. Our major international partners include the NSF-DOE Engineering Research Center for Quantum Energy and Sustainable Solar Technologies (QESST), based at Arizona State University, and the US National Renewable Energy Laboratory (NREL), as well as the Molecular Foundry, Berkeley, Stanford University, Georgia Institute of Technology, the University of California, Santa Barbara, and the Korean Green Energy Institute.



A handwritten signature in blue ink that reads "M.A. Green".

SCIENTIA PROFESSOR MARTIN GREEN

Director, ACAP

2020

HIGHLIGHTS

OUTSTANDING CELL EFFICIENCY RESULTS

A team at ANU, led by Dr Jun Peng and including A/Professor Thomas White, Dr Daniel Walter, Mike Tebyetekerwa, Dr Yiliang Wu, Dr The Duong, Dr Teng Lu, Dr Md Arafat Mahmud, Dr Olivier Lee Cheong Lem, Shenyou Zhao, Professor Yun Liu, Dr Heping Shen, Dr Li, Dr Felipe Kremer, Dr Hieu T. Nguyen, A/Professor Duk-Yong Choi, Professor Klaus J. Weber and Professor Kylie Catchpole, in collaboration with Sun Yat-Sen University and the Shanghai Institute of Microsystem and Information Technology achieved a certified power conversion efficiency of 21.6% for a 1 cm² cell with fill factor of 0.839. Polymer passivation layers have been shown to improve the open-circuit voltage of perovskite solar cells when inserted at the perovskite-charge transport layer interfaces but many such layers are poor conductors, leading to a trade-off between passivation quality and series resistance. The team's work introduces a nanopatterned electron transport layer that modifies the spatial distribution of the passivation layer to form nanoscale localised charge transport pathways through an otherwise passivated interface, thereby overcoming this trade-off. This work has been published in Science. Recently the team has improved the efficiency to a certified record steady-state efficiency of 22.6% with fill factors of over 86%. In addition to the efficiency record for 1 cm² cells, the achievement of fill factors >86% sets a new milestone towards the theoretical fill-factor limit.

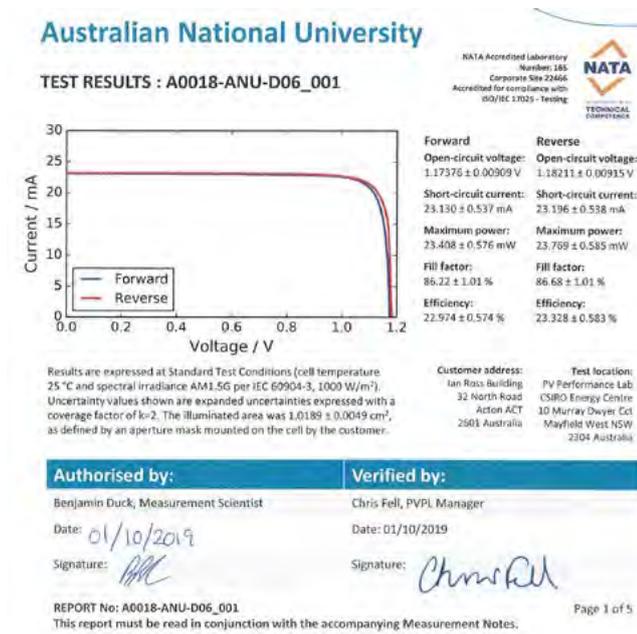


Figure 2.1: Certification of 22.6% cell with area of 1 cm².

Dr Jianjun Li, Dr Jialiang Huang, Dr Germain Rey, Dr Kaiwen Sun, Professor Xiaojing Hao and Professor Martin Green, from the UNSW node, partnered with collaborators at Jinan University, Shenzhen University, East China Normal University and Central South University achieved an independently confirmed 12.5%, a new record efficiency for pure selenide CZTSe solar cells. This work was noted in the 2019 ACAP Annual Report and it was published in 2020 (Adv. Mater. 2020, 32, 2005268). Current state-of-the-art devices experience cation-disordering defects and defect clusters, which result in severe potential fluctuation, low minority carrier lifetime, and unsatisfactory performance. The team found a way to effectively suppress detrimental intrinsic defects and activate shallow acceptor copper vacancies. This allowed the record efficiency to be demonstrated with a high open-circuit voltage of 491 mV. This demonstrates an essential route to overcome the long-standing challenge of defect control in kesterite semiconductors, which might also be more generally applicable to other compound semiconductors.

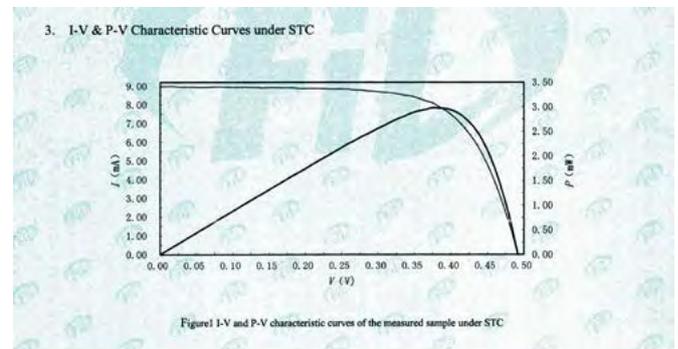


Figure 2.2: Certification of 12.5% CZTSe cell.

HIGH IMPACT PAPERS

Papers published under the ACAP program since ACAP's formation in 2013 have already been recognised as making a large impact at the international level. A total of 63 of these have been classified as "Highly Cited Papers", based on their ranking within the top 1% in their field. Nearly half of these, 29 in total, earned the additional distinction of being identified as "Hot Papers", within the top 0.1% in their field. This is a disproportionately high number relative to the total number of ACAP publications and reflects the impact and high international standing of ACAP research.

Seven additional papers were recognised as "Highly Cited Papers" in 2020 with two of these seven additionally being identified as "Hot Papers", within the top 0.1% in the field. Five of the total were based on results generated in ACAP program strand PP2: "Thin-Film, Third Generation and Hybrid Devices". With lead author Leiping Duan, affiliated with the UNSW node, the first paper published in

Energy Technology, describes the effect of air on the burn-in thermal degradation of non-fullerene organic solar cells. A second, involving researchers Udo Bach and Qiaoliang Bao from the Monash node, together with co-authors from Grenoble, Wuhan and Shenzhen, published in the *Journal of the American Chemical Society*, describes high efficiency mesoscopic solar cells using CsPbI₃ perovskite quantum dots enabled by chemical interfacial engineering.

A third, published in *Advanced Energy Materials* with lead author The Duong from the ANU node, also involving other ANU researchers and researchers from the UNSW node and ACAP partner PV Lighthouse, as well as from Flinders University and Karlsruhe Institute of Technology, investigated the effect upon solar cell performance of different strategies for combining 2D perovskites with a 3D perovskite, namely surface coating and bulk incorporation. A fourth, also published in *Advanced Energy Materials* involving researchers Xiaojing Hao and Martin Green from the UNSW node as well as from UQ and Changsha University, China, summarises the development of several types of integrated photo-rechargeable electric energy storage systems and describes their working mechanisms, plus challenges and future development opportunities in the field. The fifth, published in *Nature Energy* involving researchers Jiali Huang, Xiaojing Hao and Martin Green from the UNSW node as well as researchers from around China, describes the hydrothermal deposition of antimony selenosulfide thin films enabling the fabrication of solar cells setting a new performance milestone for this material of 10% efficiency.

The remaining two "Highly Cited" were also classified as "Hot Papers" and arose from collaboration between ACAP partners, UNSW and Colorado-based NREL, documenting recent efficiency improvements in photovoltaics across a range of technologies. Included in these two papers are the UNSW record 10% and 11% CZTS cell results, the record 21.6% ANU result for a reasonably sized perovskite solar cell, the record 20.1% result for a monolithic tandem GaAsP/Si cell fabricated by UNSW in conjunction with Ohio State University and SolAero Technologies Corp., the record 32.9% efficiency for a GaInP/GaAs multiple quantum well cell fabricated by NREL in conjunction with UNSW, as well as the UNSW 34.5% result for a one-sun

minimodule involving Si plus GaInP/GaInAs/Ge tandem cells, a UNSW concentrator submodule of 40.6% efficiency, using similar technology, and a UNSW 21.7% large-area Si concentrator cell.

Another group of papers was selected as sufficiently timely and interesting to provide the cover illustration for some of the field's most prestigious journals. One example with lead author Hieu Nguyen of the ANU node titled "Spatially and Spectrally Resolved Absorptivity: New Approach for Degradation Studies in Perovskite and Perovskite/Silicon Tandem Solar Cells" was selected as the January issue back cover of *Advanced Energy Materials* (Figure 2.3(a)). Another paper also with lead author Hieu Nguyen investigating the hydrogenation mechanisms of different capping layers on poly-Si passivating contacts was selected as the frontispiece of *Solar Rapid Research Letters* in March (Figure 2.3(b)). A third paper with lead author Raghavi Bhoopathy of the UNSW node titled "Outdoor photoluminescence imaging of solar panels by contactless switching: Technical considerations and applications" was selected for the front cover of the March issue of the journal, *Progress in Photovoltaics* (Figure 2.3(c)). A fourth paper with lead author Hong Duc Pham from UQ titled "Development of Dopant-Free Organic Hole Transporting Materials for Perovskite Solar Cells" featured on the front cover of the April issue of *Advanced Energy Materials* (Figure 2.3(d)). As a final example, a paper with lead author Da Seul Lee of the UNSW node investigating grain quality engineering for organic metal halide perovskites using mixed antisolvent spraying treatment was selected as the January frontispiece of *Solar Rapid Research Letters* (Figure 2.3(e)).

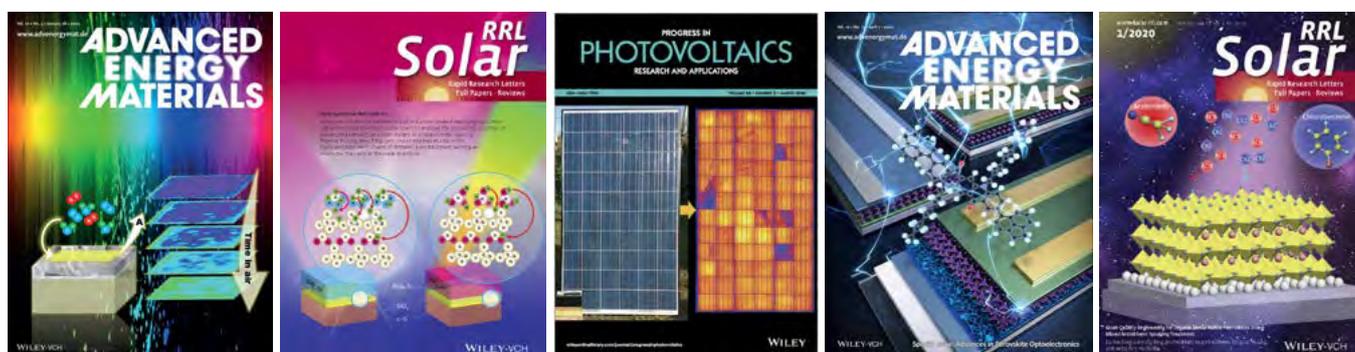


Figure 2.3: Examples of journal covers where ACAP work was featured in 2020: (a) *Advanced Energy Materials* (January). (b) *Solar Rapid Research Letters* (March). (c) *Progress in Photovoltaics* (March). (d) *Advanced Energy Materials* (April). (e) *Solar Rapid Research Letters* (January).

ACAP'S SCIENTISTS IN STANFORD WORLD RANKING

Stanford University, together with the publishing house Elsevier and SciTech Strategies, has created a list of 2% of the best scientists in the world based on their career performance, including the following current and past 15 members of ACAP:

- Udo Bach (Monash)
- Andrew Blakers (ANU)
- Paul L. Burn (UQ)
- Kylie Catchpole (ANU)
- Gavin Conibeer (UNSW)
- Andres Cuevas (ANU)
- Michael S. Fuhrer (Monash)
- Martin A. Green (UNSW)
- Andrew B. Holmes (UniMelb)
- Daniel Macdonald (ANU)
- Leone Spiccia (Monash)
- Alistair Sproul (UNSW)
- Thorsten Trupke (UNSW)
- Stuart Wenham (UNSW)
- Jianhua Zhao (UNSW)

The database of top scientists is publicly available and provides standardised information on citations, h-index, co-authorship adjusted hm-index, citations to papers in different authorship positions and a composite indicator. The database is available at: <https://doi.org/10.1371/journal.pbio.3000918>.

SCIENTIA ASSOCIATE PROFESSOR XIAOJING HAO AWARDED THE PRIME MINISTER'S PRIZE FOR SCIENCE



Figure 2.4 Scientia Associate Professor Xiaojing Hao – winner of the Prime Minister's prize.

Scientia Associate Professor Xiaojing Hao was awarded the 2020 Malcolm McIntosh Prize for Physical Scientist of the Year.

The prize, considered to be Australia's most prestigious award for outstanding achievements in scientific research, research-based innovation, and excellence in science teaching, is focused on the recognition of her development of thin-film solar cells that are flexible, stable and inexpensive.

Her work in the sulfide kesterite material Copper-Tin-Zinc-Sulfide (CZTS) has immediate and direct commercial relevance in producing thin-film solar cells on glass or on flexible surfaces.

The constituent materials are Earth-abundant, non-toxic and can be manufactured into thin-film solar cells using current commercially available equipment.

Her research in CZTS and similar materials when combined with silicon solar cells can be used to make tandem cells where a thin-film solar cell is deposited directly on top of a silicon solar cell. When properly matched, the thin-film cell will convert part of the spectrum into electricity and pass the unused spectrum to the silicon solar cell beneath it. By combining the output of both cells more energy is collected from the same area. The significance and commercial potential of Associate Professor Hao's pioneering technology is reflected in the \$23 million plus in competitive research grants that her work at UNSW has attracted since 2011. <https://www.industry.gov.au/data-and-publications/prime-ministers-prizes-for-science-2020/2020-malcolm-mcintosh-prize-for-physical-scientist-of-the-year>

PROFESSOR RENATE EGAN INDUCTED AS FELLOW IN THE AUSTRALIAN ACADEMY OF TECHNOLOGY AND ENGINEERING (ATSE)



Figure 2.5: Professor Renate Egan inducted as Fellow of the Australian Academy of Technology and Engineering.

Professor Renate Egan with the School of Photovoltaics and Renewable Energy Engineering and UNSW Lead for ACAP has been inducted as a Fellow of the Australian Academy of Technology and Engineering.

She has been recognised for making an exceptional impact on the engineering, science and business of photovoltaics for more than 25 years and is acknowledged nationally and internationally as a

thought leader in her field. She holds senior leadership positions with companies and international agencies. An innovator, entrepreneur and academic, Professor Egan is co-founder of a successful Australian start-up, an in-demand speaker and an influential member of expert panels. ATSE Fellows are elected by their peers for outstanding contributions to advancing engineering, technology, and applied science.

<https://www.atse.org.au/news-and-events/article/newfellows2020/>

ASSOCIATE PROFESSOR BRETT HALLAM AWARDED IEEE STUART R WENHAM AWARD



Figure 2.6: Associate Professor Brett Hallam has been named the 2020 recipient of the IEEE Stuart R Wenham Young Professional Award, for outstanding contributions to photovoltaics technology.

Associate Professor Brett Hallam won the 2020 IEEE Stuart R Wenham Young Professional Award, the highest award globally in the field of photovoltaic technology for young researchers.

The annual award recognises one individual for their significant contributions to the science and technology of photovoltaic energy conversion, and their potential as a future leader in the field of photovoltaics.

The award is named in honour and memory of the late UNSW solar technology pioneer Professor Stuart Wenham, in recognition of his profound contributions to photovoltaics.

ASSOCIATE PROFESSOR BRETT HALLAM AWARDED THE EDGEWORTH DAVID MEDAL



Figure 2.7: Associate Professor Brett Hallam awarded the Edgeworth David Medal.

Associate Professor Brett Hallam was awarded the Edgeworth David Medal. His work on hydrogen passivation to avoid light-induced degradation of solar cells means that the cost of PV can be reduced greatly, increasing the competitiveness of this form of electricity compared with that generated by fossil fuels.

Established in 1948, the Edgeworth David Medal is awarded annually for distinguished research by a young scientist under the age of 35 for work undertaken mainly in Australia or contributing to the advancement of Australian science.

UNSW WELCOMES GOVERNMENT MPS TO CAMPUS FOR RENEWABLES SHOWCASE



Figure 2.8: Professor Alistair Sproul, Federal MP Dave Sharma, Federal MP Trent Zimmerman and Professor Renate Egan (left to right).

Federal Member for North Sydney Trent Zimmerman MP and Federal Member for Wentworth Dave Sharma MP visited UNSW SPREE and ACAP to see work on renewable energy technology.

Renewable technology remains an important area of policy focus, as it offers Australia the chance to create new jobs and businesses, while also securing energy supply and reducing carbon emissions.

The MPs visited the Tyree Energy Technologies Building, including the rooftop solar installation, to learn about the UNSW node's pioneering work in solar photovoltaics, current and future developments in devices, technology and industry as well as energy storage technology.

RANDWICK MAYOR VISITS SPREE AND ACAP



Figure 2.9: Dr Oliver Kuntz, Professor Renate Egan, Deputy Mayor Philpa Veitch, Professor Thorsten Trupke, Robert Largent, Mayor Danny Said (left to right).

The Mayor of Randwick, Danny Said and Deputy Mayor, Philpa Veitch visited UNSW SPREE and ACAP in October to find out about photovoltaic research, view the laboratories and investigate and promote possible collaboration between the research institutions and local government.

In November, Mayor Said returned for further discussions on project-specific topics with ACAP academics.

ARENA BOARD VISITS UNSW ACAP NODE



Figure 2.10: ARENA visits UNSW SPREE and ACAP

The board of ARENA visited UNSW SPREE and ACAP in November, seeing the Thin-Film Laboratory, the Solar Industrial Research Facility and viewing a presentation by the winner of the Prime Minister's Prize for Science, Associate Professor Xiaojing Hao.

Professor Renate Egan (UNSW Lead, ACAP) presented a seminar and Q&A information session on past and current achievements of photovoltaics research in Australia, a review of ACAP's current research, industry links and the projected worldwide impact of advanced PV technology.

WORKSHOPS AND CONFERENCES

Throughout 2020 ACAP participated in workshops and conferences:

- Workshop on 100% renewable energy futures at ANU attended by 60 specialists including many from ACAP, February 2020
- IEEE 47th PVSC (online)
- Asian PVSEC in Korea (hybrid)
- EU PVSEC (online)
- APSRC 30 November – 2 December 2020 (hybrid)
- ACAP Conference 2–3 Dec 2020 (online)

EU PVSEC 2020 POSTER AWARD

Andrew Blakers (ANU, lead author) with co-authors M. Stocks, B. Lu and C. Cheng were awarded the best poster award for "Australia, a Global Renewable Energy Pathfinder" at the EU PVSEC 2020

ACAP CONFERENCE POSTER AWARDS

The 2020 ACAP best poster award for staff was awarded to two individuals in different topic areas for their outstanding work.

The best poster for staff award went to co-winners Juengeun Kim (CSIRO) for the poster "Vacuum-Free Roll-to-Roll Processed Perovskite Solar Cells Enable Ultra-Fast Composition Screening" and to Boer Tan (Monash) for the poster "The Impact of Spiro-OMeTAD Photodoping on the Reversible Light-induced Transients of Perovskite Solar Cells".



Figure 2.11: Juengeun Kim was co-winner of the ACAP best staff poster award.

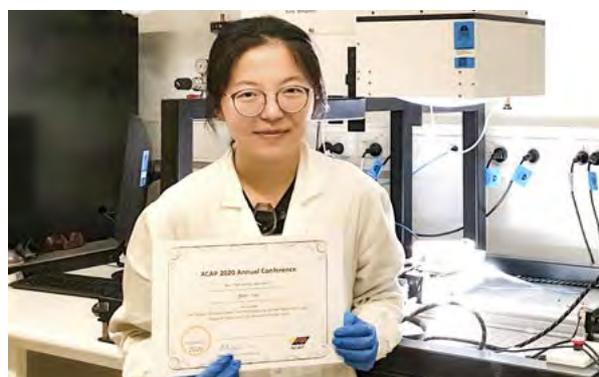


Figure 2.12: Boer Tan was co-winner of the ACAP best staff poster award.

The best student poster went to Hui Li (UQ) for the poster "Fluorinated additives for high efficiency perovskite solar cells".

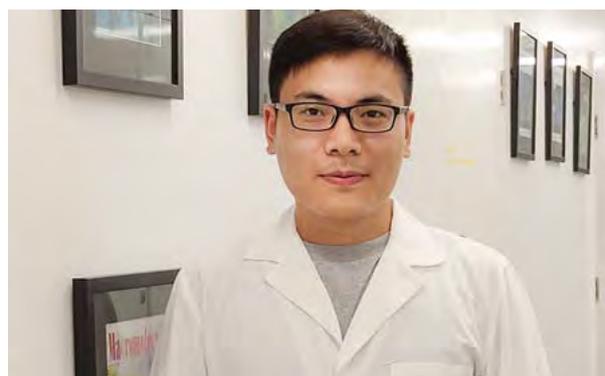


Figure 2.13: Hui Li won the ACAP best student poster award.

APSRC CONFERENCE POSTER AWARDS

The APVI Wal Read Memorial Award for Best Student Poster and the APVI Muriel Watt Prize for best poster from a woman in solar energy research were both awarded to Utkarshaa Varshney (UNSW) for "Impact of Silicon Substrate Thickness on the Degradation in Multicrystalline Silicon Wafers".

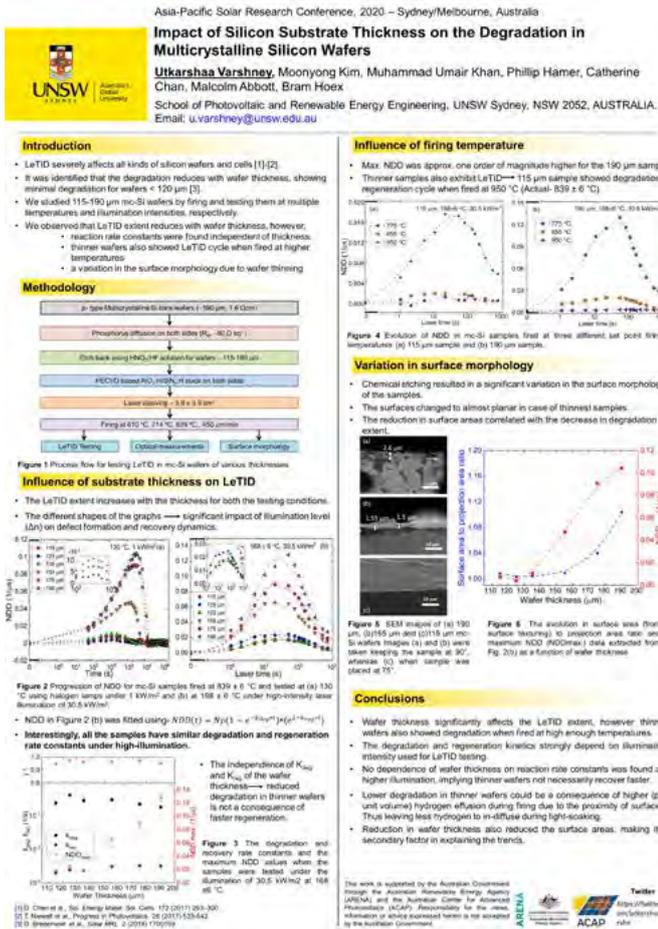


Figure 2.14: Utkarshaa Varshney was awarded the APVI's Wal Read Memorial Award and the Muriel Watt Prize.

THE IEEE PVSC 47 PAPER AWARDS



The 47th IEEE Photovoltaic Specialist Conference was held online.

Saman Jafari's (UNSW) paper "Boron-oxygen related light-induced degradation of Si solar cells: Transformation between minority carrier trapping and recombination active centers" won Best Student Paper in Area 4: Silicon Photovoltaic Materials and Devices.

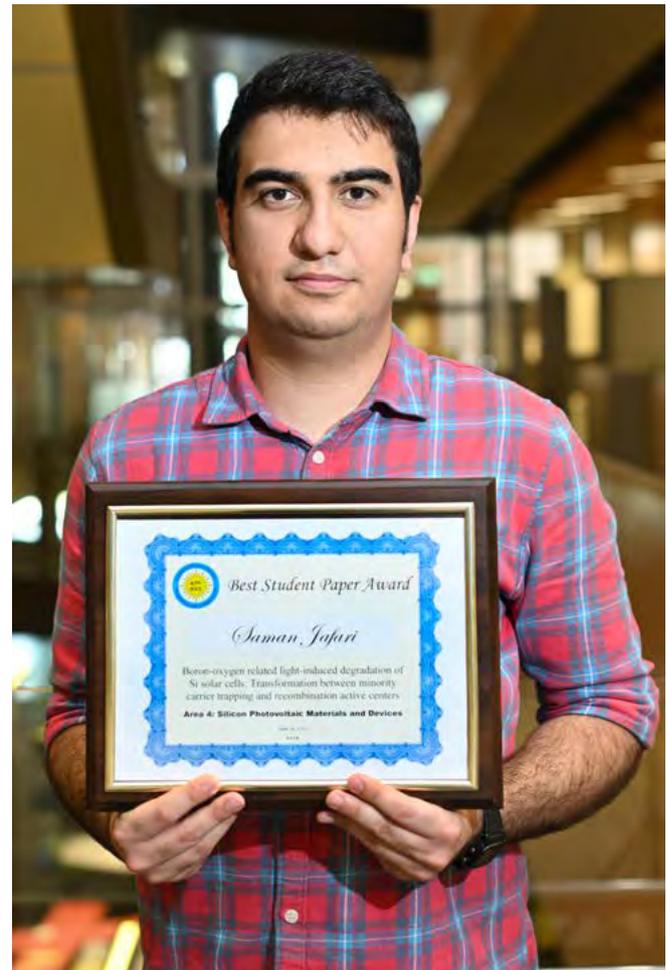


Figure 2.15: Saman Jafari awarded the IEEE PVSC Best Student Paper Award in Area 4.

Shuai Nei's (UNSW) paper "Temperature-dependent photoluminescence imaging using non-uniform excitation" won Best Student Paper in Area 5: Characterization Methods.



Figure 2.16: Shuai Nei awarded the IEEE PVSC Best Student Paper Award in Area 5.

BRUNO VICARI STEFANI WON THE THREE MINUTE THESIS

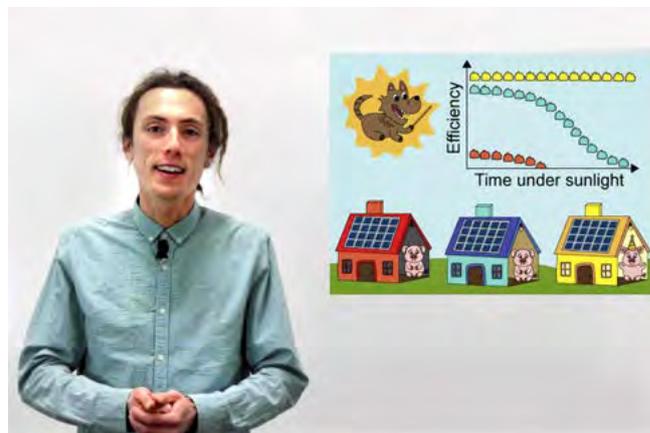


Figure 2.17: PhD candidate Bruno Vicari Stefani won first place in UNSW Three Minute Thesis.

Bruno Vicari Stefani from UNSW SPREE won the 2020 UNSW Three Minute Thesis (3MT) competition with his presentation "Low-cost solar energy with low-cost materials: a tale of three grown-up pigs."

The 2020 3MT was an online event where finalists submitted video entries lasting no more than 180 seconds to explain their research and its importance.

The award came with \$3000 in prize money.

<https://www.youtube.com/watch?v=CnObdXNm1a0>

ORGANISATIONAL STRUCTURE AND RESEARCH OVERVIEW

The Australian Centre for Advanced Photovoltaics (ACAP) was established to develop the next generations of photovoltaic technology and to provide a pipeline of opportunities for performance increase and cost reduction. The Australian partners in ACAP are the University of New South Wales (UNSW), the Australian National University (ANU), the University of Melbourne (UoM), Monash University, the University of Queensland (UQ) and CSIRO, plus our industrial partners Wuxi Suntech Power Co. Ltd, Trina Solar Ltd, BlueScope Steel, BT Imaging, PV Lighthouse, Greatcell Solar, RayGen Resources Pty Ltd and, Tindo Operations Co Pty Ltd. ACAP links with international partners, specifically the National Science Foundation and Department of Energy–supported Engineering Research Center for Quantum Energy and Sustainable Solar Technologies (QESST), based at Arizona State University, the National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory (LBNL), Stanford University, Georgia Institute of Technology and the University of California, Santa Barbara. ACAP began its life as the Australian side of an Australia–US partnership but formal collaboration began to expand globally in 2019 and beyond, with the addition of the Green Energy Institute (GEI), based in South Korea, to the set of research partners. These national and international research collaborations provide a pathway for highly visible, structured photovoltaic research collaboration between Australian and international researchers, research institutes and agencies, with significant joint programs based on the clear synergies between the participating bodies.

ACAP is driving significant acceleration of photovoltaic development beyond that achievable by institutes acting individually, with significant leveraging of past and current funding. This program is supported by the Australian Government through the Australian Renewable Energy Agency (ARENA). The Australian Government, through ARENA, is supporting Australian research and development in solar photovoltaic and solar thermal technologies to help solar power become cost competitive with other energy sources. (The views expressed herein are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained within this report.)

The organisational chart is shown in Figure 3.1. The international activities are coordinated by an International Advisory Committee with membership drawn from ARENA, researcher representatives from several countries, a representative nominated by major industry partners, and the Director of ACAP. The International Advisory

Committee is also charged with identifying, developing and monitoring progress in areas where synergies exist between Australian and international nodes that can be exploited and to monitor joint collaborative projects with existing and new partners. Some examples of current international activities, many arising from competitive ACAP Collaboration Grants, are reported in Chapter 6 and the Appendix of this report.

As well as these collaborative activities, the major partners, ACAP, QESST and NREL, conduct their own largely independent research programs meeting the specific research and training objectives of their major supporters and sponsors. In the case of ACAP, research is milestone driven with annual milestone targets established through each year's Action Plan, in accordance with the Funding Agreement with ARENA.

ACAP's National Steering Committee comprises a representative of ARENA, industrial and academic representatives and the node directors.

ACAP is managed by a Management Committee, which consists of the node leaders or delegates from each of the nodes. The Management Committee takes advice from the National Steering Committee, with an independent Charter, but with membership including representatives from each node and the Director and Manager of ACAP.

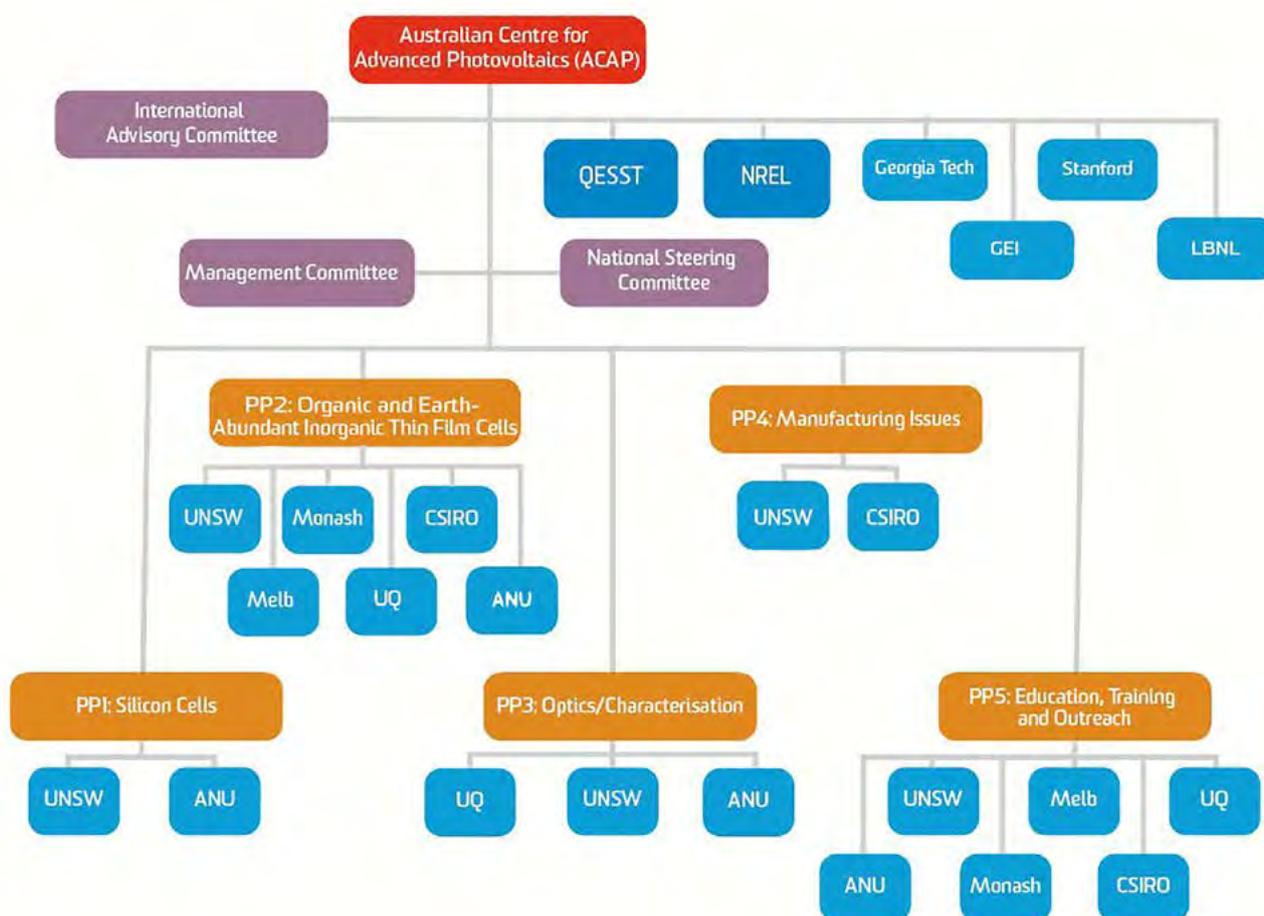


Figure 3.1: Organisational chart. Collaborating industry participants are involved in collaborative research as well as in the Advisory and Steering Committees.

As indicated in Figure 3.1, the ACAP program is organised under five Program Packages (PP1–PP5), each supported by multiple nodes. PP1 deals with silicon wafer-based cells, by far the dominant photovoltaic technology commercially, and likely to remain so for at least the next 10 years. Here the challenge is to continue to reduce manufacturing costs and degradation, while maintaining or preferably, improving, energy conversion efficiency. PP1 focuses on three main areas: cells made from solar-grade silicon, rear contact cells and silicon-based tandem cells, both monolithic and mechanically stacked.

PP2 involves collaborative research into a range of organic, organic-inorganic hybrid cells and “Earth-abundant” thin-film materials, including Si and Cu ZnSnS (CZTS), as well as more futuristic “third generation” approaches. Since ACAP’s inception, the relatively new photovoltaic material, the organic-inorganic perovskites, has been included within the scope of this program package and additional funding has been provided from 2016 to expand and intensify the research on these materials and devices. The program now has the overall goal of demonstrating high efficiencies for these new thin-film cells of above 1 cm² area and of demonstrating the feasibility of costs below the US Department of Energy SunShot targets for cost reductions.

PP3, “Optics and Characterisation”, targets experimental demonstration that theoretical conversion limits can be increased by the use of structures that have a high local density of optical states, with particular emphasis on thin-film organic and inorganic solar cells.

PP4, “Manufacturing Issues”, aims at delivery of a substantiated methodology for assessing life cycle costs of the different technologies under investigation by ACAP. The overall cost target is to undercut the US Government’s SunShot targets, for one or more of the technologies, in at least one major SunShot targeted application, as deduced by a substantiated costing methodology. Environmental costs are also considered by ACAP, through application of the rigorous life cycle assessment regime and end-of-life options.

Additional targets for PP1–PP5 may be established through the Action Plan for each year.

PP5 involves education, training and outreach. ACAP monitors the number of researchers in different categories benefiting from the support it provides, as well as outreach activities, including public lectures on material relevant to ACAP activities, newspaper and magazine articles, responses to governmental calls for submissions, visits by policy developers and their advisors, information papers and presentations to both policy developers and their advisors.

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PP1

SILICON SOLAR CELLS

OVERVIEW

Silicon-based solar cells make up more than 95% of commercial solar products worldwide. The continuous decline in costs, improved efficiencies and highly advanced and matured industrial processes indicate that this share would potentially increase further in the upcoming time. Despite tremendous growth in the past few decades, the industry continues to focus on making cheaper and more efficient solar cells. ACAP's Program Package 1 (PP1) supports the fundamental research leading towards better, cheaper and more efficient cells. In particular, it focuses on areas of low-cost solar-grade silicon material, rear-contact high efficiency cells, passivated contacts, and the growing silicon tandem structures.

PP1.1 SILICON SOLAR

Utilising a low-cost silicon material is one of the ways to further reduce the cost of industrial solar cells. Solar-grade silicon material offers one such alternative to expensive electronic-grade silicon. The research focusing on upgraded metallurgical-grade (UMG) silicon material is carried out at ANU and UNSW in collaboration with Apollon Solar (UMG silicon wafer provider). With the development of a pre-treatment step of Tabula-Rasa, ANU was successful in achieving world record efficiency of 22.6% (certified) on a 2 cm × 2 cm cell fabricated at ANU on an n-type Cz-grown UMG wafer supplied by Apollon Solar. The further progress towards achieving 23% target efficiency based on the new electroplating-free metallisation process developed at ANU, was hindered due to lab closures corresponding bushfires, hailstorms and the COVID-19 pandemic. However, the work on oxygen-related defects in silicon continued to demonstrate the role of Tabula-Rasa in inhibiting the ring defects in UMG wafers. In addition, for the first time, it was reported that the thermal donors that are generated at ~400°C causes the formation of recombination-active oxygen precipitate nuclei, which responds differently to gettering and hydrogenation steps. In 2021, significant progress in understanding the metal impurity gettering and achieving >23% efficiencies is expected.

The UNSW-led hydrogenation projects continued to further improve the performance of silicon materials using advanced hydrogenation. In 2020, $V_{oc} > 735$ mV was achieved for p-type silicon heterojunction solar cells (SHJ), demonstrating that it could be cheaper to make p-type SHJ (instead of traditional n-type) in terms of dollar per watt. Secondly, using defect engineering, an additional 0.5% (absolute) efficiency boost was achieved for industrial n-type SHJ and 0.3% for n-type PERT cells. In addition, hydrogenation also led to an 0.7–0.8% (absolute) efficiency increase on inexpensive cast-monocrystalline silicon wafers. Moreover, the quest of understanding and mitigating LeTID continued with a finding that the extent of degradation depends on wafer thickness, and the LeTID regeneration rate is dependent on excess carrier density. The trials on using an industrial-scale biased annealing tool to mitigate LeTID were performed while avoiding the increase in series resistance. Finally, surface-related degradation (SRD) was investigated to study the impact of diffused emitters. In collaboration with ANU, this work is ongoing to elucidate the formation of SRD and its potential mitigation.

PP1.2A REAR CONTACT CELLS

Rear contact solar cells inherently possess high efficiency architecture by allowing greater photon collection ability and negligible front optical losses. However, the complex design also leads to a higher cost of fabrication. This project aims at making high efficiency interdigitated back contact (IBC) solar cells using industrially feasible processes. ANU has produced a record single-junction device with an efficiency of $25 \pm 0.6\%$ using their oxide-nitride-oxide (ONO) dielectric structure. Further investigations showed a strong correlation between the native ONO film having excellent surface passivation and a high refractive index of the PECVD SiN_x layer. In the future, improving IBC structures to achieve high efficiencies using polysilicon and dopant-free contact technologies is the objective.

PP1.3B PASSIVATED CONTACTS

One of the prominent loss channels in current industrial cells is the contacts at the metal/silicon interface. Passivated contacts provide a solution to that mechanism by separating the flow of electrons and holes towards different terminals of the cell. This research focuses on developing and characterising several component layers and finally fabricating the devices. Working towards the high temperature approach, a simple process to form patterned polysilicon regions, which creates both the heavily doped and lightly doped regions in one step has been developed. Using this technique, cell efficiencies of $>24\%$ are expected in 2021. Low-cost doping methods like spin-on and printed doping were also explored. The aim is to achieve $>25\%$ efficiencies for doped polysilicon contacts on small-area cells made at ANU. For the low temperature dopant-free approach, the development of electron and hole selective contacts based on copper oxide and titanium oxide films has commenced, with an objective to achieve $>20\%$ efficiencies in 2021. In 2020, the titanium nitride electron selective contacts formed by sputtering showed excellent results, with the reported efficiency of 18.7%.

PP1.3 TANDEM CELLS

Continued progress towards improving solar cell performance has brought silicon devices closer to their theoretical limit. To further advance the efficiency, research is ongoing on various materials to form tandem solar cells. In 2020, one highlight was the development of a KCN-free and H_2S -free process for making sulfide CIGS solar cells. In addition, by optimising the copper content, an 11.6% efficient cell was achieved with better carrier collection efficiency at the rear. The optimal use of silver (Ag) alloying also led to a 12% efficient CIGS solar cell with a V_{oc} of 878 mV. In the future, this value is expected to reach $\sim 14\%$ with the use of effective anti-reflection coatings. There was also progress towards the development of a high efficiency $\text{Sb}_2(\text{S,Se})_3$ solar cell with control of Se introduction cells.

The ongoing work on perovskite/Si tandem cells found that the series resistance increase is the dominating degradation factor. A low-cost strategy with improved film morphology, increased hydrophobicity, controlled crystalline growth, and diminished ion migration was developed. This significantly increased the stability of perovskite solar cells (PSCs), which retained 96% of peak efficiency after 530 hours in wetting conditions and 94% after 2200 hours in the air. They also retained 93% of peak efficiency after ~ 2000 hours under one-sun open-circuit conditions and 90% after 1000 hours at the maximum power point (MPP), respectively. Moreover, $>24\%$ efficient single-junction PSCs and $>19\%$ inverted PSCs were achieved. In 2021, the target is to make encapsulated PSCs that will maintain 20% efficiency at 85% relative humidity, 85°C , and continuous one-sun illumination. It is also expected that PSCs beyond 25% efficiency and inverted PSCs beyond 20% will be achieved.

In case of mechanically stacked GaAs tandems, ANU is working towards modifying the epitaxial process for a two-junction (2J) III-V stack cell sourced from MicroLink Devices, USA. Future work will involve the processing of substrates for 2J devices with an open rear electrode and measuring them.

PP1.1 SOLAR-GRADE SILICON

PP1.1A SOLAR-GRADE SILICON CELLS

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ACAP, ARENA, ARC, ANU

Aims

The use of low-cost solar-grade silicon materials has the potential to contribute to further reductions in the cost and embodied energy of photovoltaic modules. However, to enable the widespread industrial application of such solar-grade materials, it is necessary to demonstrate that the cell efficiency and stability is comparable to standard electronic-grade silicon wafers. To help achieve this, the aims for the previous reporting period were to: fabricate solar-grade silicon solar cells with efficiencies above 22.5% at ANU using specially optimised processes for solar-grade silicon wafers; and to demonstrate that these devices are stable under illumination.

Progress

As reported previously, in 2019 we achieved a world record efficiency of 22.6% (certified) on a 2 cm × 2 cm cell fabricated at ANU on an n-type Cz-grown upgraded metallurgical-grade (UMG) solar-grade wafer supplied by our partners Apollon Solar. This result satisfies our efficiency target of 22.5% for 2020. The cell fabrication included a pre-treatment step known as a Tabula-Rasa (or “clean slate”) that dissolves oxygen precipitate nuclei formed during ingot growth, which can otherwise lead to detrimental ring defects in solar-grade silicon wafers. The rear side of the cell features a full-area thin tunnelling oxide with an overlying phosphorus-doped polysilicon layer, to form a high quality passivated contact. This simple rear-side structure allows for high efficiency devices while retaining a low thermal budget, and provides outstanding impurity gettering. Our objectives for 2020 were to further improve this cell fabrication process, based

on a newly developed electroplating-free metallisation scheme, and improved front-side surface passivation, aiming for efficiencies on UMG wafers of above 23%. However, due to the closure of the PV laboratory at ANU from January effectively through to July, due to bushfire smoke, hailstorms and then COVID-19, we have not yet achieved this objective. We are currently processing new batches of UMG solar cells and hope to achieve the 23% target in early 2021. Figure PP1.1.1 shows a photograph of a UMG silicon wafer with solar cell precursors, fabricated at ANU in December 2020. Device modelling using Quokka indicates that the UMG material combined with our improved cell fabrication process should enable efficiencies of above 23.5%.

We also continue to work on an improved understanding of oxygen-related defects in silicon, which are important in both solar-grade silicon, and also electronic-grade wafers grown by the Czochralski process. Our work in 2020 (Basnet et al. 2020) has further elucidated the role of a Tabula-Rasa step in inhibiting the formation of oxygen-related ring defects in UMG wafers during subsequent thermal processing. Figure PP1.1.2 shows photoluminescence images of the evolution of these ring defects in UMG wafers that were subject to different Tabula-Rasa steps, followed by a high temperature oxidation. They reveal previously unknown patterns in the emergence of ring defects under different processing conditions.

We have also demonstrated for the first time that the generation of thermal donors at moderate temperatures of around 400°C already causes the formation of recombination-active oxygen precipitate nuclei. We have shown that these oxygen precipitate nuclei emit sub-bandgap luminescence, with several distinct peaks, which respond to impurity gettering and hydrogenation in different ways. We expect that these peaks will allow new insights into the roles of metal decoration and hydrogen passivation of oxygen precipitates. Rapid progress is also being made in understanding metal impurity gettering in silicon wafers via dielectric films and polysilicon passivating contacts. Based on advanced kinetic modelling, we are making new insights into the physical mechanisms behind these gettering processes, and the key role of the very thin interfacial oxide layers that can inhibit impurity gettering. We expect several publications from this work in 2021.

Relating to the stability of solar-grade silicon cells, it is now well established that hydrogen plays a central role in both the degradation and recovery processes for many important defects in silicon solar cells. Ongoing work between ANU, UNSW and ASU is aimed at revealing important details about how hydrogen is introduced into a device, and the processes that govern its diffusion and trapping.

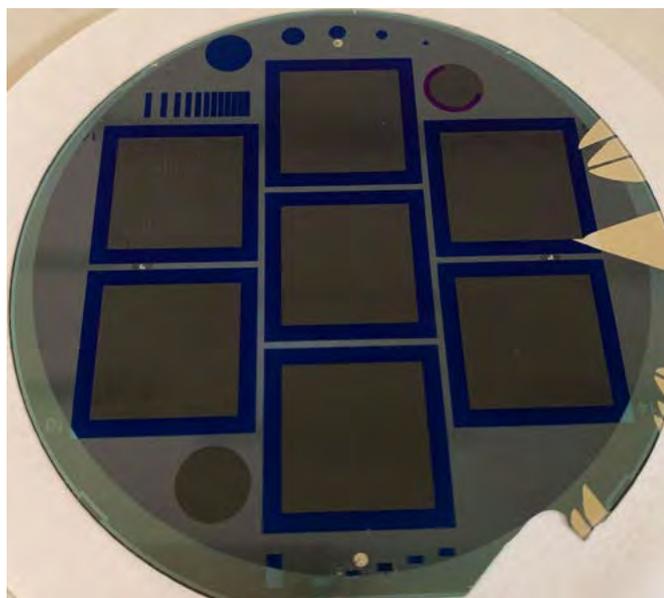


Figure PP1.1.1: Silicon wafer containing UMG solar cell precursors, fabricated at ANU.

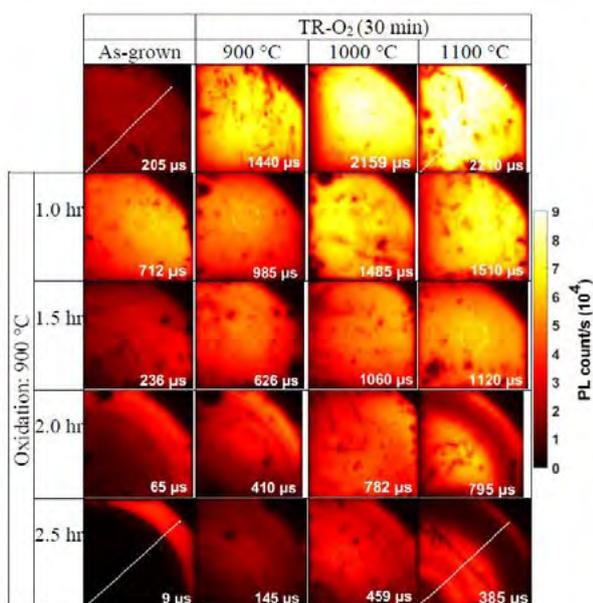


Figure PP1.1.2: Photoluminescence images of UMG silicon wafers after a Tabula-Rasa step followed by an oxidation step for various durations, revealing the emergence of oxygen-related ring defects.

References

BASNET, R., PHANG, P., SUN, C., ROUGIEUX, F. & MACDONALD, D. 2020. Onset of ring defects in n-type Czochralski silicon wafers. *Journal of Applied Physics*, 127, 153101.

PP1.1B HYDROGENATION

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ACAP, ARENA, IET AF Harvey Engineering Prize, ARC DECRA

Aims

In 2020 hydrogenation projects at UNSW focused on further improving hydrogen passivation of high efficiency technologies, as well as improving the performance and stability of current and emerging silicon materials. Excellent results have been obtained with heterojunction cell structures, and improved lifetimes and stability have also been demonstrated on cast-monocrystalline material. The group continued their work in the understanding and mitigating of LeTID in multicrystalline cells, and also investigated how surface-related degradation (SRD) might affect current and future cells.

Progress

Efficiency Improvements on Silicon Heterojunction Cells

In the last year there has been rapid progress in the efficiency of p-type silicon heterojunction (SHJ) solar cells at both UNSW and externally. In particular, efficiencies of up to 23.6% have been demonstrated (Descoeurdes et al. 2019). Recent work at UNSW has demonstrated how to make boron-doped p-type SHJ solar cells stable, with stabilised efficiencies of 22% and V_{oc} values >735 mV (Vicari Stefani et al. 2020). With this information, a Monte-Carlo simulation was performed by Chang et al. to investigate the economic feasibility of p-type SHJ solar cells. N-type wafers are currently ~10% more expensive than p-type wafers due to the strict requirements placed on wafer producers, particularly for SHJ applications. With 10% wafer premium, a 0.5% lower efficiency for p-type SHJ solar cells can be tolerated. If the difference in efficiency is less than this, it becomes cheaper to fabricate p-type SHJ solar cells in terms of \$/W.

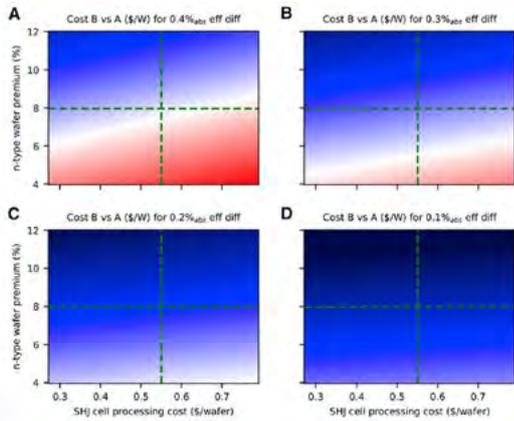


Figure PP1.13: Potential costs of n-type and p-type SHJ solar cells. Blue regions indicate where p-type devices are cheaper.

However, defect engineering is also applicable for n-type SHJ solar cells. For example, even using industrial n-type Cz wafers for SHJ applications, a significant performance enhancement can be achieved through the use of a deliberate gettering process. A collaboration with Hevel Solar has demonstrated an efficiency gain of >0.5% absolute for industrial n-type SHJ solar cells. In addition, n-type cells can benefit from the application of a post-fabrication process at the end of production to improve surface passivation and carrier transport, with efficiencies of 0.7% absolute. In the future, we will likely see the adoption of the same defect engineering processes used for p-type solar cells, such as gettering and hydrogenation, incorporated into industrial n-type SHJ solar cells.

Table 1.1.1: Efficiency of n-type SHJ solar cells before and after a post-fabrication process.

	J_{sc} (mA.cm ⁻²)	V_{oc} (mV)	FF (%)	Efficiency (%)
As received	38.18 ± 0.05	740.85 ± 0.34	77.9 ± 0.82	22.03 ± 0.23
Processed	38.18 ± 0.05	745.13 ± 0.51	79.9 ± 0.76	22.73 ± 0.22
Change	0.00 ± 0.02	4.28 ± 0.48	2.0 ± 0.72	0.70 ± 0.21

Hydrogenation Processes for n-PERT Cells

Recent years have seen n-type cell technologies rapidly gain market share. In 2020 UNSW investigated methods for improving the performance of PERT cells manufactured on n-type substrates with commercial partners. A rapid improvement in photoluminescence response was observed for hydrogenation processes up to 20 seconds (see Figure 1.1.4). This process was seen to improve efficiency by 0.3% absolute (see Table 1.1B 2), thanks to a substantial increase in open circuit voltage and fill factor. Further investigation revealed this was due to a decrease in J_0 .

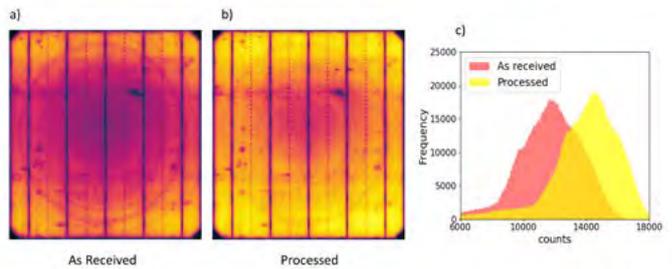


Figure PP1.1.4: Open circuit photoluminescence images (a) before and (b) after hydrogenation for 20 s.

Table 1.1B.2: Efficiency of n-type PERT solar cells before and after a post-fabrication process

	V_{oc} (mV)	J_{sc} (mAcm ⁻²)	FF (%)	η (%)
As Received	655.9	39.74	78.8	20.55
Processed	660.5	39.76	79.5	20.88
Change	+4.6	+0.02	+0.7	+0.33

Improvements in Efficiency of Cast-monocrystalline Cells

Cast-monocrystalline silicon has the potential to greatly reduce the cost of mainstream solar cells by replacing more expensive CZ wafers. In order to do so it needs to be able to demonstrate comparable performance and stability. At present, there is an enormous variation with brick height and ingot location in the efficiency of cells fabricated on cast-monocrystalline silicon, with cells from the bottom and the top of the ingot showing a 1.5% absolute difference in efficiency. This is primarily due to an increase in dislocation density near the top of the cast-monocrystalline ingot, resulting in significantly increased recombination. A post firing hydrogenation process at 390°C can passivate these dislocations (see Figure 1.1.4). This increases efficiency by 0.7–0.8% absolute on these wafers, and reduces the overall variation in efficiency to less than 1% abs.

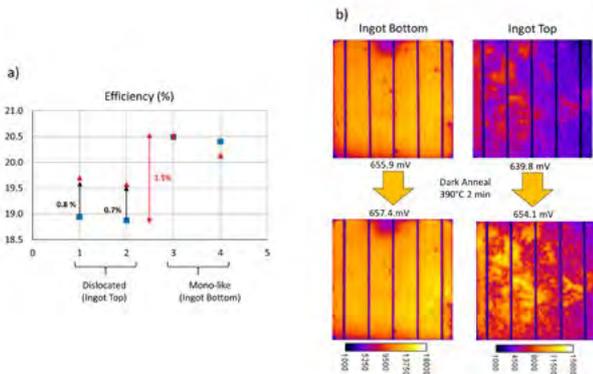


Figure PP1.1.5: (a) Efficiency before (blue squares) and after (red triangles) 390°C 2 minute dark anneal of cast-monocrystalline cells from the top (samples 1 and 2) and bottom (samples 3 and 4) of the ingot. (b) Photoluminescence images of cells before and after treatment.

Future work will focus on how to combine this increase in initial efficiency with improved stability under light soaking. If successful cast-monocrystalline silicon could rapidly increase its market share.

Understanding and Mitigating LeTID in Multicrystalline Silicon

The development of standardised testing for LeTID is an ongoing issue. Work at UNSW in 2020 has demonstrated that accelerated testing, essential for carrying out large experimental studies in a reasonable timeframe, can lead to underestimation of LeTID extent (see Figure 1.1.5). Furthermore, due to the injection-level dependence of recombination due to LeTID tracking of the voltage at maximum power point (V_{mpp}) shows a greater impact on efficiency than the more standard tracking at open circuit (Ciesla et al. 2021).

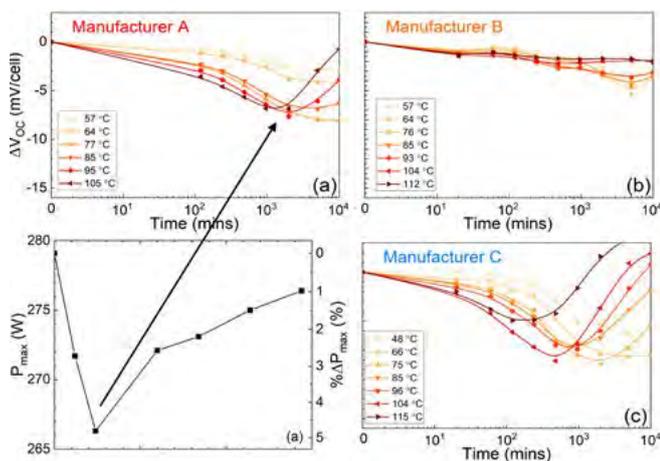


Figure PP1.1.6: (a), (b), (c) Change in open circuit voltage for multicrystalline cells under light soaking from different manufacturers. Also shown is an inset for Manufacturer A showing the corresponding loss in maximum power (note that this is on a linear scale).

The impact of wafer thickness on LeTID formation and recovery was also investigated (Varshney et al. 2021). In agreement with previous investigations it was observed that LeTID extent decreased with decreasing wafer thickness (see Figure 1.1.6). Under one-sun illumination it is also apparent that the thinner samples show a quicker recovery, leading other authors to conclude that the regeneration rate of LeTID depends on wafer thickness. However, under high intensity

illumination (30.5 suns) no significant difference in the regeneration rate is observed for the different wafer thicknesses in Figure 1.1.6 (b)). This can be explained by noting that the LeTID regeneration rate is dependent on excess carrier density. Under one-sun illumination wafers with higher extents of LeTID have much lower excess carrier densities during recovery due to their reduced carrier lifetimes. In contrast, under high intensity illumination the lifetime of all samples is limited by surface and Auger recombination, with no impact due to LeTID.

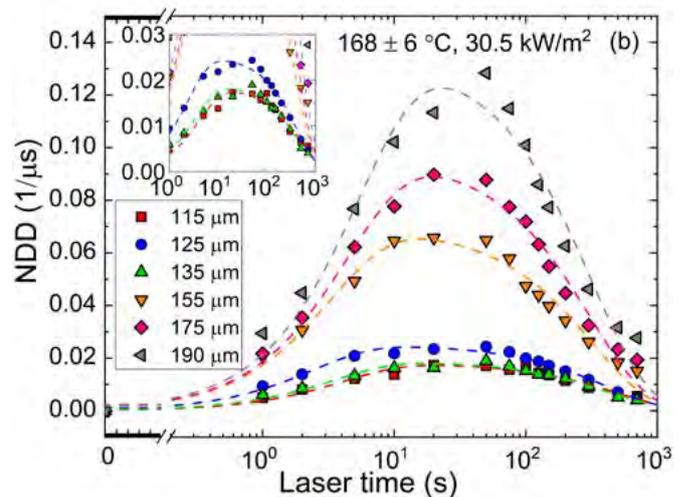
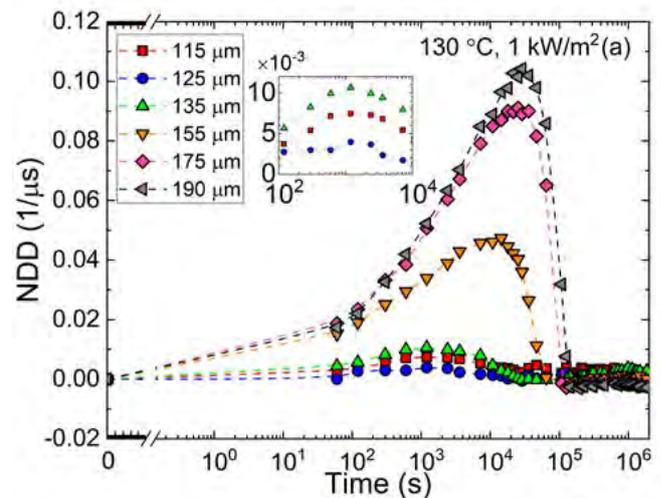


Figure PP1.1.7: Progression of normalised defect density (NDD) as a function of time for mc-Si samples fired at a sample temperature of $839 \pm 6^\circ\text{C}$ and tested at (a) 130°C using halogen lamps under 1 kW.m^2 illumination. The dotted lines are a guide to the eye and (b) at $168 \pm 6^\circ\text{C}$ under high intensity laser illumination of 30.5 kW.m^2 . The connecting lines show the actual fitting of the data. The inset shows the result in different scales.

Finally trials have been performed on using an industrial-scale biased annealing tool to mitigate LeTID while avoiding issues with series resistance. The tool is a modified version of commercial “coin-stackers”, with a very small footprint and a 400-wafer batch size. The increase in series resistance has been linked to the action of hydrogen at the front metal contacts and can be mitigated using a sufficient

reverse bias. A stack of 10 multicrystalline PERC cells was annealed at 319°C under a 30 V reverse bias for 2 hours, followed by an optimised cooling process. Figure 1.1.7 shows a median improvement in cell efficiency of 0.2% absolute, largely driven by an increase in the open circuit voltage. Importantly the Fill Factor did not drop as a result of the process, indicating there were no series resistance issues. Light soaking showed no significant decay in performance with open circuit voltages remaining above “before process” values through over 200 hours at 80°C. The commercial viability of the process was also evaluated, with the power consumption during the process identified to be the main cost driver. As such significant work has been done to reduce power consumption with a reduction of over 80% achieved on the initial best known method.

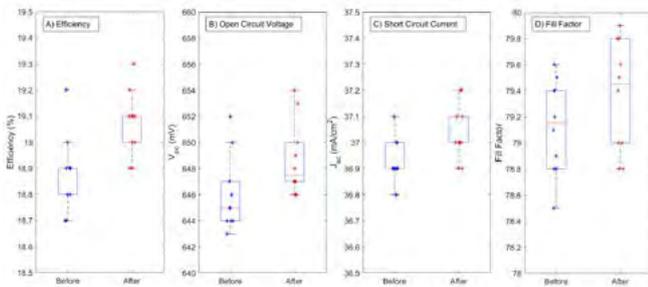


Figure PP1.1.8: (a) Efficiency; (b) open circuit voltage; (c) short circuit current; and (d) fill factor of multicrystalline cells before and after the reverse biased annealing process.

Investigating Surface-related Degradation for Silicon Solar Cells

There is increasing interest in a form of degradation that affects the near-surface region of silicon solar cells. In PERC structures this surface-related degradation (SRD) usually affects performance over time scales even longer than LeTID. In contrast to previous results (Sperber et al. 2018) UNSW observed significant SRD in samples with lightly diffused emitters (see Figure 1.1.8). SRD was also observed to occur rapidly in n-type samples with diffused surfaces under low illumination intensities (Chen et al. 2020). This is of particular importance for cells based on passivated contact structures, which often have a shallow dopant diffusion into the silicon base. Collaboration is ongoing with ANU looking at formation and mitigation of SRD in these structures.

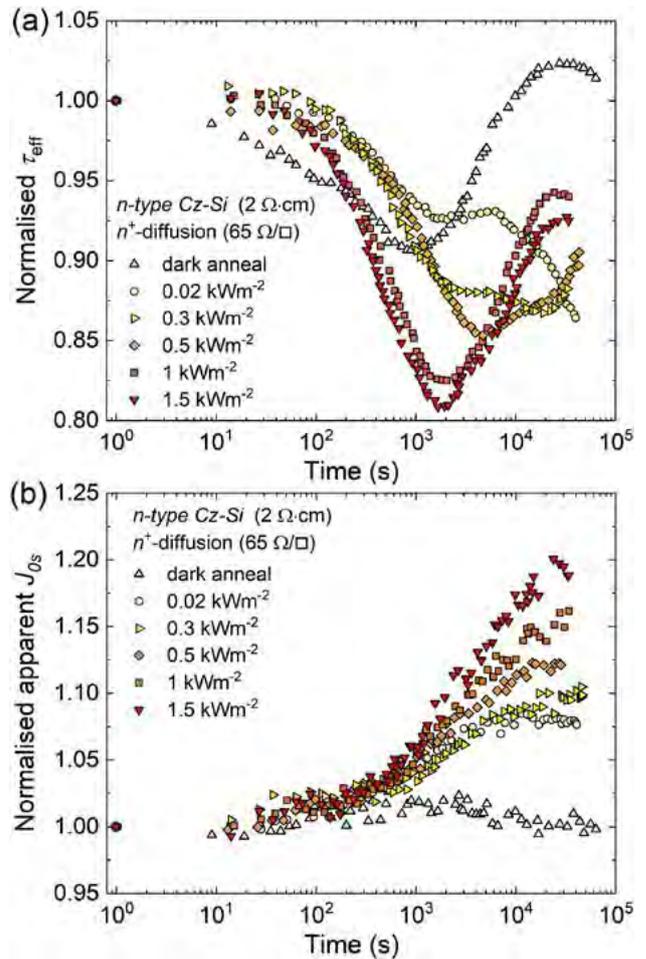


Figure PP1.1.9: (a) Normalised effective lifetime (τ_{eff}) and (b) normalised apparent surface dark saturation current (J_{0s}) as a function of time for n-type, phosphorus-diffused samples annealed at 160°C under a varying illumination intensity between 0.02 kWm⁻² and 1.5 kWm⁻². Control samples are annealed in the dark at identical temperatures (white triangle).

These results were shown to be consistent with a model of surface damage induced by a build-up of hydrogen in these regions during light soaking, with illumination acting to reduce the internal electric field which can act to repel hydrogen from the near-surface region.

Highlights

- An open-circuit voltage of over 735 mV has been demonstrated using heterojunctions on p-type silicon.
- >0.5% absolute gain in efficiency for n-type heterojunction cells as a result of the hydrogenation process.
- >0.7% absolute gain in efficiency for PERC cells on cast-monocrystalline silicon from the top of the ingot as a result of the hydrogenation process.
- Extent of LeTID confirmed to depend on wafer thickness, however regeneration rate does not.
- Industrial process demonstrated to mitigate LeTID without increasing series resistance.
- Surface-related degradation studied in a range of cell structures.

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PP1.2A REAR CONTACT

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Funding Support

ARENA, ANU

Aims

The objectives of PP1.2A are twofold: to develop very high efficiency laboratory-based silicon solar cells; and, in parallel, to develop cell fabrication techniques and processes compatible with industrially feasible low-cost implementation of interdigitated back contact (IBC) solar cells. IBC cells, by their very nature, are both inherently capable of very high efficiencies owing to superior optics compared to conventional cell architectures and owing to an improved ability to tailor fabrication processes to meet specific goals of cell features. However, such cells are also characterised by more complex and expensive fabrication processes. The target for the end of the program is to fabricate cells using any techniques with efficiencies of 26% or above, and in parallel to produce cells using industrially applicable techniques, and by doing so meeting an informal or internal efficiency target of 24% or above.

Progress

This project has produced the ANU record single-junction Si device efficiency, with an independently measured efficiency of $25\% \pm 0.6\%$. A cross-section of the IBC cell design is illustrated in Figure PP1.2A.1. The front surface is covered in light phosphorus diffusion with an improved random texturing process with monoTEX surfactant (Liang et al. 2021). Both front and rear surfaces are coated with the ANU-developed dual function passivating and anti-reflection oxide-nitride-oxide (ONO) dielectric layer, which provides excellent passivation to both phosphorus and boron diffusion surfaces.

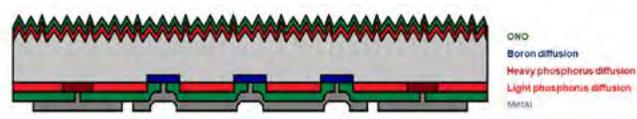


Figure PP1.2A.1: Cross-section of the ANU champion IBC cell design.

Given the promising results achieved using the ONO film, we continued investigation on the PECVD SiNx film (within the ONO stack) to further understand the correlation between deposition condition to the optical and electrical properties of the film. Thorough understanding of this fundamental effect is crucial for further advancement in its implementation on IBC solar cells due to the need to simultaneously passivate both boron- and phosphorus-diffused surfaces where the trade-off between the two must be carefully considered. Key results of this correlation are presented in Figure PP1.2A.2, where the recombination was measured via photoconductance decay, effective charge via capacitance-voltage (C-V), and refractive index measured via ellipsometry measurements, as fully detailed in the publication by Kho et al. 2020. The key outcome is that the native ONO film shows a strong correlation between having excellent surface passivation to the high refractive index PECVD SiNx layer, which also provides high effective surface charge density. This is extremely promising since it is synergistic to the needs for a high refractive index to achieve optimal anti-reflection properties within the film. Finally, the ONO layers respond very well to corona-charging and subsequent annealing, enabling a highly stable tunable ONO passivating layer applicable to both boron- and phosphorus-diffused surfaces.

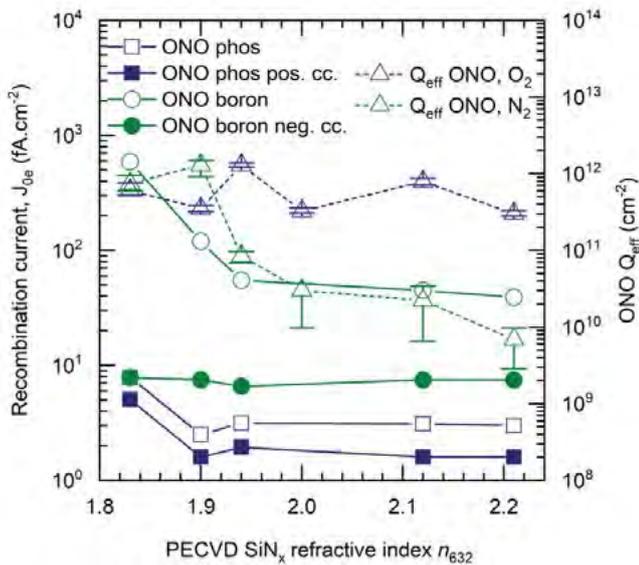


Figure 1.2A.2: Experimental data of correlation between refractive index of the PECVD SiN_x layer within the ONO stack to the passivation quality (J_{0e}) and the effective surface charge density (Q_{eff}).

The dark IV curve in log scale is presented in Figure 1.2A.3, noting the champion cell presents very high V_{oc} and J_{sc} consistent with empirical data attesting to the improvements to the effective surface passivation and high bulk lifetimes as achieved within this project. The fill factor (FF) in this cell is lower than expected, which is identifiable as a non-ideal recombination factor within the dark-IV curve linked to metal contact recombination effects (Kho 2019).

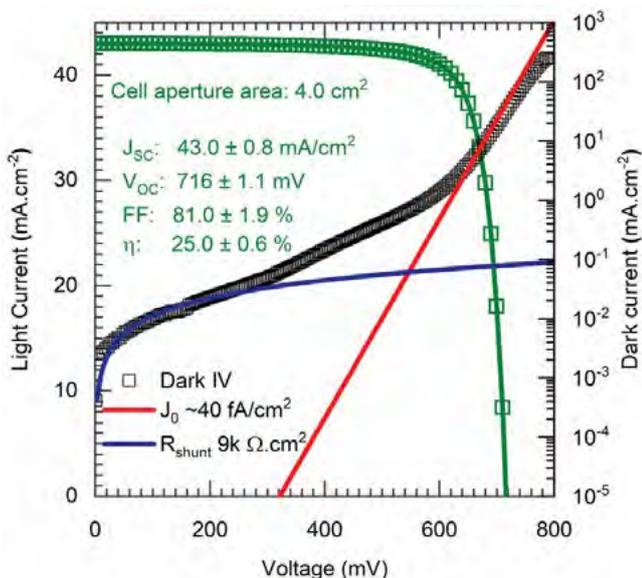


Figure 1.2A.3: Light- and dark-IV curve of the 25% champion IBC cell.

The future plan of this project is to continue improvement of the IBC cell design via incorporating polysilicon and dopant-free contact technologies, which are likely key for further improvement of the fill factor and V_{oc} of the devices.

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PP1.2B PASSIVATED CONTACTS

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Aims

The most advanced silicon solar cells use “passivated contacts” to selectively transport electrons and holes towards the cell terminals, while minimising recombination at the metal/silicon interfaces. This project aims to help bring such passivated contacts to the broader PV industry, by developing low-cost and simple approaches to creating such contacting schemes. The first strand of our work is based on the proven high temperature approach of depositing doped silicon films onto an ultrathin dielectric layer, enabling tunnelling to take place. A second class of low temperature approaches is also being explored, based on depositing dopant-free materials that have either a very high or a very low work function, which makes them selective to the transport of holes or electrons, respectively.

Progress

Building on our previous success with full-area high temperature polysilicon passivated contacts, we are continuing to develop low-cost processes for localised polysilicon passivating contacts underneath the metal fingers of silicon solar cells. This will enable reduced recombination losses at the front contacts without causing unwanted absorption in the polysilicon layer between the fingers. To this end, we have developed a simple process for forming patterned polysilicon regions that only requires a single dopant diffusion process, creating

both the heavily doped polysilicon regions and the lightly doped regions between the fingers in a single high temperature step. We aim to demonstrate cell efficiencies above 24% with this approach in early 2021.

We have continued to optimise the processes commonly used for forming doped polysilicon contacts. This work has included the optimisation of deposition temperature, power and pressure for both plasma-enhanced chemical vapour deposited (PECVD) and physical vapour deposited (PVD) silicon films (Chen et al. 2020a,b, Truong et al. 2020a). We have conducted a comprehensive comparison of the key properties of such films deposited by PECVD, PVD and low-pressure chemical vapour deposition (LPCVD) (Truong et al. 2020b). Figure PP1.2.4 below shows an example of transmission electron micrographs of such structures. We are also exploring novel low-cost methods for doping these films, based on spin-on doping and printed doping. We have developed new methods for characterising doped polysilicon passivating contacts based on spectrally resolved photoluminescence (Truong et al. 2020a; Wu 2020), which allow high resolution mapping of their quality, and new insights into their structure and electrical properties. In terms of solar cell fabrication with doped polysilicon contacts, this was heavily disrupted in 2020 due to extensive PV lab closures at ANU due to bushfires, hailstorms and COVID-19. However we have now resumed cell fabrication, and based on improved processes for metallisation and front surface passivation, we aim to achieve cell efficiencies above 25% in 2021 on small-area cells made at ANU.

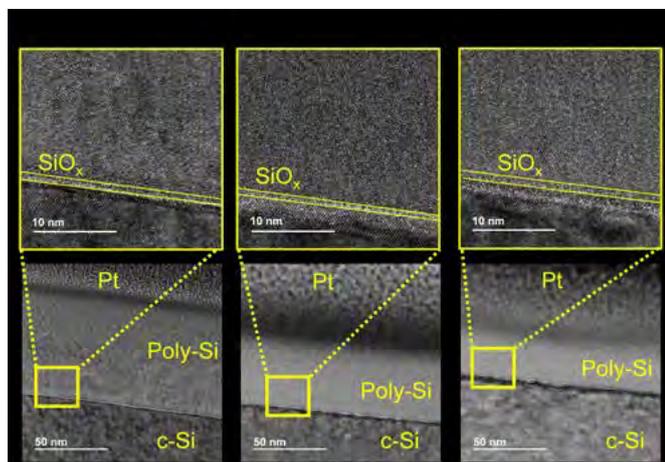


Figure PP1.2.4: Transmission electron microscopy (TEM) images of phosphorus-diffused poly-Si/SiO_x/c-Si stacks formed by (a) Sputtering, (b) PECVD, and (c) LPCVD.

For the low temperature dopant-free passivated contact approach, we have commenced the development of electron and hole-selective contacting schemes based on copper oxide and titanium oxide films, with various thin tunnelling interlayers. These films should allow simple fabrication of solar cells with no patterning steps required for the rear side. Initial results in terms of surface passivation and contact resistance are very promising, and we aim to demonstrate proof-of-concept solar cells with efficiencies above 20% in 2021. We have also continued the development of titanium nitride electron selective contacts formed by sputtering, with our first cell results reported in 2020, achieving a proof-of-concept efficiency of 18.7% (Yu et al. 2020). A schematic of this device and measured IV curve is shown in Figure PP1.2.5.

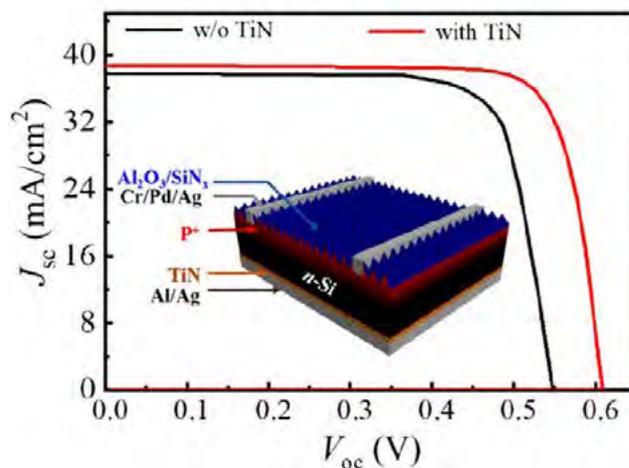


Figure PP1.2.5: IV curve and schematic diagram of n-type silicon solar cells with a sputtered TiN passivated contact on the rear side.

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PP1.3 SILICON TANDEM CELLS

PP1.3A III-V MATERIALS AND CHALCOGENIDES FOR SILICON-BASED TANDEM CELLS

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Jinko Solar
Tianjin Institute of Power Sources
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Aims

The dominant Si solar cells have achieved record efficiency close to their theoretical limit. One promising approach to boost the efficiency beyond the limit is integrating high bandgap top cells with Si cells to fabricate tandem solar cells. The aim of this project is to work with collaboration partners, which have world-leading expertise on tandem solar cells and complementary characterisations, to exploit the synergies for the development of a new generation of Si wafer cell technology by stacking top cells based on inorganic materials, with performance of the Si cell substantially improved by the deposition of thin layers of high performance top cells on its surface to produce tandem devices.

III-V is one of the promising top cell candidates. The III-V/Si tandem cells can be realised through direct growth, wafer bonding and mechanical stacking. Due to the differences in lattice constants and thermal expansion coefficients, the efficiency of direct grown III-V/Si is limited to ~20% owing to the poor material quality. The wafer bonding method has a high requirement on surface roughness which involves the high cost and low throughput processes and encounters the current mismatch issue. In contrast, the mechanical stacking method

allows the fabrication of four-terminal III-V/Si tandem cells with the advantage of no restriction on lattice or current matching between the top and bottom cells.

As an alternative to III-V materials, chalcogenide semiconductors are another group of promising photovoltaic materials due to their direct and tunable bandgaps, high absorption coefficient ($>10^4 \text{ cm}^{-1}$), high energy conversion efficiency, low-cost potential, and stable device performance. In 2020, we continued the work on Earth-abundant and environmentally friendly adamantine materials, RoHS-compliant ($\text{Sb}_2(\text{S,Se})_3$) and high bandgap pure sulfide CuInGaS_2 solar cells, breaking the benchmark of these technologies.

Progress

Pure sulfide $\text{Cu}(\text{In,Ga})\text{S}_2$ (CIGS) is an excellent light-absorbing energy material for thin-film solar cells due to its suitable optical and electrical properties. The bandgap of CIGS can be readily adjusted from 1.5 eV to 2.4 eV by altering the $\text{Ga}/(\text{Ga}+\text{In})$ (GGI) ratio, making it one of the most promising upper cell candidates for the top cells in tandem solar cells. Good progress has been made on fabrication of high performance CIGS solar cells in 2020 (He et al. 2020).

The current high performance CIGS process involves the use of either a toxic KCN process or H_2S gas during the sulfurization process. We developed a KCN-free and H_2S free process for sulfide CIGS. The influence of the critical Cu content ($\text{Cu}/(\text{In}+\text{Ga})$ ratio) of the CIGS on phase formation, morphology and device performance has been investigated. The Cu/III ratio has been carefully adjusted from 0.90 to 0.99 with a similar $\text{Ga}/(\text{In}+\text{Ga})$ ratio of ~0.27 as shown in Table PP1.3A.1. Samples with a low Cu content (A and B) present a rough and inhomogeneous surface morphology with small triangular-shaped grains (size around 0.2–0.5 μm) as indicated in Figure PP1.3.1. Contrastingly, sample D, which is close to stoichiometric, has larger and rounder-shaped grains (size around 1–2 μm) with a relatively dense and flat surface morphology. Notably, sample C shows an intermediate morphology between the Cu-poor and Cu-rich phases (B–D).

Table PP1.3.1: Device fabrication by CuGa/In co-sputtering onto Mo glass with different $\text{Cu}/(\text{In}+\text{Ga})$ ratios.

No.	$\text{Cu}/(\text{In}+\text{Ga})$	$\text{Ga}/(\text{In}+\text{Ga})$
A	0.90	0.27
B	0.94	0.28
C	0.96	0.26
D	0.99	0.27

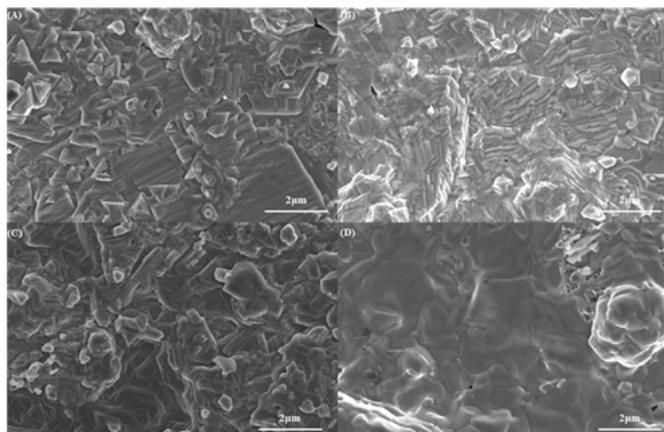


Figure PP1.3.1: SEM images of pure sulfide CIGS with different compositions (A–D).

The Cu content also has impact on the structure and impurities of the CIGS film. From Figure PP1.3.2, all of the samples demonstrate the main diffraction peaks of $\text{CuIn}(\text{Ga})\text{S}_2$ and Mo. Samples A, B, and C show the coexistence of In-rich secondary phases CuIn_3S_5 or CuIn_5S_8 and InGaS_2 , respectively (Sinaoui et al. 2013). However, these In-rich secondary phases disappear as the Cu content increases in sample D, suggesting that the excess Cu reacts with In-rich phases and forms the CuInGaS_2 phase.

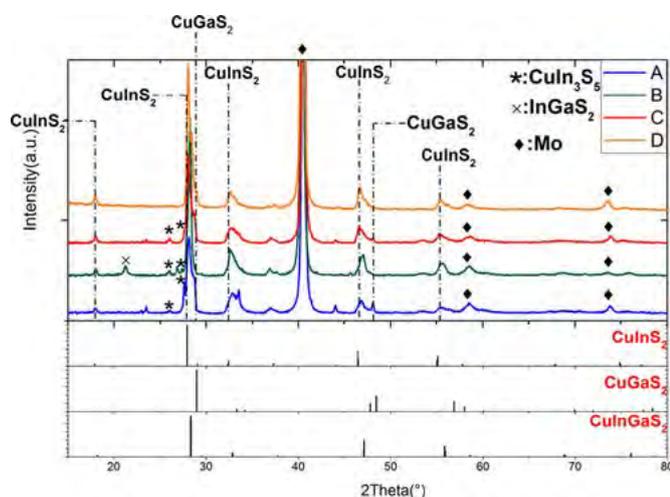


Figure PP1.3.2: XRD patterns of pure sulfide $\text{Cu}(\text{In,Ga})\text{S}_2$ with different Cu contents.

The corresponding device performance of CIGS solar cells fabricated based on the absorber with different Cu contents has been studied. As shown in Figure PP1.3.3, sample A shows the lowest V_{oc} , FF, and J_{sc} values. This might be due to Cu deficiency at the back forming N-type OVC $\text{CuIn}_3\text{S}_5/\text{CuIn}_5\text{S}_8$ phases at the CIGS/ MoS_2 interface, which leads to a reduced built-in electric field of the heterojunction and severe bulk recombination (Li et al., 2016). Sample D with the highest Cu concentration shows a decreased efficiency compared to sample C, which might be caused by no or fewer OVC phases present in sample D compared to that of sample C, according to the XRD data. The best efficiencies for all compositions are summarised in Table PP1.3.2, with the corresponding J–V curves displayed in Figure PP1.3.3(a) and EQE data shown in Figure PP1.3.3(b). Sample C with a moderate Cu

content of $\text{Cu}/(\text{In}+\text{Ga}) = 0.96$ yields a very high efficiency of 11.6% with $V_{\text{oc}} = 827.2$ mV, $J_{\text{sc}} = 20.1$ mAcm^{-2} , and FF = 69.7% along with a 1.54 eV bandgap. Samples B and C yield a higher EQE value within a wide wavelength range (500–800 nm) compared to the relatively Cu-poor sample A and Cu-rich sample D. This indicates that samples B and C should have a higher collection efficiency at the heterojunction with lower recombination. In addition, sample C with an optimal Cu content shows a squarer curve at long wavelengths, which indicates that it has a longer minority collection length and a better carrier collection efficiency near the rear region.

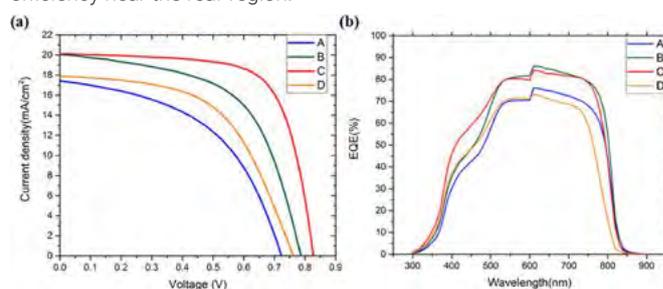


Figure PP1.3.3: (a) Representative J–V curves of four best cells with different Cu compositions. (b) EQE curves of the four best cells with different compositions.

Table PP1.3.2: $\text{Cu}(\text{In,Ga})\text{S}_2$ device performance parameters with different compositions.

No.	V_{oc} (mV)	J_{sc} (mAcm^{-2})	FF (%)	Efficiency (%)	E_g (EQE) (eV)
A	722.5	17.4	49.1	6.2	1.53
B	784.8	20.1	60.4	10.3	1.53
C	827.2	20.1	69.7	11.6	1.54
D	740.0	17.9	52.4	7.4	1.59

Ag alloying or Ag substitution for copper is expected to enhance the efficiency for CIGS solar cells owing to its effectiveness for increasing the grain size, reducing the temperature for synthesising CuInGaS_2 and improving the electrical properties by changing the defect chemistry of CIGS. Firstly, we showed a well-controlled composition for Ag alloyed CIGS with an Ag content of 5%, 10% and 20%. After optimisation of the Ag content, a 12% efficient CIGS solar cell with 878 mV open circuit voltage has been achieved.

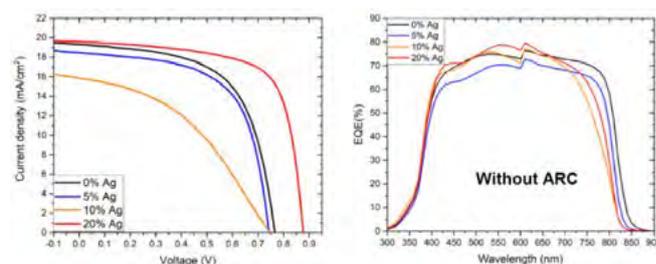


Figure PP1.3.4: (a) The representative J–V curves of four best cells with different Ag content. (b) EQE curves of the four best cells with different Ag content.

Table PP1.3.3: Cu(In,Ga)S₂ device performance parameters with different Ag content. The data presented here represent the highest efficiency cell for each composition.

	V _{oc} (mV)	J _{sc} (mAcm ⁻²)	FF (%)	Efficiency (%)	E _g (EQE) (eV)
0% Ag	766	19.5	60.9	9.1	1.51
5% Ag	743	18.5	62.2	8.5	1.53
10% Ag	749	16.4	41.4	5.1	1.57
20% Ag	878	19.6	69.9	12.0	1.55

The loss mechanism of high bandgap CIGS solar cells has also been performed using our simulation tool. The experimental and simulated J-V curves of the high-bandgap CIGS/(Zn,Sn)O solar cells using the measured material and device characteristics are shown in Figure PP1.3.5. These two curves are almost identical to each other, indicating the critical parameters of simulation should be in good accordance with the real ones. The high bandgap CIGS absorber has a bandgap of 1.55 eV (derived from the EQE data) and moderate carrier density ($N_A \sim 5 \times 10^{15} \text{ cm}^{-3}$, measured by DLCP). The carrier density of the CIGS absorber is suitable for high efficiency high bandgap thin-film solar cells as it helps to suppress heterojunction interface recombination. Moreover, though higher carrier density may lead to slight increase of V_{oc}, the reduced depletion region width and enhanced radiative recombination will lead to significant J_{sc} and efficiency loss. The conduction band offset (CBO) of the present CIGS/(ZnSn)O heterojunction has been adjusted to a slight spike which is also favourable to suppress the heterojunction interfacial recombination. The interface defect density used for simulation is $5 \times 10^{11} \text{ cm}^{-2}$, which is a relatively high value. However, this type of solar cell seems not sensitive to the interface defects.

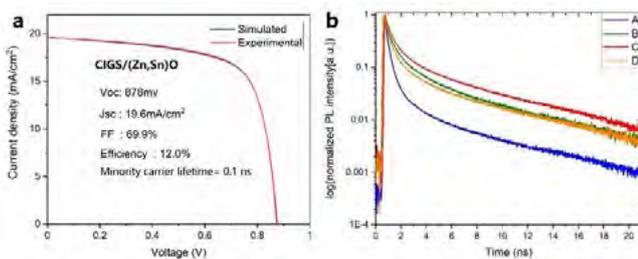


Figure PP1.3.5: (a) Simulated and experimental J-V curves of the high bandgap CIGS/(Zn,Sn)O solar cells. For SCAP-1D simulation, the bandgap of the CIGS layer is 1.55 eV, carrier density is $5 \times 10^{15} \text{ cm}^{-3}$, the minority carrier lifetime is 0.1 ns, and the interface defect density is $5 \times 10^{11} \text{ cm}^{-2}$. These data are set using EQE, DLCP and TRPL data. (b) Measured TRPL data of CIGS solar cells. The effective minority carrier lifetimes are around 0.1–0.3 ns.

The device performance of these CIGS/(Zn,Sn)O solar cells is mainly limited by the short minority carrier lifetime. The measured minority carrier lifetime of the CIGS absorber is in a scale of 0.1–0.3 ns as shown in Figure PP1.3.6, in good accordance with the simulated result in Figure PP1.3.5. If an effective anti-reflection coating is applied, the current 12% efficient device would show 14% efficiency gaining from about 3 mAcm⁻² increase of J_{sc}. As shown in Figure PP1.3.6(a), the device performance could be dramatically boosted to >18% if the minority carrier lifetime could be improved to >1 ns, and >20% if further

improved to >10 ns. After that, the efficiency improvement will be saturated by simply increasing minority carrier lifetime. In contrast, the simulated J-V curves are almost identical when the interface defect density is reduced (Figure PP1.3.6(b)). In other words, the severe bulk and SCR recombination caused by short minority carrier lifetime is the dominant loss mechanism of current CIGS/(Zn,Sn)O solar cells rather than interface recombination. These results identified the large efficiency potential of this type of high bandgap thin-film solar cell and that the critical strategy towards 20% efficiency is to improve the minority carrier lifetime to a level of 10 ns. This could be realised by improving the bulk electronic quality via either modifying the growth process or introducing advanced alkali doping.

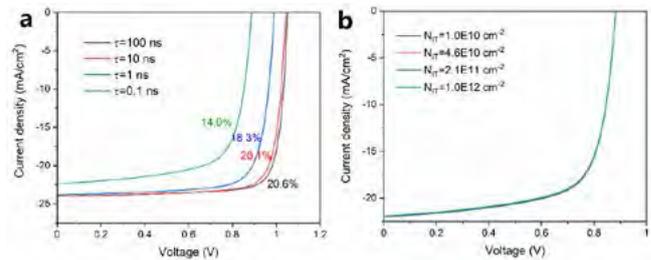


Figure PP1.3.6: The simulated J-V data based on the 14% baseline (if ARC coated) with (a) improved minority carrier lifetime and (b) suppressed interface defects.

Antimony selenosulfide offers another kind of stable and cost-effective light harvesting material for the top cell candidate. In 2020, we enhanced our collaboration with USTC and studied the deliberate control of S/(S+Se) in the Sb₂(S,Se)₃ and its impact on the film quality and device performance (Tang et al. 2020).

Different atomic ratios of Se/(S + Se) in the films are 0%, 17%, 29% and 48%, corresponding to the Selenourea/Na₂S₂O₃ molar ratios of 0%, 2.5%, 5% and 25% in the precursor solutions. First of all, we found that the introduction of selenium in the reaction system also alters the morphology of the as-obtained Sb₂(S,Se)₃ films (Figure PP1.3.7). Typically, pure Sb₂S₃ films display a flat morphology, with the average grain size reaching 1.5 μm (Figure PP1.3.7(d)). The films, however, exhibit abundant pinholes. Once selenium is introduced into the reaction system, the films Sb₂(S,Se)₃-17% and Sb₂(S,Se)₃-29% become much more compact with an average grain size of ~480 nm (Figure PP1.3.7(f)). However, the higher concentration of selenium (48%) in the reaction system leads to pinholes and inhomogeneity in the Sb₂(S,Se)₃ film (Figure PP1.3.7(g)).

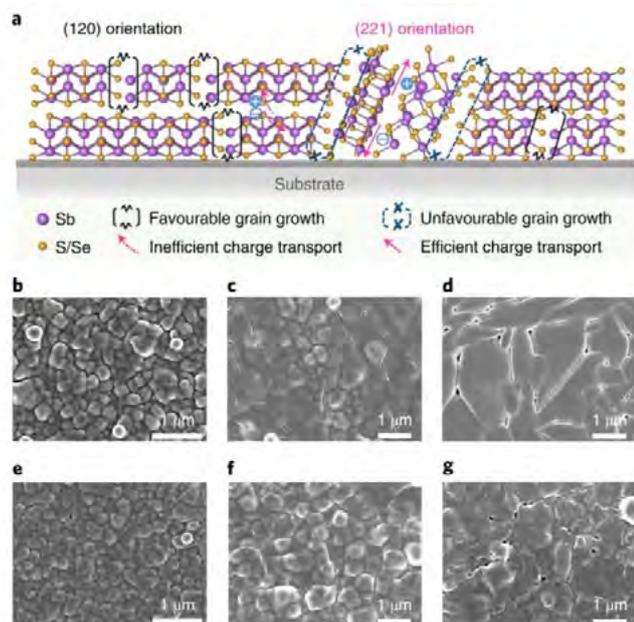


Figure PP1.3.7: (a), Atomic structure illustration of the oriented $(\text{Sb}_4\text{S}(\text{e})_6)_n$ ribbons and the impact on grain growth. Surface SEM images of Sb_2S_3 precursor films deposited at 135°C (b) and with post-deposition annealing at 250°C (c) and 350°C (d). Surface SEM images of $\text{Sb}_2(\text{S,Se})_3$ -29% precursor films deposited at 135°C (e) and with post-deposition annealing at 350°C (f). (g) Surface SEM images of $\text{Sb}_2(\text{S,Se})_3$ -48% film annealed at 350°C .

We conducted an annealing treatment after the hydrothermal deposition at different temperatures to investigate the morphological change of the $\text{Sb}_2(\text{S,Se})_3$ films. Prior to the annealing, both the Sb_2S_3 and $\text{Sb}_2(\text{S,Se})_3$ films exhibited similar morphologies with clear patches (Figure PP1.3.7(b), (e)), with the films being amorphous. Upon annealing at 250 and 350°C , the patches of Sb_2S_3 film seem to merge together to form large grains (Figure PP1.3.7(c), (d)), while the $\text{Sb}_2(\text{S,Se})_3$ films exhibit nearly the same grain size as the original patches (Figure PP1.3.7(f)). We suspect that this morphological difference stems from the different crystal growth behaviour. Consequently, we compared the texture coefficients (T_c s) of the two typical crystal planes, (221) and (120), in the crystallised Sb_2S_3 and $\text{Sb}_2(\text{S,Se})_3$ films (Zhou et al. 2015). A general observation is that the $T_c(221)/T_c(120)$ ratio becomes larger with the introduction of selenium. The [221]-oriented grains indicate that $(\text{Sb}_4\text{S}(\text{e})_6)_n$ ribbons stack more vertically to the substrate, while $(\text{Sb}_4\text{S}(\text{e})_6)_n$ ribbons lying flat on the substrate correspond to [120]-oriented grains (Figure PP1.3A.7a). Due to the quasi 1D crystal structure, the crystal (grain) growth occurs preferentially at the end of the ribbons, while the sides present “inert” characteristics for grain growth (Figure PP1.3.7(a)). Therefore, Sb_2S_3 tends to form a large grain size with flat surface morphology, while the $\text{Sb}_2(\text{S,Se})_3$ film displays smaller grain size and a less-flat surface morphology. We also compared other $T_c(\text{hk}1)/T_c(\text{hk}0)$ ratios, with all displaying an increasing trend with increasing selenium in the $\text{Sb}_2(\text{S,Se})_3$ film, affirming the oriented crystal growth.

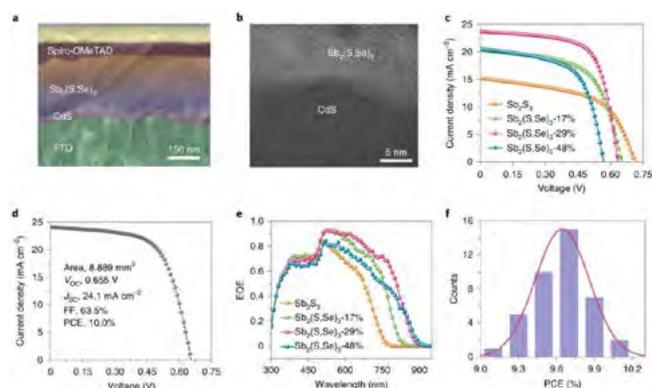


Figure PP1.3.8: (a), (b) Cross-sectional SEM image of the best device and HAADF image of the CdS– $\text{Sb}_2(\text{S,Se})_3$ junction. (c) J-V characteristics of devices Sb_2S_3 , $\text{Sb}_2(\text{S,Se})_3$ -17%, $\text{Sb}_2(\text{S,Se})_3$ -29% and $\text{Sb}_2(\text{S,Se})_3$ -48% under standard AM 1.5G illumination. (d) The certified J-V curve and the corresponding photovoltaic parameters of the best device. (e) EQE spectra of devices Sb_2S_3 , $\text{Sb}_2(\text{S,Se})_3$ -17%, $\text{Sb}_2(\text{S,Se})_3$ -29% and $\text{Sb}_2(\text{S,Se})_3$ -48%. (f) Statistics of the PCE distribution for 40 independently fabricated devices.

The devices were fabricated based on the different $\text{Sb}_2(\text{S,Se})_3$ absorbers. A cross-sectional scanning electron microscopy (SEM) image of the device structure is displayed in Figure PP1.3.8(a). The current density versus voltage curves is presented in Figure PP1.3.8(c), with photovoltaic parameters summarised in Table PP1.3.4. The device based on Sb_2S_3 delivers a PCE of 6.02%, where the corresponding V_{oc} , J_{sc} and FF are 0.707 V, 15.2 mAcm^{-2} and 55.9%, respectively. With the introduction of selenourea to generate $\text{Sb}_2(\text{S,Se})_3$, the J_{sc} increases to 20.3 and 23.7 mAcm^{-2} for devices based on $\text{Sb}_2(\text{S,Se})_3$ -17% and $\text{Sb}_2(\text{S,Se})_3$ -29%, respectively. The narrowed bandgap contributes to the increased J_{sc} owing to the photocurrent generation extending to longer wavelengths. On the other hand, the upward shift of the valence band and decreased bandgap with increasing selenium concentration led to a gradually decreased V_{oc} . Notably, the FF is substantially increased from 55.9% ($\text{Sb}_2(\text{S,Se})_3$ device) to 60.6% and 67.7% for devices based on $\text{Sb}_2(\text{S,Se})_3$ -17% and $\text{Sb}_2(\text{S,Se})_3$ -29%, respectively. With the increase in J_{sc} and FF, $\text{Sb}_2(\text{S,Se})_3$ -17%- and $\text{Sb}_2(\text{S,Se})_3$ -29%-based devices achieve PCEs of 7.96% and 10.10%, respectively. Further increasing the selenourea concentration to form $\text{Sb}_2(\text{S,Se})_3$ -48%, however, leads to the PCE decreasing to 7.10%, most likely due to the deterioration of film morphology (Figure PP1.3.8(g)) inducing a substantial loss in FF (61.7%) (Limpinsel et al. 2014).

Table PP1.3.4 Photovoltaic parameters of devices based on Sb_2S_3 and $\text{Sb}_2(\text{S,Se})_3$ -17%, $\text{Sb}_2(\text{S,Se})_3$ -29% and $\text{Sb}_2(\text{S,Se})_3$ -48%.

Device	V_{oc} (mV)	J_{sc} (mAcm^{-2})	FF (%)	PCE (%)
Sb_2S_3	0.707	15.2	55.9	6.02
$\text{Sb}_2(\text{S,Se})_3$ -17%	0.647	20.3	60.6	7.96
$\text{Sb}_2(\text{S,Se})_3$ -29%	0.630	23.7	67.7	10.10
$\text{Sb}_2(\text{S,Se})_3$ -48%	0.561	20.5	61.7	7.10

We thus identify the best condition for device fabrication as that used for $\text{Sb}_2(\text{S,Se})_3$ -29%, where a PCE of 10.0% is independently certified (Figure PP1.3.8(d)). In the best condition for the fabrication of an $\text{Sb}_2(\text{S,Se})_3$ -29% device, the efficiency statistics of 40 devices are shown in Figure PP1.3.8(f), demonstrating an average PCE of 9.65%.

Highlights

- Development of a high bandgap Cu(In,Ga)S₂ solar cell with efficiency of 11.6%.
- Demonstrated Ag alloyed Cd-free CIGS solar cell with efficiency of 12%.
- Analysis of the loss mechanism of a high bandgap CIGS solar cell.
- Development of a high efficiency Sb₂(S,Se)₃ solar cell with control of Se introduction cells by collaborating with USTC.

Future Work

Future work in 2021 will be focused on:

- Exploration of new PV absorber materials.
- Further improving the efficiency of high bandgap CIGS solar cells based on the loss mechanism analysis.
- Understanding the performance loss and further improving the efficiency of Sb₂(S,Se)₃ solar cells.

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PP1.3B NON-EPITAXIAL TANDEM CELLS ON SILICON – PEROVSKITES ON SILICON

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ACAP, ARENA

Aims

- Develop strategies to fabricate stable and efficient perovskite/Si tandem solar cells.
- Evaluate light-induced degradation activation energy (E_a) of perovskite top cells to get insight of degradation mechanism.
- Develop low-cost strategies for a p-doped and stable hole transport material layer for high performance stable perovskite and perovskite/Si tandem solar cells.
- Fabricate high performance inverted perovskite and perovskite/Si tandem solar cells with different hole transport strategies.

Progress

For gaining insight into the degradation factors in the perovskite top cell to tackle the critical stability issue, the normalised values of each PV parameter as a function of light-heat soaking time at different light soaking temperatures were investigated. By fitting these values into the temperature-dependent activation energy equation, the E_a of each PV parameter was obtained. Different parameters showed different activation energies where primary degradation is due to the increase in series resistance, which also led to a reduction in short-circuit current. Open-circuit voltage and shunt resistance also changed with each different E_a, suggesting the mechanism of the reduction is likely to be due to different reasons. Despite each parameter exhibiting slight variation over time for each temperature, the overall trend converges, indicating that each parameter is likely to be primarily reduced by a single dominant reaction, which is the series resistance. Microstructural and chemical characterisations revealed that the degradation of Spiro-OMeTAD due to oxidation and ion migration is the main cause of the series resistance increase. This result offers a guidance for the following stability improvement study.

In order to improve the stability of perovskite top cells and therefore perovskite/Si tandem solar cells, a low-cost strategy was developed for attaining a p-doped and stable hole transport material layer (HTL). Stabilities of perovskite solar cells (PSCs) with a tailored Spiro-OMeTAD HTL under wetting, thermal and illumination stresses are all improved. Unencapsulated PSCs retain 96% of peak efficiency after 530 hours in wetting conditions and retain 94% of peak efficiency after 2200 hours in the air. Five-fold enhanced thermal stability of PSCs at 50-85°C is observed. Upon continuous one-sun illumination, PSCs retain 93% of peak efficiency after ~2000 hours under the open-circuit condition and retain 90% of peak efficiency after 1000 hours of operation at the maximum power point (MPP), respectively. The improved long-term stability of the tailored Spiro-OMeTAD HTL and consequently PSCs owes to the merits of simultaneously improved film morphology, increased hydrophobicity, controlled crystalline growth, and diminished ion migration. Moreover, a >24% efficiency PSC was achieved by transferring and updating technologies used in cells fabricated by the one-step method to cells fabricated by the two-step method.

In addition, different hole transport strategies have been investigated to fabricate stable and efficient inverted PSCs aiming at high performance perovskite/Si tandem solar cells. On non-doped PTAAHTL, over 19% efficiency inverted PSC was achieved. It was found that a pre-deposited thin layer may have passivation effects on the perovskite film resulting in an elevated photoluminescence intensity. On the magnetron sputtered NiO_x HTL with no doping nor passivation, over 15% efficiency inverted PSC was reached. Moreover, treatment strategies for fabricating high performance magnetron sputtered NiO_x were developed. The treated magnetron sputtered NiO_x showed a better uniformity, a higher light transmittance, and a preferred crystallinity with lower defect density.

Highlights

- Degradation analysis of the perovskite top cell showed that the series resistance increase is the dominating degradation factor.
- Stable perovskite solar cells without encapsulation under 50% RH wetting, 50-85°C thermal, and continuous one-sun illumination stresses.
- Single-junction perovskite solar cells with efficiency beyond 24%.
- Single-junction inverted perovskite solar cells with efficiency beyond 19%.

Future Work

- Activation energy employed degradation study of the 2-T encapsulated perovskite/Si tandem solar cell.
- Target encapsulated perovskite solar cells that maintain 20% efficiency at 85% relative humidity, 85°C, and continuous one-sun illumination combined ageing stress.
- Target perovskite solar cells with efficiency beyond 25%.
- Target inverted perovskite solar cells with efficiency beyond 20%.

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PP2

THIN-FILM, THIRD GENERATION AND HYBRID DEVICES

OVERVIEW

Program Package 2 (PP2) encompasses research into a range of next generation cell technologies with the overall goals of demonstrating efficiency above 16% for cells of greater than 1 cm² area and of demonstrating the feasibility of significantly reduced costs. The current program is divided into tasks to address the key materials groups: organic photovoltaics (OPV), organic-inorganic hybrid cells, “Earth-abundant” inorganic thin-film materials and the hot topic of organic-inorganic perovskites. Good progress has again been made in 2020 in all target areas.

PP2.1 ORGANIC PHOTOVOLTAIC DEVICES

The thin-film organic photovoltaics task (PP2.1) aims to identify and address roadblocks in organic photovoltaics to enable cost-effective, mass manufacture of modules using this technology. The research targets lower-cost materials and/or processes compared to those of conventional cells or, alternatively, applications such as flexible or partly transparent cells for which conventional cells are not well suited. Organic photovoltaic (OPV) devices have a theoretical power efficiency (PCE) of >20%, with single-junction cells now reported with PCEs of over 18%. There is still considerable scope to molecularly engineer organic semiconductor materials. In addition, they can be solution-processed, leading to the possibility of low embedded energy manufacturing. In 2020, the team gained a deeper understanding of the structural effects on high dielectric constant organic semiconductors and developed new non-fullerene acceptors that can be used in thick films and/or low donor content cells.

While significant progress is being made on the photoactive materials there is still room for improvement in areas such as device architecture, including choice of interlayers, transparent conducting electrodes, and inverted and standard device architectures. Underpinning these activities are key structure-property relationship measurements that can guide the development of the next generation materials. During 2020, a ternary blend OPV device with 16.1% PCE was reported, as were luminescent solar concentrators with decreased concentration quenching and efficient graphene anode-based organic solar cells. The team also developed highly efficient semitransparent organic solar cells with colour rendering index and transparency and gained greater morphology control of donor and acceptor systems for different donor/acceptor-based organic solar cells and increased understanding of the mechanism of initial photo-degradation of organic solar cells.

Finally, in addition to the significant strides the team has made in these fundamental areas, there has also been an important focus on upscaling of materials and printing large-area solar cells. Highlights for 2020 included: construction of a digitally controlled solar coater and tester for optimisation of R2R fabrication conditions, development of printable OPV materials with thickness-tolerant and thermally stable polymers, and the highest PCE from R2R-processed OPV (with vacuum-deposited electrodes) reported in the literature, was achieved at an industrially acceptable film thickness of 200–300 nm.

PP2.2 CZTS SOLAR CELLS

Thin films of the compound semiconductor $\text{Cu}_2\text{ZnSnS}_4$ (CZTS) are the focus of PP2.2. In 2020 UNSW has developed two effective strategies to manipulate the deep intrinsic defects and the dominant shallow acceptor-like defects respectively. The formation of deep intrinsic defects and defect clusters can be effectively suppressed by engineering the local chemical environment during the synthesis of the kesterite phase, leading to a new record efficiency of 12.5% for pure-selenide CZTSe solar cells. The dominant acceptor CuZn in kesterite can be replaced with shallower LiZn defects with a high doping rate, resulting in a much better p-type doping density and shallower Fermi-level.

In addition, the loss mechanisms of the record CZTSe solar cells have been identified, pointing out the strategies for further essential improvements. Moreover, the manufacturing cost vs. different substrate and efficiency and potential market niches for $\text{Cu}_2\text{ZnSnS}_4$ (CZTS) solar cells has been analysed. The results indicate that 15% is the benchmark efficiency required to make CZTS solar cells competitive in the PV market.

PP2.3, Thin-Film Inorganic (Si), closed in 2015 and PP2.4, Third Generation Approaches, closed in 2018

PP2.5 PEROVSKITES

A new work program was started in 2016, to advance the organohalide perovskite technologies, addressing scale and durability. Advances in 2020 include: certified efficiency of 22.6% for a 1 cm^2 cell; a new technique for early detection of perovskite degradation; I_3^- incorporation in perovskites improved the efficiency of FAPbI₃ cells from 17.5% to 20.6%; a better understanding of the temporal storage effect on perovskite defect property and HTM energy level; a clearer picture of the impact of mobile ions on steady-state efficiency; a new photolithography-free patterning process for back contact perovskite cells, enabling large-area uniform patterning and significantly improving device performance; improved open-circuit voltage for sulfoiodobismuthate lead-free devices; discovery of an oxygen-free photo-doping effect in Spiro-OMeTAD under light soaking; simulations confirming the driving force for photo-induced phase segregation; a low-cost polyisobutylene encapsulation method for improving the durability of perovskite solar cells; MA-containing perovskite cells exceeding, for the first time, the IEC61215:2016 durability standard; PCE of 18.3% for fully slot-die coated devices in an inverted device structure; and a highly reproducible one-step hot-deposition R2R method.

PP2.1 ORGANIC PHOTOVOLTAIC DEVICES

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Organic photovoltaic (OPV) devices have a theoretical photoconversion efficiency (PCE) of >20%, with single-junction cells now reported with PCEs of over 17%. There is still considerable scope to molecularly engineer organic semiconductor materials, which is one of their key advantages. In addition, they can be solution-processed leading to the possibility of low embedded energy manufacturing. An example of how molecular engineering has advanced the field is the development of non-fullerene acceptor materials for bulk heterojunction devices, which have led to more efficient devices than those that traditionally used the earlier developed fullerene acceptors. While bulk heterojunction organic solar cells are still leading efficiencies there are now questions being raised as to whether the bulk heterojunction is necessary if the dielectric constant of the materials can be increased. Furthermore, while significant progress is being made on the photoactive materials there is still room for improvement in areas such as device architecture, including choice of interlayers, transparent conducting electrodes, and inverted and standard device architectures. Underpinning these activities are key structure-property relationship measurements that can guide the development of the next generation materials. Finally, in addition to the significant strides the team has made in these fundamental areas it has also had an important focus on up-scaling of materials and printing large-area solar cells. Thus, the team provides cohesive activities from basic to application at scale. For ease of reading the program has been divided into three broad sections: Materials, Characterisation and Device Architectures, and Printing and Scale-up.

MATERIALS

Aims

To this end the materials development program has had the following aims:

- Development of donors and non-fullerene materials for bulk heterojunction active layers.
- Creation of and understanding the properties of organic semiconductor materials designed to have a high dielectric constant.
- Controlling morphology development through materials design.
- Understanding materials performance.

Progress

Donor and non-fullerene acceptor materials

One active-layer morphology for organic semiconductor solar cells has a bi-continuous interpenetrating network composed of crystalline domains allowing charge transport to the device electrodes, along with a small degree of amorphous intermixing for exciton harvesting (see also Characterisation and Device Architecture section). Sidechain

engineering is a crucial tool towards achieving this morphology, as the position and lengths of sidechains have been shown to greatly impact both molecular packing and bulk properties in the active layer. These factors are also of particular importance for intermolecular charge transport as this occurs primarily through π - π interactions, with high mobility dependent on the (a) relative overlap of the π -conjugated chromophores, where charge transfer integrals are maximised with a complete cofacial alignment, and (b) the orientation of π -stacking with respect to the device substrate, where vertically π -stacked layers maximally facilitate transport to the electrodes. The inclusion of alkyl sidechains, particularly for oligothiophenes, has been shown to result in ideal π -stacking alignments, with non-alkylated oligothiophenes shown to possess non-ideal face-to-edge herringbone packing structures.

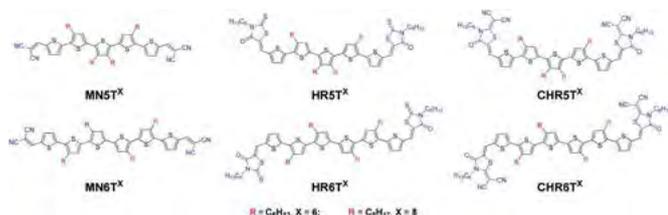


Figure PP2.1.1: Chemical structures of the A-D-A oligothiophene materials and their naming conventions

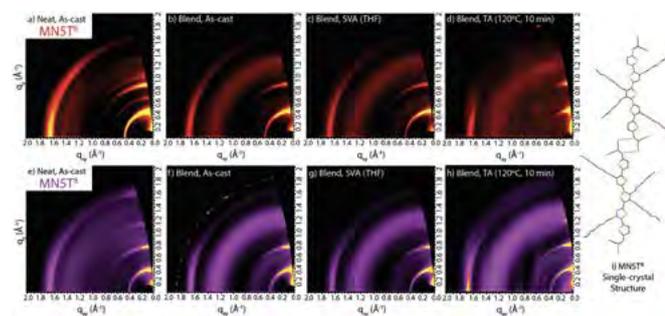


Figure PP2.1.2: GIWAXS diffractions patterns for MN5T6 and MN5T8 films that are: (a) and (e) neat, as-cast; and 1:1 blends with PC71BM that are: (b) and (f) as-cast; (c) and (g) SVA (THF, 20 seconds); (d) and (h) TA (120°C, 10 minutes), and (i) the solid-state geometry of MN5T8 as determined by its single-crystal structure. Hydrogen bonding between the dicyanomethylene moieties is marked in green.

The synthesis and characterisation of a series of functionalised oligothiophenes were reported in 2020 (Figure PP2.1.1), all of which featured regio-regular sidechains oriented away from the oligothiophene core. This differs from previously studied small molecule materials, which generally feature either regio-irregular sidechains or sidechains oriented towards the core. Studies in the literature on similar compounds, as well as our own previously published sidechain engineering efforts, have shown that sidechain regio-regularity can lead to increased backbone planarisation and short-circuit currents (J_{sc}), while the outward-facing sidechain positioning has been shown to reduce π -stacking distances relative to those with inward-facing sidechains (Figure PP2.1.2).

Another route to the desired active-layer morphology is through fully conjugated block copolymers. We have been developing block copolymer systems where the p-type or n-type blocks are hydrophilic

allowing for exquisite control of the resulting phase separation and morphology. There are significant synthetic challenges inherent in the use of high-performance polymeric materials in fully conjugated block copolymers, which lie in the development of the needed asymmetric macromonomers. We have developed a new approach to the controlled synthesis of the hydrophilic donor (p-type) organic semiconductor and have been developing routes to hydrophobic acceptor (n-type) organic semiconductors (Figure PP2.1.3).

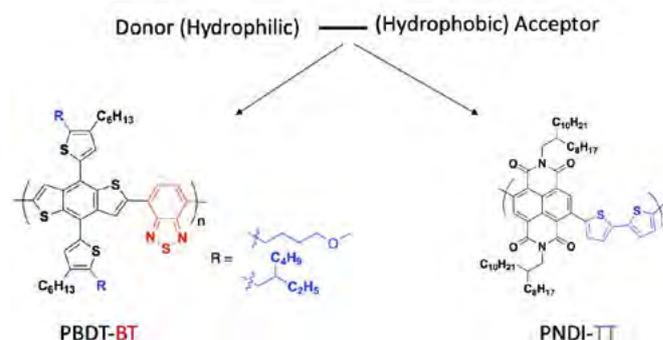


Figure PP2.1.3: Targeted fully conjugated polymers to be used as components in conjugated block-copolymers.

The team has also been developing new families of non-fullerene acceptors based on perylenediimides, with comparison between planar and three-dimensional materials. The photoconversion efficiencies of the standard bulk heterojunction solar cells at this stage are modest (around 2.2%), however, an interesting feature of the materials is that the efficiency does not necessarily decrease for thick films suitable for printing. Furthermore, the efficiency can remain relatively high for low donor content blends.

Homojunction materials

Homojunction organic photovoltaic devices require high dielectric constant organic semiconductor materials to overcome the exciton binding energy. The team has continued to explore how structural features affect the dielectric constant and in particular the optical frequency dielectric constant. We have compared the properties of 2,2'-[({4,4',4'-Tetrakis[2-(2-methoxyethoxy)ethyl]-4H,4'H-[2,2'-bis(cyclopenta[2,1-b:3,4-b']dithiophene))-6,6'-diyl]bis[benzo[c][1,2,5]thiadiazole-7,4-diyl]bis(methanylylidene)]dimalononitrile with equivalent material without the two benzothiadiazoles. We find that for films of comparable thickness (20 nm) the material without the benzothiadiazole units has an optical frequency dielectric constant around 25% less than the material that does, indicating that the size of the internal dipole moment and/or polarisation of the chromophore is important when designing homojunction materials. Interestingly, the new material could be processed from solution or evaporation, and surprisingly it was found that the solution-processed material had the higher optical frequency dielectric constant. Furthermore, evaporated films of the material were found to only transport electrons while the solution-processed material was capable of also transporting holes, albeit with an \approx two orders of magnitude imbalance. The reasons for this are still under investigation.

Highlights

- Further understanding gained towards the structural effects on high dielectric constant organic semiconductors.
- New non-fullerene acceptors that can be used in thick films and/or low donor content cells.

Future Work

- Design new classes of high dielectric constant materials to overcome the limitations of charge generation.
- Investigate new non-fullerene acceptors.
- Use design criteria developed for improved SF materials to energy match SF materials to solar cells.
- Develop synthetic routes to amphiphilic fully conjugated block-copolymers for morphology control.

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CHARACTERISATION AND DEVICE ARCHITECTURES

Aims

- To develop luminescent solar concentrators (LSCs).
- Understand the relationship between film structure and performance.
- Create ternary blend device architectures.
- To understand the basis of device burn-in.
- Fabricate and test semitransparent OPV devices for window applications.
- Creation of ITO-free organic solar cells.

Luminescent solar concentrators

One route to harvesting solar energy is the use of large-area luminescent solar concentrators, where a secondary harvesting molecule is used to absorb light and direct the emitted light through a wave guide to a solar cell at the edge of the concentrator. However, the photoluminescence quantum yield (ϕ_{PL}) is often limited by aggregation caused quenching (ACQ) at high concentration or in the neat solid-state, as is the case for perylene diimide derivatives (PDI)s. Energy transfer in high dye concentration systems is also a key factor in determining ϕ_{PL} as a result of energy funneling to trap sites in the sample. We have developed a number of PDI chromophores by tuning the substituents, resulting in PDIs with aggregated or insulated cores. By combining these fluorophores in a polymer film, we demonstrate highly emissive samples (85% ϕ_{PL}) at high concentration (140 mM or 20% w/w). While insulated fluorophores maintain respectable ϕ_{PL} at high concentration, an improved ϕ_{PL} can be achieved in the presence of appropriately oriented fluorophore aggregates as emissive traps.

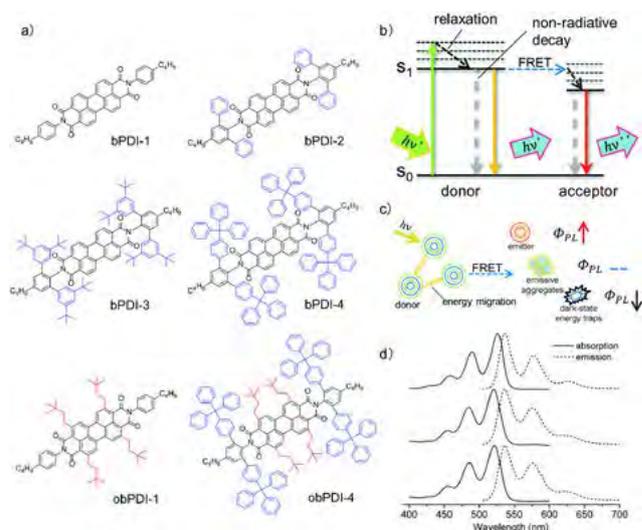


Figure PP2.1.4: (a) The chemical structure of all PDI derivatives. The imide substituents are highlighted blue while the ortho-substituents are red. bPDI-1, 2, 3 and 4 have been reported previously. (b) Simple Jablonski diagram illustrating the FRET process which requires a certain proximity of fluorophores or high concentration of bPDIs. (c) Illustration of possible FRET acceptors: single emitters, emissive aggregates and non-emissive aggregates. (d) The absorption and emission spectra ($\lambda_{ex} = 490$ nm) of the bPDIs (bPDI-3 for example), obPDI-1 and obPDI-4 recorded in dilute solution conditions.

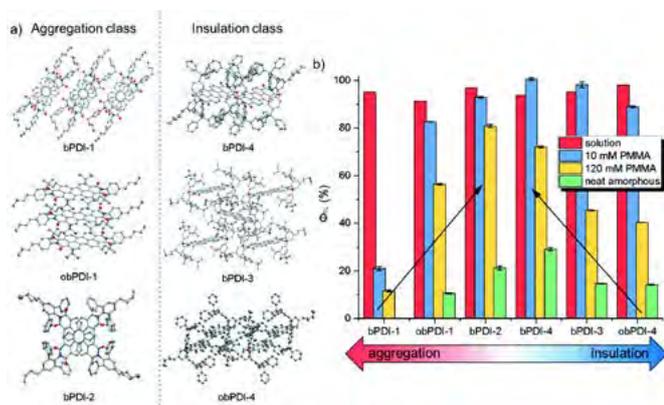


Figure PP2.1.5: (a) The crystalline packing of bPDI-1, obPDI-1 and bPDI-2 shows clear π - π stacking among molecules, but the packing arrangements are different. However, the crystalline packing of bPDI-4, bPDI-3 and obPDI-4 indicated the bulky-substituents prevented any possibility of π - π stacking among these molecules. (b) The ϕ_{PL} of all six PDIs under different conditions. The PDIs with hybrid characteristics of molecular aggregation and insulation in general exhibit higher ϕ_{PL} values in this series. The ϕ_{PL} of the solution sample was measured by the relative method using perylene orange (ϕ_{PL} 99%) as the reference and the solid-state samples were measured by the absolute method using an integrating sphere (averaging over three measurements). The uncertainty of the relative and absolute ϕ_{PL} measurement are $\sim 6.0\%$ and 5.5% respectively.

Understanding BXR materials performance

To improve materials design, a detailed understanding of materials performance is often required. The team has previously reported the excellent performance of OPV devices containing a class of p-type organic semiconductors designated as the benzodithiophene-X-thiophene-rhodanine (BXR) materials, of which benzodithiophene-quaterthiophene-rhodanine (BQR) demonstrates the best performance and is able to maintain device performance even with thick active layer films (for OPV up to 500 nm). In conjunction with collaborators at Princeton University and the University of Swansea a detailed understanding of the device under illumination has been developed. Surprisingly, after solvent vapour annealing of the active layer OPV device performance is enhanced from around 4.5% PCE to around 10% PCE, a performance that is maintained even in films of up to 320 nm thickness.

As discussed above, the morphology of organic semiconductors is critical to their function in optoelectronic devices and is particularly crucial in the donor-acceptor mixture that comprises the bulk heterojunction of organic solar cells. We have previously demonstrated how energy landscapes can play integral roles in charge photo-generation and have been recently shown to drive the accumulation of charge carriers away from the interface, resulting in the build-up of large nanoscale electric fields, much like a capacitor. Here we combine morphological and spectroscopic data to outline the requirements for this interdomain charge accumulation, finding that this effect is driven by a three-phase morphology that creates an energetic cascade for charge carriers (Figure PP2.1.6). By adjusting annealing conditions, we have demonstrated that domain purity, but not size, is critical

for an electro-absorption feature to grow in. This demonstrates that the energy landscape around the interface shapes the movement of charges and that pure domains are required for charge carrier build-up that results in reduced recombination and large interdomain nanoscale electric fields.

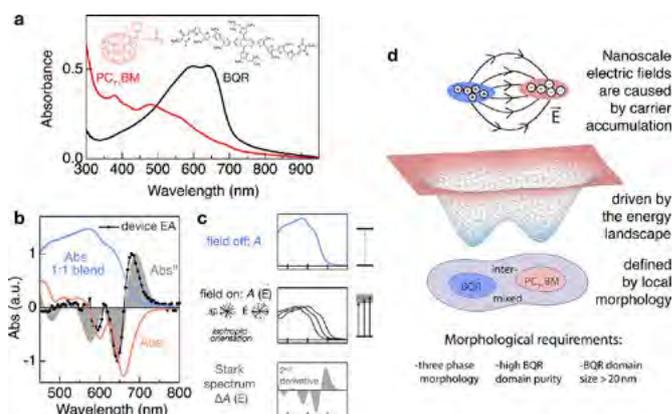


Figure PP2.1.6: (a) Molecular structures and ground state absorbance spectra of BQR and PC₇₁BM films. (b) Absorption spectrum of a 1:1 BQR:PC₇₁BM blend after 20 s of solvent vapour annealing (SVA), showing the first and second derivative of this absorption spectrum. The device electro-absorption spectrum is shown in black, where a voltage is applied via electrodes to the blend film. Here, the electro-absorption response is dominated by the change in dipole moment, $\Delta\mu$, with the applied field, E . (c) How an electric field can produce the second derivative of the absorption spectrum via the Stark effect. Here, the change in dipole moment with electric field shifts the energy levels of the molecule, where a variety of relative orientations between transition dipole moment and electric field broadens the "field on" absorption, and the difference between "field on" and "field off" gives a second derivative line shape. (d) Nanoscale electric fields in these systems caused by charge carrier build-up. This is driven by the energy landscape and defined by a local morphology that is the subject of this work.

BTR or BQR/PCBM blends show significantly reduced bimolecular recombination relative to the Langevin recombination rate. The strongly reduced recombination has been previously attributed to a high probability for the interfacial charge-transfer (CT) states (formed upon charge encounter) to dissociate back to free charges. However, whether the reduced recombination is due to a suppressed CT-state decay rate or an improved dissociation rate has remained a matter of conjecture. In recent work we investigated the BQR/PCBM system (Figure PP2.1.7) that exhibits significantly reduced recombination upon solvent annealing. On the basis of detailed balance analysis and the accurate characterisation of CT-state parameters, we provide experimental evidence that an increase in the dissociation rate of CT states upon solvent annealing is responsible for the reduced recombination. We attribute this to the presence of purer and more percolated domains in the solvent-annealed system, which may, therefore, have a stronger entropic driving force for CT dissociation.

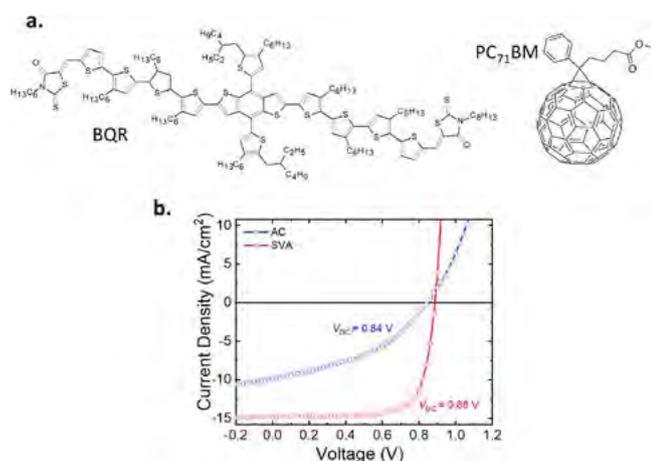


Figure PP2.1.7: (a) Molecular structure of BQR and PC₇₁BM. (b) The corresponding J–V curves of as-cast (AC) and SVA BHJ solar cells.

In this work we have developed a theoretical/experimental methodology to obtain the number density of CT states in one system relative to another. The method is generic, with the limitation that the two systems are required to have similar or known CT-state oscillator strengths. This method has been applied on the as-cast and solvent-annealed BQR:PC₇₁BM solar cells, with the latter showing significantly reduced recombination rate constants. Using detailed balance analysis together with the accurate characterisation of CT-state and free-charge parameters, we have been able to relate the CT-state kinetics to the observed strongly suppressed bimolecular recombination of free charges. Our results show that the reduced recombination in SVA devices is due to the improved dissociation rate of CT states upon solvent annealing, whereas a marginal reduction in the CT states' decay rate was observed. These results shed considerable light on the nature of reduced bimolecular recombination in BHJ OSCs and is a step towards understanding how to engineer the thicker junctions needed for industrially viable OSCs (Figure PP2.1.8).

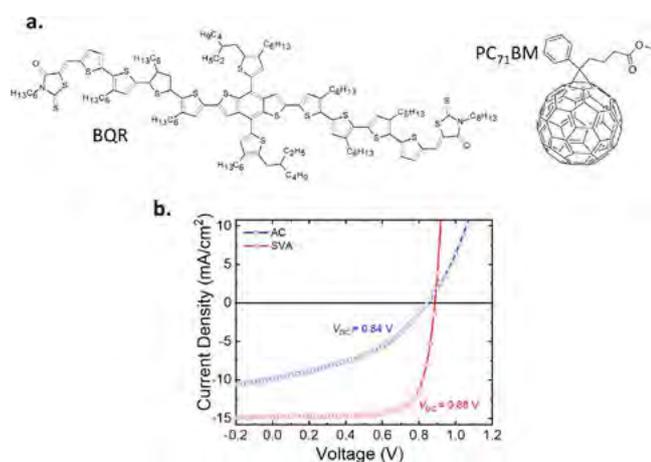


Figure PP2.1.8: Schematic of the charge generation and recombination in a BHJ OSC. The transition illustrated by the dashed downward arrow is the effective recombination rate of separated charge carriers.

BTR device performance

Recently, we have adopted an efficient approach to tune the molecular packing, energy level, and morphology of BTR, by modifying the sidechain on the BDT core unit from dialkylthienyl to 2-ethylhexylthio (TE) and triisopropylsilylethynyl (TIPS), termed as BTR-TE and BTR-TIPS, respectively (Figure PP2.1.9).

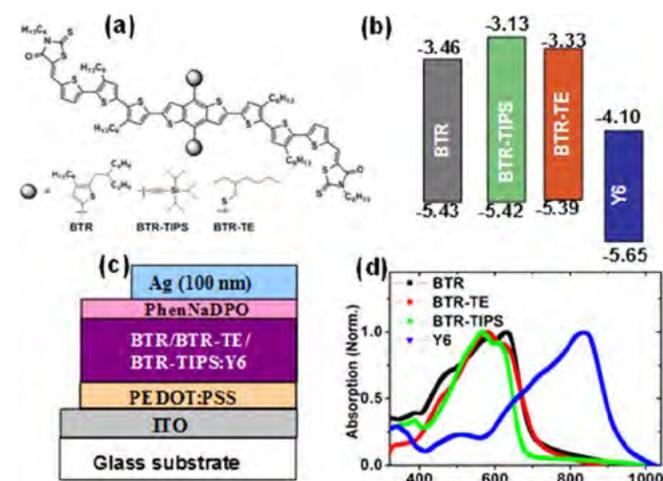


Figure PP2.1.9: (a) Chemical structure of BTR, BTR-TE and BTR-TIPS donor molecules; (b) energy level of donor and acceptor molecules; (c) schematic diagram of the device geometry; and (d) normalised optical absorption spectra of donor and acceptor thin films.

In this extension of our previous work, we have used the small-molecular material Y6 as an acceptor along with BTR analogue donor materials in OPV devices. The higher lowest unoccupied molecular orbital (LUMO) offset energy and optimum energy level match of these donor small molecules and Y6 NFA can provide enough driving force for efficient exciton dissociation and charge generation, resulting in optimised OSCs showing PCEs of 13.2%, 11.10% and 8.3% for BTR-TE-, BTR- and BTR-TIPS-based solar cells, respectively (Figure PP2.1.10). This work demonstrates that the thioether sidechain appended to the BDT core showed a profound effect on molecular packing, crystallinity, charge transports, recombination and device efficiency.

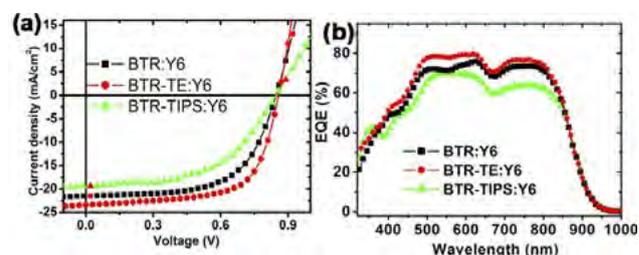


Figure PP2.1.10: (a) J–V curves and (b) EQE spectra of the OPV devices based on BTR:Y6, BTR-TE:Y6 and BTR-TIPS:Y6.

Ternary blend device architectures

The ternary organic solar cell is a promising technology towards high power conversion efficiency, with blends having the capability to absorb across the UV-visible to the near IR region. Ternary blends contain three organic materials either donor:donor:acceptor (D₁:D₂:A) or donor:acceptor:acceptor (D:A₁:A₂), and can give higher device performance than binary blends. The general approach is to add a small amount of the third component (D₂ or A₂) to a binary blend.

We have fabricated ternary blend solar cells with an inverted device geometry as shown in Figure PP2.1.11. In this ternary OPV, we used the small molecules BTR/BTR-TE/BTR-TIPS as the third component along with a PM6:Y6 blend film, with the optimum device performance found at 10% loading of the small molecular donor materials in the ternary blend. The control devices based on a binary PM6:Y6 active layer exhibited the best PCE of 16.1% with a J_{sc} of 24.2 mAcm^{-2} , V_{oc} of 0.83, and FF of 75%.

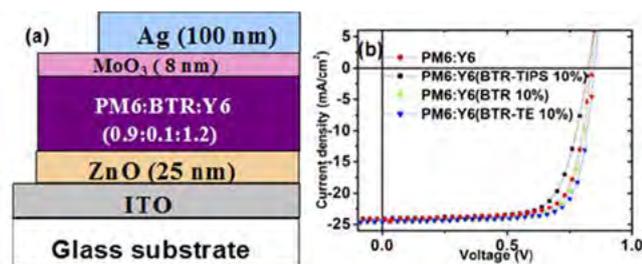


Figure PP2.1.11: Ternary blend OPV devices with 16.1% PCE. (a) Device geometry; and (b) J-V plots of ternary blend OPV devices.

In further work we have demonstrated a novel ternary organic solar cell by incorporating non-fullerene acceptor Y6 as the additional component into the PTB7-Th:ITIC non-fullerene binary system. The Y6 adding ratio is optimised for best performance, with the PTB7-Th:Y6(5%):ITIC(95%) ternary devices showing the highest PCE enhancement of around 29% compared to PTB7-Th:ITIC binary devices. Schematic diagrams of device structure, energy level diagram, and chemical structures of PTB7-Th, ITIC and Y6 and J-V curves of cells are shown in figure PP2.1.12 and PP2.1.13.

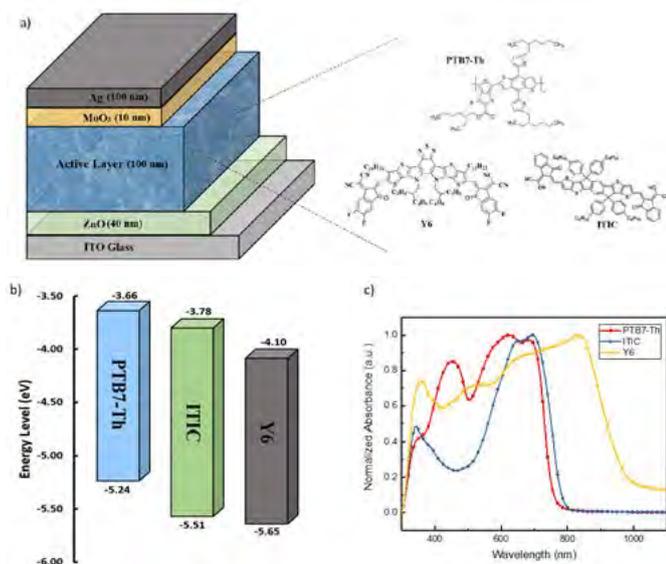


Figure PP2.1.12: (a) Schematic diagram of the inverted device structure for organic solar cells fabrication with the chemical structure diagrams of the PTB7-Th, Y6 and ITIC. (b) Energy band diagram for cascade energy level alignment for PTB7-Th, ITIC and Y6. (c) UV absorption spectra versus light wavelength for pristine PTB7-Th, ITIC and Y6 films (Leiping Duan et al., DOI: <https://doi.org/10.1002/ente.201900924>).

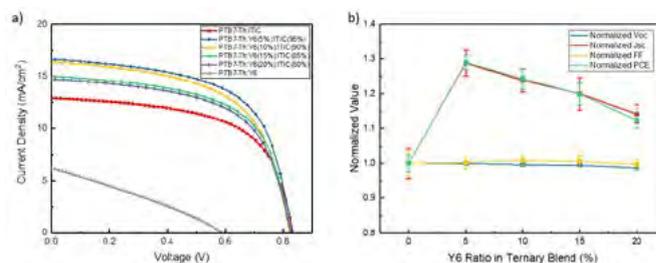


Figure PP2.1.13: (a) Current-voltage characteristics of the fabricated solar cells for both binary and ternary devices at room temperature under one-sun test condition (AM1.5G illumination at 100 mW cm^{-2}). (b) Normalised photovoltaic parameters including V_{oc} , J_{sc} , FF and PCE for devices versus different Y6 adding ratio measured under one-sun test condition (AM1.5G illumination at 100 mW cm^{-2}) (Leiping Duan et al., DOI: <https://doi.org/10.1002/ente.201900924>).

Investigation of burn-in degradation

Burn-in photodegradation, which is caused by continuous light illumination, can result in a significant initial drop in performance. Recently, there have been some studies that suggest burn-in degradation can be considered as an ineluctable barrier to long-term stable organic solar cells. However, there is still insufficient evidence to explain the detailed mechanism of this burn-in process. In this work, we firstly investigated the mechanism of the burn-in process in the high-efficiency PM6:N3-based non-fullerene organic solar cells. The PM6:N3-based device achieved an average PCE of 14.10% but also showed a significant performance loss after the burn-in degradation. The following characterisations such as dark J-V, PL, TRPL, Urbach energy estimation, and EIS reveal that the burn-in degradation observed is closely related to the current extraction, energy transfer, non-radiative recombination, and charge transport process in the PM6:N3-based devices. At the same time, it has small effects on the exciton dissociation process and energetic disorder in the PM6:N3-based device. AFM, SEM, TEM and GIXRD measurements gratifyingly found that the morphology of the PM6:N3 active layer is relatively stable during the burn-in degradation. Therefore, the observed degradation is thought to result from the instability of interfaces and electrodes. The atoms in the carrier transport layers and electrodes may diffuse into the active layer during the degradation, which changes the energy levels of each layer and causes traps at the interface and in the active layer. Conquering the instability of interfaces and electrodes is proposed as the priority task for PM6:N3-based organic solar cells to achieve long-term stability. Our study provides insights into the mechanism behind the burn-in degradation of the PM6:N3-based organic solar cells, which takes the first step to overcoming this barrier. The current density to voltage (J-V) curves for all devices have been shown in Figure PP2.1.14(a) and the corresponding photovoltaic output data are listed in Table PP2.1.1. The degradation was monitored by measuring these photovoltaic parameters hourly during the five-hour degradation testing. By using the inverted device structure, fresh PM6:N3 devices have achieved an average PCE value of 14.10%, and it is apparent that degraded devices show significant performance loss when compared to fresh devices. After five hours of burn-in degradation, the average PCE of the device dropped by around 50% to only 7.14% with simultaneously reduced J_{sc} , V_{oc} and FF values. Figure PP2.1.14(b) displays the burn-in aging curves of photovoltaic parameters, including V_{oc} , J_{sc} , FF and PCE.

Figure PP2.1.14: (a) Current density to voltage (J - V) curves of both fresh and degraded devices tested at room temperature under one-sun test condition (AM1.5 G illumination at 100 mWcm^{-2}).

(b) Normalised photovoltaic parameters of the device in the burn-in degradation process under simulated one-sun light at a temperature of 85°C in the ambient for up to five hours (Leiping Duan et al., DOI: <https://doi.org/10.1021/acsami.0c05978>).

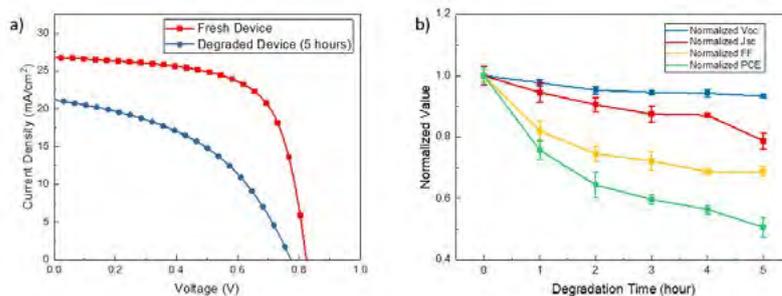


Table PP2.1.1: Open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), fill factor (FF), power conversion efficiency (PCE), shunt resistance (R_{sh}) and series resistance (R_s) of both fresh and degraded devices under the simulated one-sun test conditions. Average of at least five devices (Leiping Duan et al., DOI: <https://doi.org/10.1021/acsami.0c05978>).

Device	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF	Ave PCE	R_{sh} ($\Omega \text{ cm}^2$)	R_s ($\Omega \text{ cm}^2$)
Fresh Device	0.825	26.33	0.649	14.10%	456.1	4.21
Degraded Device (5 hours)	0.770	20.74	0.447	7.14%	160.1	12.11

Semitransparent organic solar cells

By using the $\text{MoO}_3/\text{Ag}/\text{MoO}_3$ -based D/M/D transparent electrodes, we have fabricated semitransparent organic solar cells based on the poly[(2,6-(4,8-bis(5-(2-ethylhexyl-3-fluoro)thiophen-2-yl)-benzo[1,2-b:4,5-b']dithiophene))-alt-(5,5-(1',3'-di-2-thienyl-5',7'-bis(2-ethylhexyl)benzo[1',2'-c:4',5'-c']dithiophene-4,8-dione)] (PM6):N3 active layer for the first time. N3 is a small molecule acceptor with the third position containing branched alkyl chains. In the device fabrication, the D/M/D transparent electrode was optimised by varying the thickness of the outer MoO_3 layer. As a result, we found that increasing the thickness of the outer MoO_3 layer can increase the average visible transmittance (AVT) but decrease the power conversion efficiency (PCE) of the device. By varying the outer MoO_3 layer thickness from 0 to 30 nm, the average PCE of the device decreased from 13.79% to 7.89%, with an increase in the AVT from 24.45% to 31.26%. The outer MoO_3 layer with 10 nm thickness was found to deliver the optimum case, where its corresponding device showed the PCE of 9.18% with a high AVT of 28.94%. Moreover, by following the CIE protocol, the CRI values were calculated for all semitransparent organic solar cells. As a result, all the devices displayed a neutral colour perception with a high CRI value over 90. The inverted device structure of the PM6:N3-based semitransparent organic solar cells (ITO/ZnO/active layer/ $\text{MoO}_3/\text{Ag}/\text{MoO}_3$) is displayed in Fig. PP2.1.15.

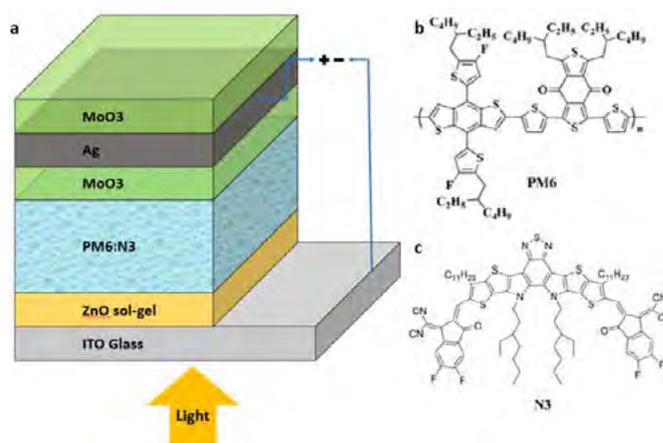


Figure PP2.1.15: (a) The schematic diagram of the inverted device structure of ITO/ZnO/active layer/ $\text{MoO}_3/\text{Ag}/\text{MoO}_3$ for the fabricated semitransparent devices; (b) the diagram of chemical structures of PM6; (c) the diagram of chemical structures of N3 (Lich Chang et al., DOI: <https://doi.org/10.3390/nano10091759>).

Figure PP2.1.16 shows the current density to voltage (J - V) curves for all fabricated devices. The corresponding photovoltaic parameters of the device are displayed in Table PP2.1.2. For all the devices, the V_{oc} values are around 0.8 V, pointing out that the variation of the Ag thickness and the outer MoO_3 layer thickness has a negligible effect on the device voltage. The opaque device with 100 nm thick Ag layer achieved 25.29 mAcm^{-2} of J_{sc} , 66.9% of FF and 13.8% of PCE. By reducing the thickness of the Ag layer to 10 nm, J_{sc} dropped from 24.3 to 19.15 mAcm^{-2} , with a 27.8% decrease in PCE.

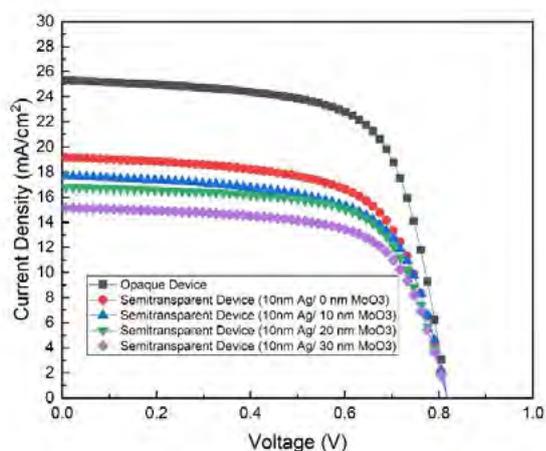


Figure PP2.1.16: The current density to voltage (J - V) curves of the opaque device and all fabricated semitransparent devices (Lich Chang et al., DOI: <https://doi.org/10.3390/nano10091759>).

Table PP2.1.2: Photovoltaic parameters summary including the open-circuit voltage (V_{oc}), short-circuit current (J_{sc}), fill factor (FF), power conversion efficiency (PCE), series resistance (R_s) and shunt resistance (R_{sh}). The parameters were measured at room temperature under one-sun test condition (AM1.5 G illumination, 100 mWcm^{-2}), and the average value and the standard deviation were determined from the measurement of at least five devices. (Ref: Lich Chang, et al., DOI: <https://doi.org/10.3390/nano10091759>).

Devices	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	PCE (%)	R_s ($\Omega \text{ cm}^2$)	R_{sh} ($\Omega \text{ cm}^2$)
Opaque Device (100 nm Ag/ 0 nm MoO_3)	0.82	25.29	66.91	13.79	131	18444
Semitransparent Device (10 nm Ag/ 0 nm MoO_3)	0.80	19.15	64.92	9.96	144	18511
Semitransparent Device (10 nm Ag/ 10 nm MoO_3)	0.79	17.68	65.41	9.18	147	19200
Semitransparent Device (10 nm Ag/ 20 nm MoO_3)	0.81	16.79	65.46	8.86	191	25089
Semitransparent Device (10 nm Ag/ 30 nm MoO_3)	0.80	15.15	64.67	7.84	207	23333

The colour coordinates of all devices are plotted in the CIE colour space chromaticity diagram, as presented in Figure PP2.1.17. The calculated colour coordinates of the ST devices sit close to the achromatic (white point) on the colour space diagram. This indicates a pleasant colour sensation when the viewers look through cells under AM 1.5 G illumination. The colour coordinates of the devices with 30 nm thickness of the outer MoO_3 layer are close to the illuminant D65 (0.31, 0.33) at (0.27, 0.30). These devices are capable of letting the light pass through them without affecting too much the original colour of an object. For the devices with a thinner layer thickness (10, 20 nm), the colour coordinates are located near the blue colour on the CIE chromaticity diagram. According to the definition, the CRI equals the ratio of sample "colour rendering ability" to that of standard source in percentage. It ranges between 0 and 100, the higher the CRI value, the better capability to reveal the original light. The CRI can be calculated by following the CIE 13.3 1995 protocol. The (x , y) coordinates are converted to (u , v) coordinates in the colour space. The coordinates are adjusted from eight test colour samples, which are known as reference samples, and are divided from the visible spectrum and illuminated under the D65 source. Moreover, the test samples are colours of light which transmitted through the device.

The different reflection result of each sample accounts for the change of transmitted light colour. As a result, the CRI values of all fabricated ST-OSCs are above 90, and the CRI decreases as the outer MoO_3 layer thickness increases. Generally, all fabricated PM6:N3-based semitransparent devices display neutral-colour perception.

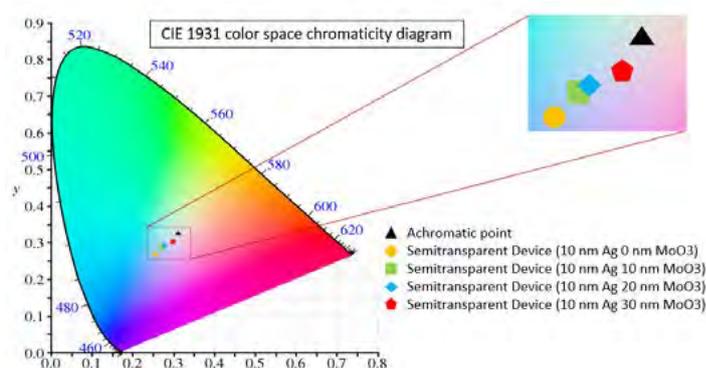


Figure PP2.1.17: Representation of the colour coordinates (x , y) of all devices using a standard D65 illumination light source on the CIE 1931 colour space (Lich Chang et al., DOI: <https://doi.org/10.3390/nano10091759>).

Graphene-based flexible solar cells

Graphene has shown tremendous potential as a transparent conductive electrode (TCE) for flexible organic solar cells. However, the trade-off between electrical conductance and transparency as well as surface roughness of the graphene TCE with increasing layer number limits power conversion efficiency enhancement and its use for large-area organic solar cells. This year in the program, we used a 300 nm-thick poly[(2,5-bis(2-hexyldecyloxy)phenylene)-alt-(5,6-difluoro-4,7-di(thiophen-2-yl)benzo[c]-[1,2,5]thiadiazole)]:[6,6]-phenyl-C₇₁-butyric acid methyl ester as the photoactive layer and benzimidazole (BI)-doped graphene as the transparent anode to demonstrate efficient OSCs with good flexibility. It is found that 3-layer (3L) graphene had the best balance between sheet resistance, optical transmittance and surface roughness for optimised cell design. A 0.2 cm² cell with a 3L BI-doped graphene anode achieved a PCE of 6.85%, which is one of the highest PCE values reported so far for flexible graphene anode-based organic solar cells. The flexible cells are robust, showing only a small performance degradation during up to 250 flexing cycles. Moreover, the combination of the thick photoactive layer with the optimised 3L BI-doped graphene TCE enabled production of 1.6 cm² flexible organic solar cells with a PCE of 1.8%. Our work illustrates the importance of graphene TCE development for flexible OSCs as well as other wearable optoelectronic devices.

Table PP2.1.3: Summary of average device performance based on PET/3-layer graphene with/without BI-doping and comparison with devices using commercial ITO. Values in brackets are from the best devices.

Anode	V _{oc} (V)	J _{sc} (mA cm ⁻²)	FF	PCE (%)
3L G	0.73±0.01	12.4±0.33	0.58±0.05	5.31±0.46 (6.14)
3L BI-doped G	0.76±0.01	13.7±1.22	0.62±0.01	6.46±0.40 (6.85)
ITO	0.76±0.01	14.0±0.18	0.66±0.02	6.96±0.15 (7.12)

Highlights

- A ternary blend OPV device with a 16.1% PCE has been reported.
- Luminescent solar concentrators with decreased concentration quenching.
- Morphology control of donor and acceptor systems for different donor/acceptor-based organic solar cells.
- Increased understanding of the mechanism of initial photo-degradation of organic solar cells.
- Developed highly efficient semitransparent organic solar cells with colour rendering index and transparency.
- Efficient graphene anode-based organic solar cells.

Future Work

- Continued investigation into morphology control of donor/acceptor materials in bulk heterojunction solar cells.
- Extended lifetimes study and degradation mechanism in organic solar cells.
- Develop high efficiency ternary blend organic solar cells.
- Develop highly efficient semitransparent organic solar cells with high AVT for window applications.
- Investigate alternative electrode materials.
- Develop singlet fission enhanced solar cells.

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PRINTING AND SCALE-UP

Aims

The record power conversion efficiency (PCE) for small-scale polymer solar cells (PSCs) has recently reached 18.2%. This increase has largely been attributed to the development of new active donor and acceptor materials. However, the active layer thicknesses in record PCE cells are typically around 100 nm, a thickness which in principle is not practical for production using industrial methods without defect formation. Finding materials that can be deposited by roll-to-roll (R2R) methods, which require thicker active layers and increased air stability, while still giving comparable PCEs has been a great challenge. Remarkable progress has been made in the fabrication of thick-film PSCs over the last several years using spin coating, with

studies demonstrating cells with a PCE of 15% at a thickness around 320 nm. However, the conditions used for spin coating cannot be applied directly to R2R-coating processes and the deposition of thicker film by increasing the concentration of the active layer precursor solution seems unlikely due to their low solubility. This creates significant challenges in translating the processes used to make lab cells to large-area modules, thereby hindering the commercialisation of high-performance PSCs. To overcome these drawbacks, the team and Korean researchers have synthesised two conjugated polymers with a typical donor-acceptor (D-A) architecture which have shown promising results when produced by R2R methods.

Another approach is the use of multi-component systems, which provide an opportunity to potentially raise the PCE of PSCs beyond 20%. However, it also presents a new challenge in exploring numerous possible material combinations together with thickness variations, thermal annealing conditions and processing additives when using our existing R2R printer manually. To reduce the human input required in testing and achieve precise control over the system complexity, the team designed and developed a bench-top digital solar coater as well as an auto-tester to enable fabrication/testing of >4000 devices per day to accelerate the optimisation process.

The activities include:

- Development of printable OPV materials with thickness tolerant and thermally stable conjugated polymers for additive-free devices.
- A digital transformation in photovoltaic research.

Progress

Development of printable OPV materials with thickness tolerant and thermally stable conjugated polymers for additive-free devices

The promising electron-donating and electron-withdrawing components of benzodithiophene (BDT) and quinoxaline (Qx) derivatives were selected as the basic building blocks of the target D-A type polymers. Multiple fluorine atoms were carefully incorporated into selected positions of BDT and Qx monomers to favourably modify the electronic structures of the polymers to generate the target polymers PB-QxF and PBF-QxF, respectively (Figure PP2.1.18). All the polymers showed good solubility in common organic solvents such as chloroform, THF and toluene because of the presence of the 2-ethylhexyl and 2-butyloctyl chains on the BDT and Qx units.

During the R2R process, films must undergo heating cycles in air during deposition, thus the material must be robust enough to survive relatively harsh conditions. Thermogravimetric analysis (TGA) of all the polymers at a heating rate of 10°C min⁻¹ in an inert atmosphere showed that they exhibited good thermal stability, and the two polymers had a similar high onset of decomposition temperature of 5% weight loss at over 400°C. The optical properties of the polymers were investigated by UV-Vis absorption spectroscopy. Like other D-A-type polymers, PB-QxF and PBF-QxF exhibited two broad absorption

bands in the short (350–480 nm) and long (520–680 nm) wavelength regions in the film state (Figure PP2.1.18(b)). The optical bandgaps of PB-QxF and PBF-QxF obtained from the absorption edges were 1.63 and 1.66 eV, respectively. The Y6 acceptor demonstrates high electron mobility and broad absorption range at longer wavelengths and was therefore used as the non-fullerene acceptor to fabricate PSCs.

The photovoltaic properties of the polymers were investigated using R2R slot-die coated inverted-type PSCs with a configuration of ITO/ZnO/polymer:Y6/MoO₃/Ag on PET substrate. From the detailed studies obtained by spin coating on glass substrates, it was found that the hole mobility of PBF-QxF films shows one of the highest values among those of recently developed polymers based on the Y6 acceptor ($1.1 \times 10^{-3} \text{ cm}^2 \text{ V}^{-1} \text{ S}^{-1}$). Furthermore, PBF-QxF showed less bimolecular recombination and better charge transport and extraction behaviour than PBQxF, and it was therefore then selected for device fabrication.

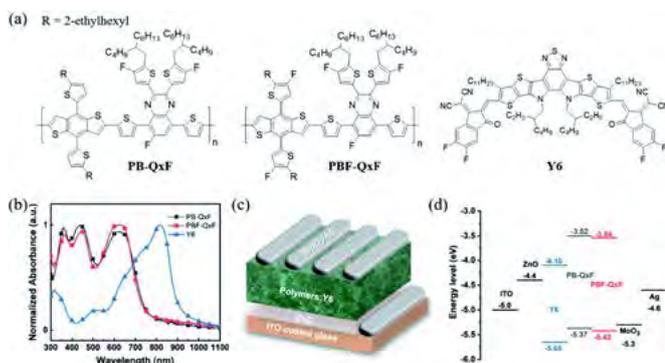


Figure PP2.1.18: (a) Chemical structures of PB-QxF, PBF-QxF, and Y6. (b) Normalised UV-Vis absorption spectra of PB-QxF, PBF-QxF and Y6 in the film state. (c) Device structure of a lab-scale inverted-type PSC. (d) Energy level diagrams of all materials in the inverted-type PSCs.

To improve device performance through morphological control, the temperatures of both the solution and the substrate during slot-die coating were fixed at 90°C and 130°C, respectively. The thickness of the active layer in R2R-processed devices was changed by controlling the concentration, flow rate, coating speed and width. R2R PSC with PBF-QxF exhibits a maximum PCE of 9.63% with a VOC of 0.76 V, a JSC of 20.39 mAcm⁻², and an FF of 0.62 with a film thickness of 202 nm without any additives present. To the best of our knowledge, this is the highest PCE value among all the R2R-processed PSCs on flexible substrates. Moreover, an impressive PCE value of 8.49% was maintained in a very thick film of 354 nm. These results clearly indicate the outstanding thickness tolerance of PBF-QxF, which is one of the key requirements for R2R compatible materials (Figure PP2.1.19).

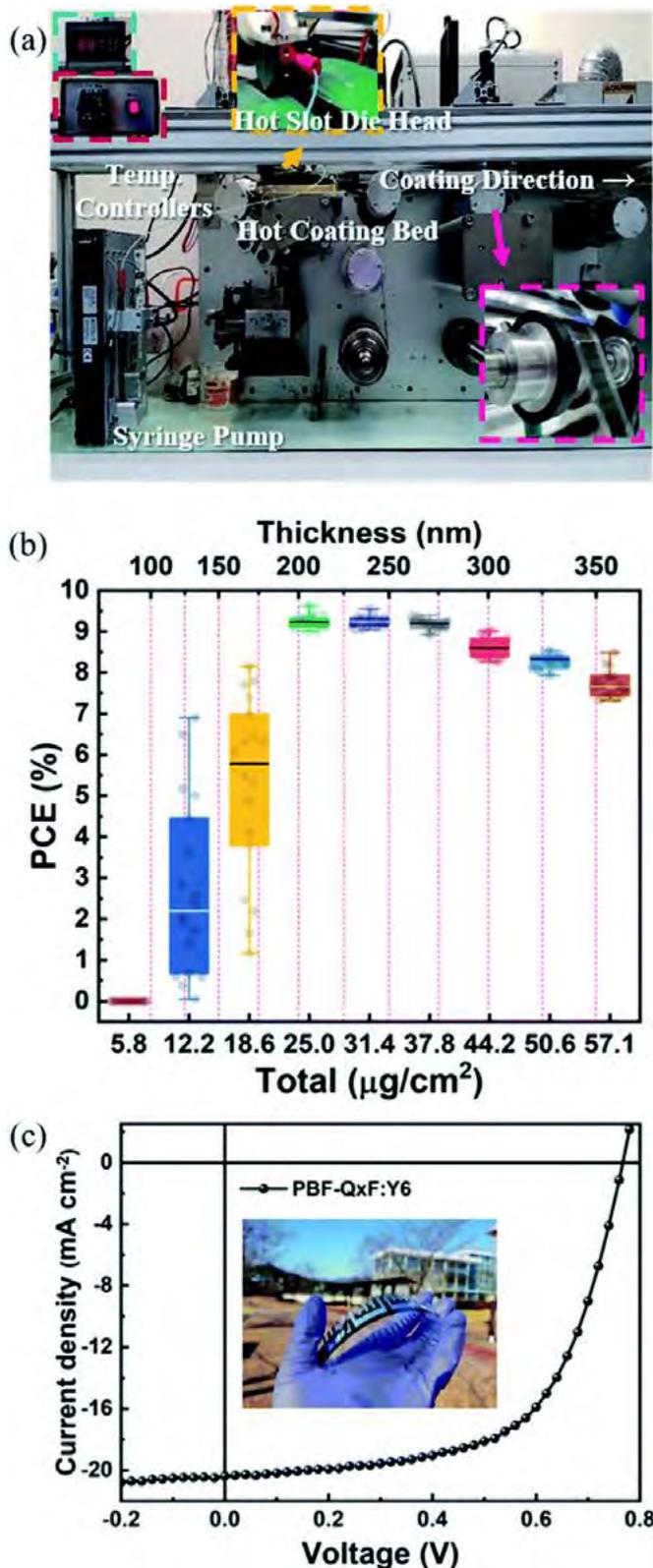


Figure PP2.1.19: (a) Experimental setup for temperature-controlled R2R deposition. 90°C and 130°C were used for the slot-die head and green hot plate, respectively. (b) PCEs of R2R slot-die coated PBF-QxF-based PSCs with different thicknesses. (c) J-V curve of the best R2R-processed device with a PCE of 9.63% and (inset) a photograph of R2R slot-die coated flexible devices.

Digital Transformation of Photovoltaic Research

Limiting the amount of material required to achieve the best outcome is the preferable and economical approach during device optimisation. Although numerous solar cells can be made using the existing R2R coater, there is difficulty in reliably optimising device fabrication in well-controlled conditions when dealing with multi-component systems. To address this, the team has designed and built a bench-top high-throughput auto R2R solar coater which is equipped with multi-solution injection channels with digital control. This auto-coating system enables composition, deposition parameters and the temperature of heaters to be programmed. As a result, complex experiments can be carried out without the presence of an operator, that is, thousands of research cells can be fabricated overnight under precisely controlled conditions. To achieve this, in-house software has been programmed which can independently control pumps for in situ optimisation of each component ratio and concentration with a gradient change. Heating of slot-die heads, coating stages and hot plates are separately controlled. Deposition parameters such as flow rate on the desired coating length can be preset (Figure PP2.1.20). The availability of this auto-coater enables us to fabricate complex formulated devices in a well-controlled environment, in addition to greatly accelerating the translation process from small cells to modules. The capacity of nearly 10,000 unique devices per day can be prepared using this new coater. Further modification of this coater is still being developed.

After the generation of thousands of solar cells in less than one day, manual testing of cells one by one is not practical. However, the fabricated cells must be measured in a timely fashion to avoid any unnecessary influence arising from either intrinsic material properties or external environments. This inspired us to design and develop an R2R auto-testing system at a similar scale as the newly developed auto-coater. After coating, the coated roll is removed from the auto-coater and transferred directly onto the auto-tester (Figure PP2.1.21) for rapid measurement under ambient air without encapsulation. Using this process, 4000 devices can be fabricated and tested in one day by one person, dramatically increasing effectiveness. A total of less than 50 mg of materials is enough for 4000 lab-scale devices (donor + acceptors), largely reducing material consumption and the cost for optimisation.

As reported in the previous year, machine learning (ML) technology emerged as a powerful research tool, especially for dealing with large and complicated data sets. Fast, statistic analysing, as well as a filtering function, would greatly help to summarise and identify the best parameters. The in-house developed software has been updated in response to feedback from the team. Figure PP2.1.21 shows the trend of the performance of thousands of cells under variable conditions across different batches. Moreover, one can selectively choose any specific data set for analysis. For instance, by selecting a PCE higher than a certain number, all devices with a PCE above that

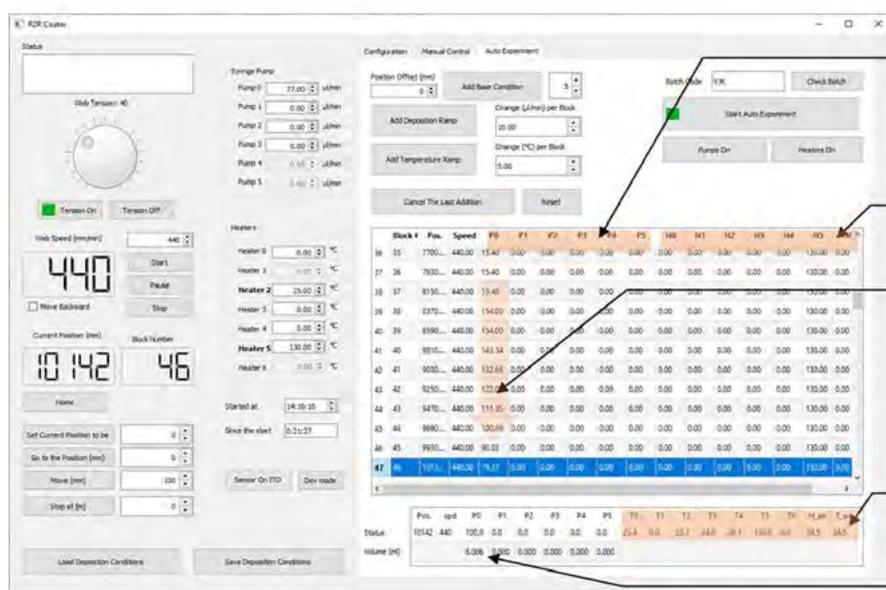
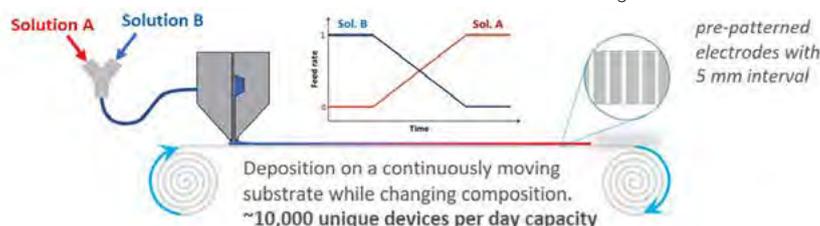


Figure PP2.1.20: (top) Schematic diagram of R2R auto-coating; (bottom) Digital coating parameters setting.

number are filled out, and the detailed information for each device can be found by clicking each data point in the plot. This ML is becoming a routine tool for analysing several thousands of devices in a short period of time.

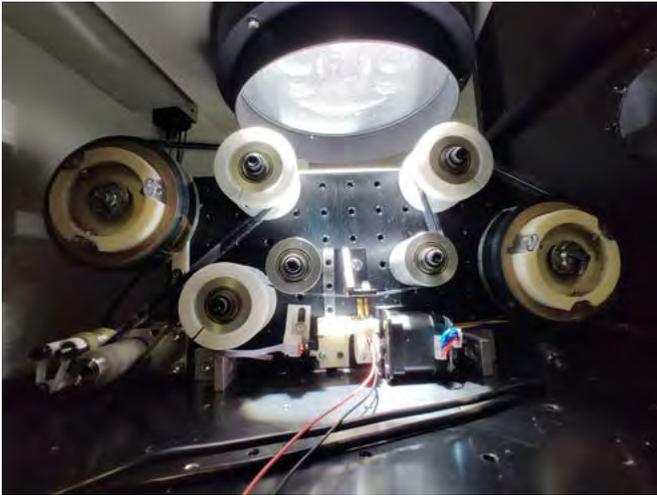


Figure PP2.1.21: Photograph of the bench-top R2R auto-testing system.

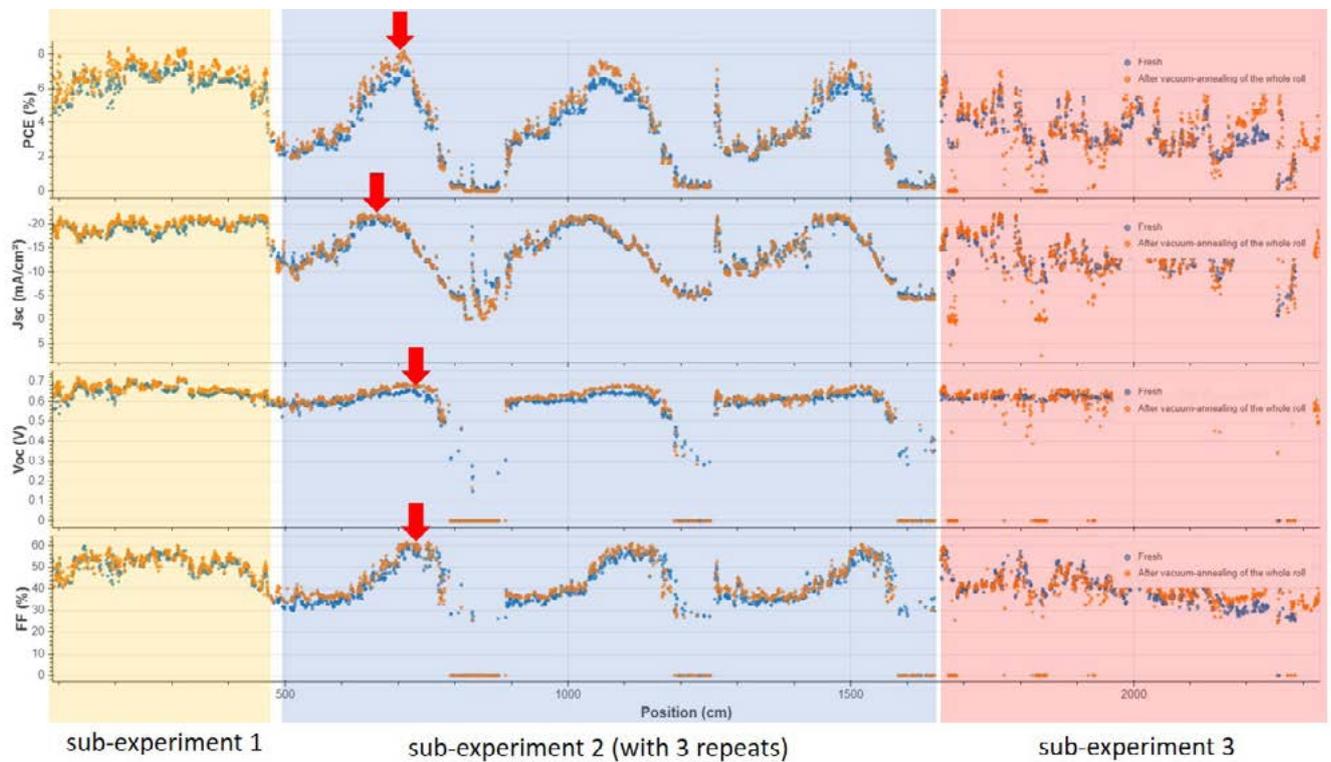


Figure PP2.1.22: Tracking performance of thousands of cells in a minute.

Highlights

- Digitally controlled solar coater and tester have been built for maximal optimisation of R2R fabrication conditions while conserving labour resources.
- Less than 50 mg of materials for 4000 lab-scale devices (donor + acceptors) was required, largely reducing materials consumption.
- 4000 devices were fabricated and tested in one day by one person.
- Printable OPV materials with thickness tolerant and thermally stable polymers have been developed.
- 9.6 % @ 0.14 cm², the highest PCE from R2R-processed OPV (with vacuum-deposited electrodes) in the literature, was achieved at an industrial acceptable film thickness of 200–300 nm.

Future Work

- Target of PCE 10% at 0.14 cm² from fully R2R-printed (including back electrode) OPV.
- Attempts to achieve a PCE 8% at 100 cm² from fully R2R-printed (including back electrode) OPV.

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PP2.2 CZTS SOLAR CELLS

Lead Partner

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Funding Support

ARENA, ACAP, ARC, Baosteel

Aims

All successfully commercialised non-concentrating photovoltaic technologies to date are based on silicon or chalcogenides (semiconductors containing Group VI elements, specifically Te, Se and S). The successful chalcogenide semiconductor materials, CdTe and Cu(In,Ga)Se₂ (CIGS), can be regarded as “synthetic silicon” where the balance between atoms in these materials provides the same average number of valence band electrons as in silicon, resulting in the same tetrahedral coordination (Figure PP2.2.1) (Walsh et al. 2012). Cd is toxic while Te and In are among the 12 most scarce elements in Earth’s crust. These factors would seem to clearly limit the long-term potential of the established chalcogenide technologies. By delving more deeply into the Periodic Table, an alternative option can be uncovered with the same number of valence band electrons on average but involving only Earth-abundant, non-toxic elements.

A kesterite Cu₂ZnSnS₄ (CZTS) compound semiconductor has emerged, based on such reasoning, as a promising candidate for thin-film solar cells. Analogous to the chalcopyrite structure of CIGS, CZTS shares similar optical and electrical properties. CZTS has a bandgap of around 1.5 eV, and a large absorption coefficient of over 10⁴ cm⁻¹. Notable is that the bandgap of the CZTS family can be tuned to span a wide range beyond 2.25 eV, even above the accessible range of the highest efficiency III-V cells. This makes the material suitable for tandem cells. For thin-film solar cells, energy conversion efficiency up to 12.6% and 11% have been achieved so far for CZTS_{Se} and CZTS solar cells by IBM/DGIST and UNSW, respectively.

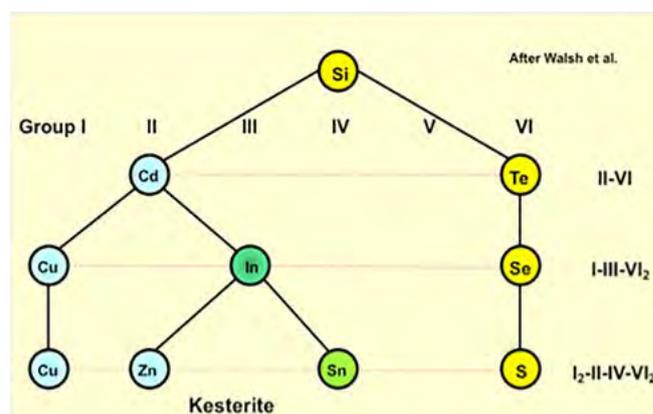


Figure PP2.2.1: The schematic of “Synthetic Si” showing how the CZTS is derived.

ACAP’s work in the CZTS area takes the sputtering fabrication direction, a low-cost, high-throughput and up-scalable manufacturing process which has been used in the commercialised high performance CIGS solar cells. In this regard, CZTS offers a realistic potential to achieve the efficiency levels required for transferring lab-scale processes to commercialisation in the short term as being fully compatible with current CIGS production lines. Using kesterite materials less than two microns thick, cells can be light and flexible if grown on a flexible substrate, which has the wide applications in areas such as building integrated photovoltaics (BIPV), transport

vehicles, unmanned aerial vehicles (UAVs), and Internet of Things (IoT), harvesting light and reducing greenhouse gas emissions.

Work in this strand includes the development of high efficiency CZTS solar cells on soda–lime glass and flexible stainless steel.

Progress

Suppressed intrinsic defects by engineering of local chemical environment

Abundant detrimental intrinsic defects and associated dominant non-radiative recombination in the bulk of CZTSSe absorbers is the current limiting factor for the stagnated efficiency. We found that the formation mechanism of these detrimental defects is closely related to the local chemical environment at the point in time when the formation of the CZTSSe phase initiates. By engineering the oxidation states and local chemical composition of the precursor (Figure PP2.2.2), the formation of detrimental intrinsic defects like $\text{Sn}_{\text{Zn}}+2\text{Cu}_{\text{Zn}}$ and $\text{Sn}_{\text{Zn}}+\text{Cu}_{\text{Zn}}$ clusters has been greatly suppressed, resulting in suppressed potential/bandgap fluctuation, much longer minority carrier lifetime, and activated desirable defect Cu vacancies (Figure PP 2.2.3). These encouraging features of absorbers enable the independently conformed 12.5% efficiency.

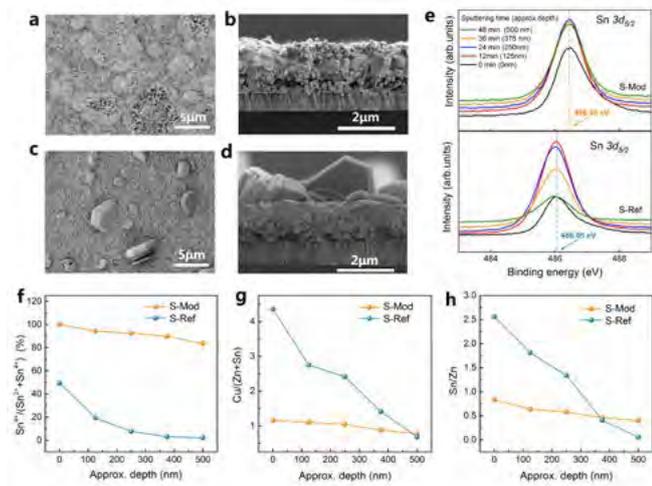


Figure PP2.2.2: Morphologies, oxidation states of Sn, and local chemical compositions of half-selenised samples. Surface and cross-section SEM images of (a), (b) half-selenised S-Mod and (c), (d) half-selenised S-Ref. (e) Sn 3d5/2 XPS depth profiles of half-selenised S-Mod and half-selenised S-Ref. (f) Depth profile of proportion of Sn^{2+} in Sn ions, (g) ratio of $\text{Cu}/(\text{Zn}+\text{Sn})$, and (h) ratio of Sn/Zn for half-selenised S-Mod and half-selenised S-Ref.

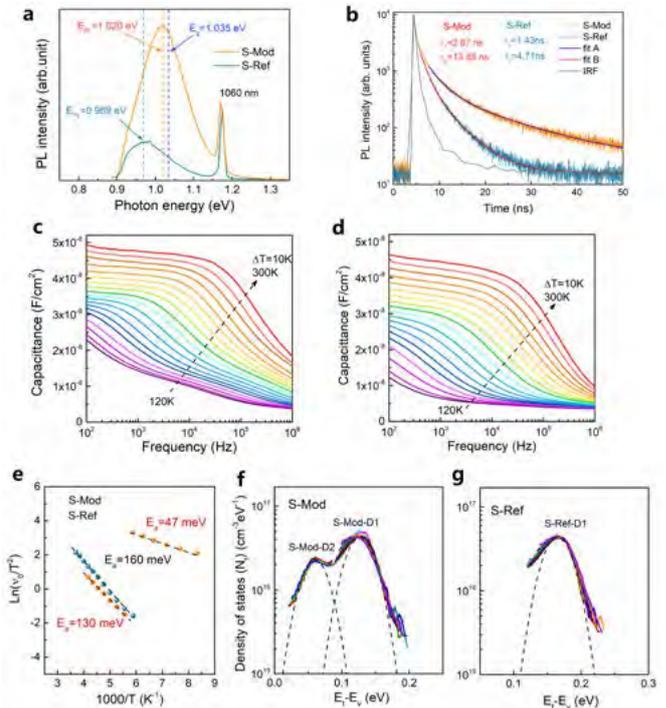


Figure PP2.2.3: Carrier recombination mechanisms and defect profiles. (a), (b) PL and TRPL spectra for S-Mod and S-Ref. The PL peaks at 1060 nm in (a) is the binary divided frequency signals of the 530 nm laser. (c), (d) Admittance (C-f-T) spectra of S-Mod and S-Ref, respectively. (e) Arrhenius plots for S-Mod and S-Ref obtained from admittance spectra. (f), (g) Energy profiles of the defect states in S-Mod and S-Ref, respectively.

Replacement of Cu_{Zn} with Li_{Zn} shallow acceptor defects enabled by solution-based Li-PDT treatment

Lithium incorporation in kesterite $\text{Cu}_2\text{ZnSn}(\text{S,Se})_4$ (CZTSSe) materials has been experimentally proven effective in improving electronic quality for application in photovoltaic devices. We developed a feasible and effective solution-based lithium post-deposition treatment (PDT), enabling further efficiency improvement on the high performance baseline. In this way, lithium is uniformly incorporated into grain interiors (GIs) without segregation at grain boundaries (GBs) (Figure PP2.2.4), which can occupy the Zn sites with a high solubility in the CZTSSe matrix, producing high density of Li_{Zn} anti-sites with shallower acceptor levels than the intrinsic dominant defect (Cu_{Zn} anti-sites) (Figure 2.2.5). As a result, CZTSSe absorber with better p-type doping is obtained, leading to a pronounced enhancement in fill factor and a corresponding gain in open circuit voltage and short-circuit current and consequently a significant efficiency boost from 9.3% to 10.7%. This work provides a feasible alternative alkali-PDT treatment for chalcogenide semiconductors and promotes a better understanding of the mechanism of Li incorporation in kesterite materials.

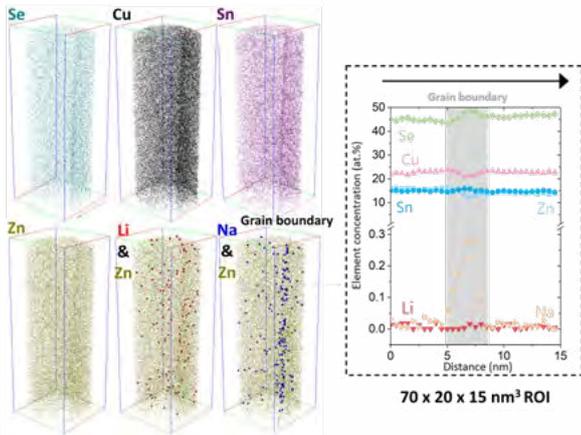


Figure PP2.2.4: 3D elemental maps of the Li-doped CZTSSe with both grain interior and grain boundary included (left) and the composition profiles across the grain boundary (right).

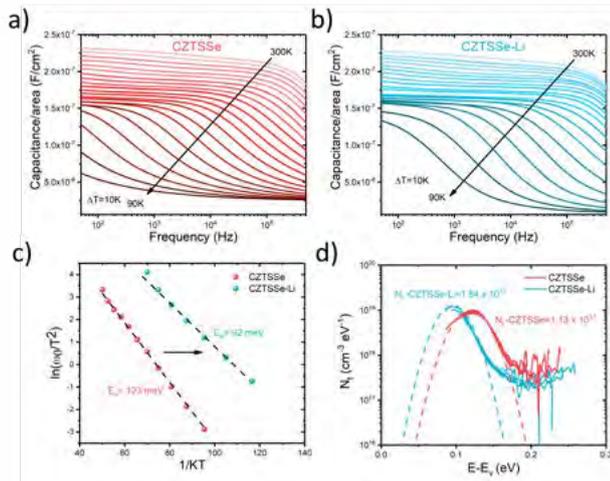


Figure PP2.2.5: AS data of (a) CZTSSe and (b) Li-doped CZTSSe, measured in the frequency range from 20 to 106 Hz from 90–300 K with a step of 10 K. (c) The Arrhenius plots of the inflection frequencies, determined from the derivative of the AS data. The dashed lines are the linear fit of the Arrhenius plots. (d) The density of states of the defects derived from admittance. The dash lines are the Gaussian fitting.

Identified loss mechanisms of the state-of-the-art CZTSe and CZTS solar cells

The development of kesterite thin-film PV technology is currently hindered by the poor carrier transport, attributable to short minority carrier lifetime, prevalent potential fluctuations, and severe interface recombination. We systematically investigated the carrier transport characteristics of over 12% efficiency $Cu_2ZnSnSe_4$ (CZTSe) solar cells combining nanoscale structure and opto-electronic analysis, temperature-dependent I-V and capacity-voltage measurements. The heterojunction interface recombination is effectively passivated by an in situ epitaxially grown ZnSe nano-layer (Figure PP2.2.6), giving rise to a recombination activation energy well aligned to the bandgap energy (Figure PP2.2.7). A quasi-ohmic back contact with negligible barriers is observed, contributing to fill factors over 70%. The photocurrent

of these CZTSe devices is mainly limited by electron loss within the grains underlying near-horizontal grain boundaries (Figure PP2.2.8). Our results demonstrate promising robust carrier transport at the heterojunction and back contact interfaces and indicate a pathway to further efficiency improvement approaching 14%.

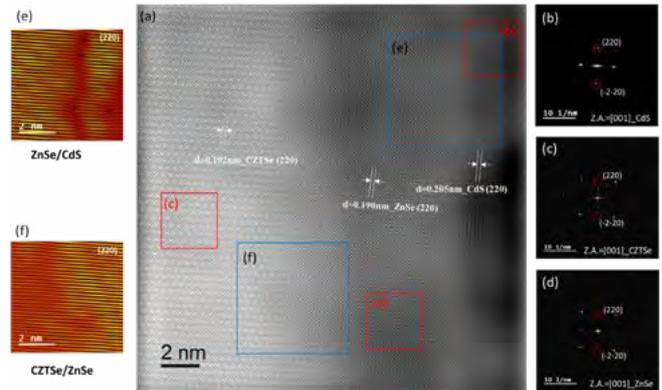


Figure PP2.2.6: (a) HRTEM image; (b)–(d) selected-area electron diffractions (SAED) patterns; (e) and (f) the inverse FFT images of the selected reflections revealing the dislocations (T marked) at the CZTSe/ZnSe/CdS heterostructure interface.

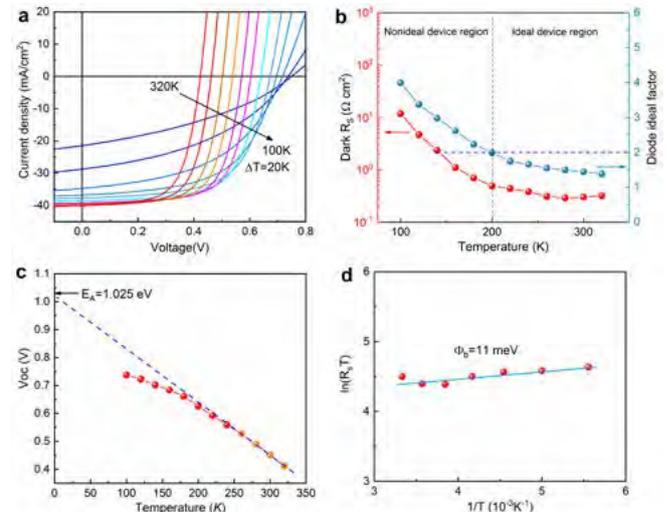


Figure PP2.2.7: (a) Temperature-dependent J-V curves under one-sun illumination. (b) Temperature-dependent R_s and diode ideal factor. The black dash line indicates the boundary between the ideal device region and non-ideal device region. (c) Plot of V_{oc} vs. temperature and the linear fit of the recombination activation energy EA. The data of yellow dots are selected for fitting. (d) Plot of $\ln(RST)$ vs. $1/T$ and the linear fitting showing back contact barrier height. The data of temperature-dependent R_s is abstracted from the dark J-V curves.

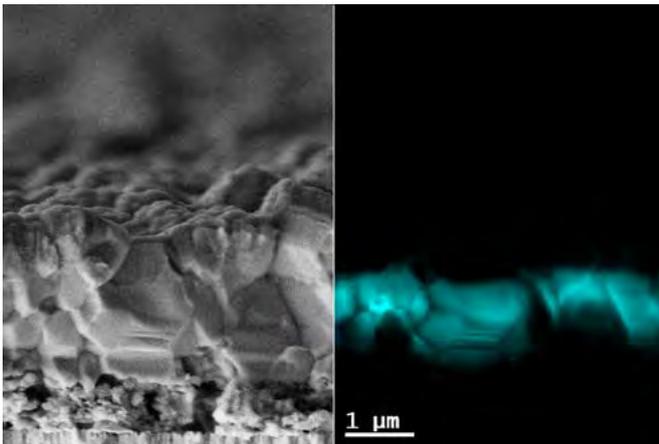


Figure PP2.2.8: Cross-section SEM image (left) and EBIC image (right) of a cleaved high performance CZTSe device. The yellow frames are the eye guide of the boundaries of the CZTSe grains which do not contribute to the EBIC signal (the regions in the red frames in EBIC image).

Analysis of manufacturing cost and market niches for Cu₂ZnSnS₄ (CZTS) solar cells

We have calculated the cost of three CZTS products using a Monte Carlo cost model and previous CIGS cost analysis data. At a production volume of 1 GW per year, the manufacturing cost of CZTS for different substrates is between \$41 and \$52 per m². The glass substrate configuration can cost less than \$0.3 per watt, an efficiency of 15%. Further cost reductions are likely to be achieved by reducing depreciation of equipment and material costs through mass production (Figure PP2.2.9). Given the similarity between CZTS and the already commercialised CIGS technology, and the expectation that efficiency limits are similar, we therefore would expect that with sufficient R&D to achieve these efficiencies, the cost in \$ per W will be improved compared to CIGS.

In considering market niches, we first identified the technical features of the CZTS technology that might be valued in different markets. We then selected three promising market niches and evaluated the potential for a fully developed CZTS technology to compete in these. In the traditional rooftop PV market dominated by crystalline silicon (with a large market share and significant economies of scale), there is a high barrier to entry for a new product such as CZTS. However, for the “weak roof” segment of this market, such as commercial membrane roofs, CZTS needs only compete with other thin-film products, where it might survive if the price–performance ratio is attractive. As for the IoT market, CZTS with plastic and steel substrates both have good prospects owing to their low weight, flexibility, and high voltage from monolithic integration. In the roof BIPV market, we propose the marginal LCOE (levelized cost of energy) to quantify PV technologies in terms of cost performance. CZTS with stainless steel will be able to compete with the counterpart CIGS in marginal LCOE under the assumption that its efficiency can be improved to 15%.

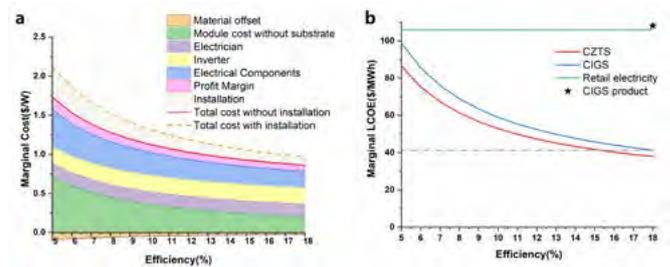


Figure PP2.2.9: (a) The marginal breakdown cost of CZTS at different module efficiencies (with and without installation cost); and (b) the marginal LCOE of CZTS, CIGS, CIGS commercial products, and retail electricity.

Highlights

UNSW has developed two effective strategies to manipulate the deep intrinsic defects and the dominant shallow acceptor-like defects respectively. The formation of deep intrinsic defects and defect clusters can be effectively suppressed by engineering the local chemical environment during the synthesis of the kesterite phase, leading to breakthroughs in V_{oc} and the new record efficiency of the 12.5% pure-selenide CZTSe solar cells. The dominant acceptor Cu_{Zn} in kesterite can be replaced with shallower Li_{Zn} defects with a high doping rate using a solution-based Li PDT treatment, resulting in much better p-type doping density and shallower Fermi-level. The loss mechanisms of the record CZTSe solar cells have been identified, pointing out the strategies for further essential improvements. Moreover, the manufacturing cost vs. different substrate and efficiency and potential market niches for Cu_2ZnSnS_4 (CZTS) solar cells has been analysed. The results indicate that 15% is the benchmark efficiency required to make CZTS solar cells competitive in the PV market.

Future Work

Future work in 2021 will be focused on the integration of our recently developed effective strategies (control of deep and shallow defects in kesterite absorber) and front and back surface bandgap grading using gradient of Ag, S and Ge substitution, which is expected to further improve the device performance. Strategies for interface defect engineering like type inversion and back surface field will be further investigated.

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Aims

Since the establishment of ACAP in 2013, mixed organic-inorganic halide perovskites have emerged as a new class of solar cell with potential as a material for the development of efficient, lower cost photovoltaic (PV) cells.

The potential of perovskites for PV cells as an absorber material lies in its ability to achieve good cell efficiencies, while being relatively cheap to produce and simple to manufacture (i.e. competitive cell efficiency at a potentially lower cost).

A significant effort has been initiated internationally on this materials class, and ACAP has several unique advantages that place the proposed activities at the forefront of these international efforts. Foremost among these advantages are the different relevant perspectives that ACAP is able to offer given the expertise within the different groups constituting ACAP in the dye-sensitised, organic photovoltaics (OPV), inorganic thin-film and silicon cell and module areas, as well as the strong contacts to the commercial sector, and the coordination of this expertise and research effort made possible through the ACAP organisational structure.

To capture these research efforts within ACAP, a new program package for Perovskite Solar Cells under PP2 Thin-Film, Third Generation and Hybrid Devices with additional funding was established to carry out focused and highly collaborative Australian research and industry efforts in perovskite photovoltaics. The aim is to establish an internationally leading activity in this exciting new materials group, and consistent with the original intent of ACAP, the team will undertake highly innovative and competitive research with a strategic focus on PV technologies that targets breakthroughs in the cost of solar energy. With a focus on issues that need to be resolved to enable low-cost, full-scale production, the work would enhance the commercial viability of perovskites.

The research is divided into the following main areas.

1. Thorough understanding of basic material and device properties by taking full advantage of the expertise, facilities and experience within the partner organisations. The project will undertake research in a diverse range of applications of perovskite materials and devices to develop a path to cost-effective, stable perovskite solar cells.
2. Investigation of prospects for Pb-free perovskite materials.
3. Understanding the stability of these materials and on both material synthesis and on encapsulation approaches to addressing present stability and durability issues.
4. Development of tandem thin-film cells both within the perovskite material system and in combination with inorganic thin films (Si wafer tandems specifically excluded since they are covered by another ARENA project).
5. Scaling to commercially relevant devices including improving the performance of reasonably large devices (>1 cm² in area) rather than on the tiny devices (<0.1 cm² in area) where the majority of international attention is focused. This task also includes the evaluation of manufacturing costs for the most promising of the fabrication approaches identified and scaling issues.

Progress

Materials and device properties

At UNSW, the group has improved perovskite cell efficiency by precursor engineering. Firstly, the correlation between the perovskite precursor and the resulting device performance has been investigated. It is found that the colloids, that is, iodoplumbates in the precursor solution get smaller with the addition of a certain amount of I₃⁻ owing to the formation of high-valent iodoplumbate (Figure PP2.5.1). This enables the formation of a more uniform perovskite layer with good crystallinity and fewer defects as demonstrated by a series of characterisations including atomic force microscopy (AFM), X-ray diffraction measurement (XRD), time-resolved photoluminescence (PL) and space charge limited current (SCLC) (Figure PP2.5.2). The improvement in the film formation and defect property have led to a much improved device (FAPbI₃) efficiency from 17.5% to 20.6% (Kim et al. 2020).

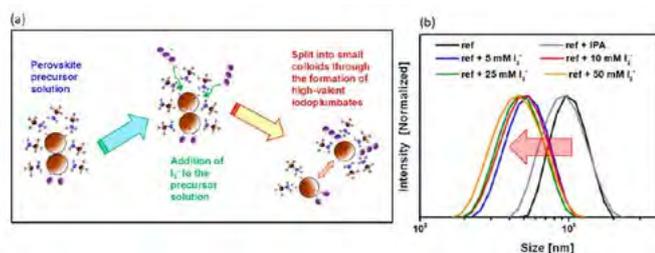


Figure PP2.5.1: (a) Schematic illustration of the colloidal state changes obtained by adding I₃⁻ ions as an additive into the perovskite precursor solution; and (b) colloid size distributions in the perovskite precursor solution obtained by dynamic light scattering measurement (DLS) (UNSW).

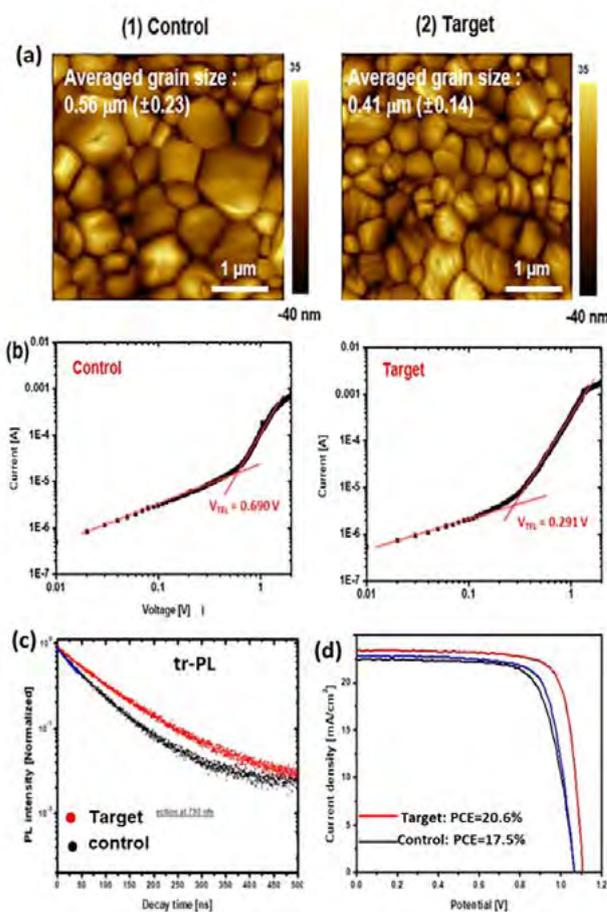


Figure PP2.5.2: (a) Surface topography measured by AFM showing more compact grains with smaller size variation in the target sample. SCLC spectra in (b) and TR-PL in (c) show smaller V_{TFL} and a longer lifetime for the target samples indicating that the I₃⁻ ion addition can reduce the defect density in the film, hence improving device efficiency as shown by the I-V curves in (d) (UNSW).

The effect of adding chlorine (Cl) in the dynamic sequential precursor solution has also been investigated at UNSW for FA_{0.3}MA_{0.7}PbI₃ perovskite solar cells by comparing (i) the roles of two different Cl sources (MACl and FAcI) and (ii) the time at which the Cl sources are added: (a) into PbI₂-DMSO in the first deposition step or (b) into MAI-FAI in the second deposition step (Bing et al. 2020). It is that Cl in general (regardless of the type of source and at which step it is added) that improves the perovskite film with better coverage, better crystallinity, and higher photoluminescence (PL) response and longer carrier lifetime due to reduced trap densities. The amount of Cl remaining on the final film is most crucial in determining film quality. This in turn is controlled when Cl is added. When Cl is added in the second step, the higher Cl content initiates the DMSO complex formation and perovskite formation too rapidly producing films with excess PbI₂, which are more disordered and have lower crystallinity. FAcI exacerbates this while MACl reduces the detrimental effect by slowing down perovskite formation. Therefore, for a dynamic sequential process, it is recommended that MACl is used as the preferred source over FAcI and Cl should be added in the first step of

the process allowing sufficient Cl to leave the film in the second step of the sequential process (Figure PP2.5.3). This work has provided great insights into the film formation mechanism by sequential processing with additive engineering.

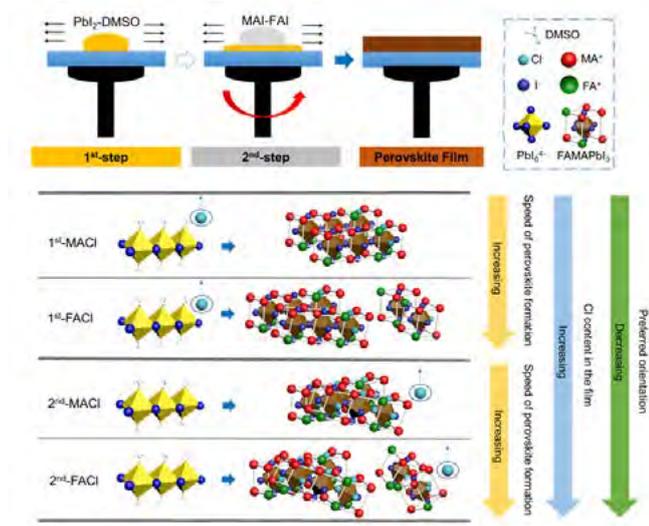


Figure PP2.5.3: Illustration of different film formation mechanisms for the four processes, 1st-MACl and 1st-FACl: Cl added in the first step, 2nd-MACl and 2nd-FACl: Cl added in the second step. (UNSW)

Researchers at UQ have completed their collaboration with Potsdam University, which has led to a final publication on the defect/interface recombination limited quasi-Fermi level splitting and open-circuit voltage in mono- and triple-cation perovskite solar cells (Zhang et al. 2020). UQ has continued to study a range of in-house synthesised bespoke cations, which were originally designed for the creation of two/three-dimensional perovskite solar cells. This year UQ researchers have investigated the properties of these perovskite solar cells that contain methylammonium lead iodide blended with differing amounts of 2-(pentafluorophenyl)ethylammonium iodide (FEAI). It was found that the devices with highest efficiency contained 0.3 mol% of the FEAI. Critically, at this concentration of FEAI there was no two-dimensional component. XPS indicated that for the most efficient devices the FEAI was concentrated at the interface with the electron transport layers indicating that the FEAI phase separates during the perovskite film-forming step. The work has been accepted for publication in *Nature Communications*. UQ researchers continue to explore inverted solar cells containing their bespoke cations, achieving hero devices with efficiencies of up to 22%. They are continuing to investigate the factors that affect the performance of such devices.

Perovskite solar cells contain various defects within the perovskite absorber and the corresponding interfaces, affecting device performance and stability. Developing passivation strategies has been an important research topic in the field. At UNSW, researchers have developed a simple but effective passivation method by using acetic acid (Ac) as the additive for the antisolvent chlorobenzene solution process to fabricate mixed halides triple-cation mixed-halide perovskite (Figure PP2.5.4(a)) (Li et al. 2020). It is found that

the additive helps to modify perovskite film morphology producing an ultra-uniform surface. 2D Grazing-Incidence Wide-Angle X-ray Scattering (GIWAX) results show that residual PbI_2 on a perovskite surface was greatly reduced as a result of using Ac in the antisolvent (Figure PP2.5.4(b)). Furthermore, X-ray photoelectron spectroscopy (XPS) characterisation shows that film quality improves due to the carboxyl (C=O) passivation effect. Collectively, the combined benefits of this method produces a smoother perovskite film with fewer defects and fewer non-perovskite phases as evidenced by a longer PL lifetime (Figure PP2.5.4(c)), enabling the corresponding best perovskite solar cell to achieve a PCE of 22.0% for $\text{Cs}_{0.05}\text{FA}_{0.80}\text{MA}_{0.15}\text{Pb}(\text{I}_{0.85}\text{Br}_{0.15})_3$, which is the highest (to the best of our knowledge) reported efficiency for a bandgap ~ 1.6 eV perovskite (which contains Br ~ 0.15) and the highest for cells fabricated using antisolvent additive engineering as well. This also improves device stability producing a cell that maintained 96% of its initial efficiency after 2400 hours storage in an ambient environment (with controlled relative humidity (RH) <30%) without any encapsulation.

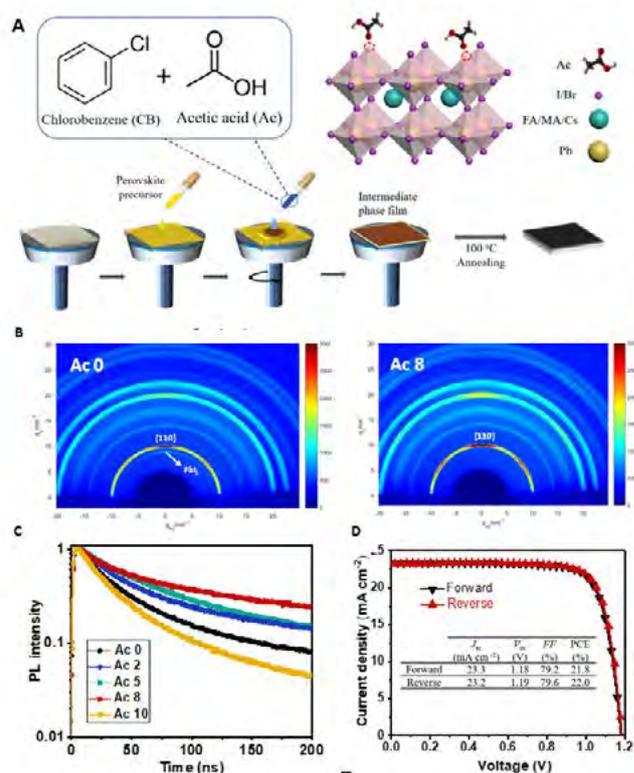


Figure PP2.5.4: (a) Schematic illustration of the Ac-assisted crystallization process. (b) 2D Grazing-Incidence Wide-Angle X-ray Scattering (GIWAX) results for reference (Ac0) and Ac treated perovskites (Ac8). (c) The TR-PL of a perovskite film with different Ac treatment. (d) Forward and reverse scanned current density-voltage (J-V) curves of best performing device (Ac8). Ac0-Ac8 stand for the samples treated by 0%–10% Ac (UNSW).

Inserting polymer layers between perovskite and charge transport layers has been proven to be another efficient way to passivate interface defects and improve V_{oc} (Peng et al. 2018). However, many such layers are poor conductors, leading to a trade-off between passivation quality and series resistance. ANU researchers have developed a nanopatterned electron transport TiO_2 layer as shown in Figure PP2.5.5(a) that overcomes this trade-off by modifying the spatial distribution of the passivation layer to form nanoscale localised charge transport pathways through an otherwise passivated interface (Peng et al. 2021). By combining the nanopatterned electron transport layer with a dopant-free hole transport layer, they achieved the best efficiency at 23.17% for small devices (Figure PP2.5.5(b)). The devices have also demonstrated improved stability with an encapsulated cell retaining 91.7% of its initial efficiency after 1000 hours of damp heat testing. Based on this work, ANU further improved the efficiency of 1 cm^2 perovskite cells to a record 22.6% with fill factors (FF) of over 86% (certified by CSIRO).

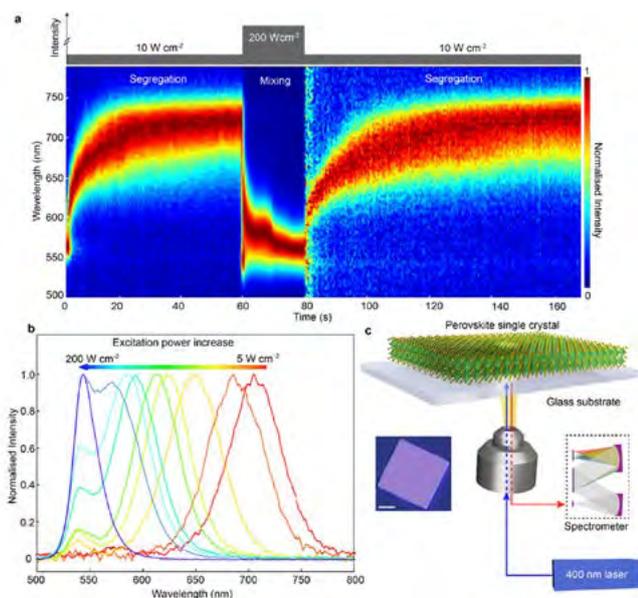


Figure PP2.5.5: (a) Schematic of a nanopattern perovskite cell with nanostructured TiO_2 ETL. (b) J-V performance of the champion perovskite cell fabricated using nanostructured TiO_2 nanorods with a spacing of 300 nm (ANU).

Photo-induced halide-ion segregation (PHS) in mixed-halide perovskites leads to the formation of halide-rich domains and localised variations in material bandgap (Mao et al. 2019). The Monash group have investigated the interaction between photo-generated carriers and halide ion distributions within the perovskite lattice based on well-designed experiments and theoretical simulation (Mao et al. 2020). They discovered that the light-induced ion segregation effect is highly relying on the input excitation power and revealed the fact that PHS is fully reversible when the excitation power density is applied to eliminate the strain gradient via a process called Photo-induced Halide-ion Mixing (PHM) (Figure PP2.5.6). Several mechanisms have been proposed to describe PHS in mixed-halide perovskites. However, none of these models describes PHM observed under high photon flux, at least not in their current form. The Monash group have developed a lattice model, which builds on the concept of polaron-induced

segregation, to model changes in halide distribution in response to a wide range of illumination powers. The model considers three driving forces: (i) a force which locally attracts iodides towards polarons due to the strain gradients which they generate, (ii) a force which attracts carriers/polarons towards iodide-rich regions due to the reduction (or funnel) in the bandgap, and (iii) a force which drives the halides to mix homogeneously in the absence of strong strain gradients (Figure PP2.5.7(a)). With this physical picture, and a reasonable limit on how strongly polarons can overlap, remixing will naturally occur under strong illumination due to the reduction in strain gradient where the polarons overlap or merge. This model qualitatively accounts for all phenomena observed from low to high excitation intensities and rationalises the change in halide distribution (in both time and space) in terms of the local polaron density. The key results for different excitation regimes are presented in Figure PP2.5.7(b)–(d). The positions of the I^- and Br^- and corresponding photoluminescence spectra information are shown in Figure PP2.5.7(e)–(j), providing insight into the coupling between the polaron and halide distributions. This work creates a new pathway for the application of mixed-halide perovskites in photovoltaics, including tandem solar cells and concentrator solar cells.

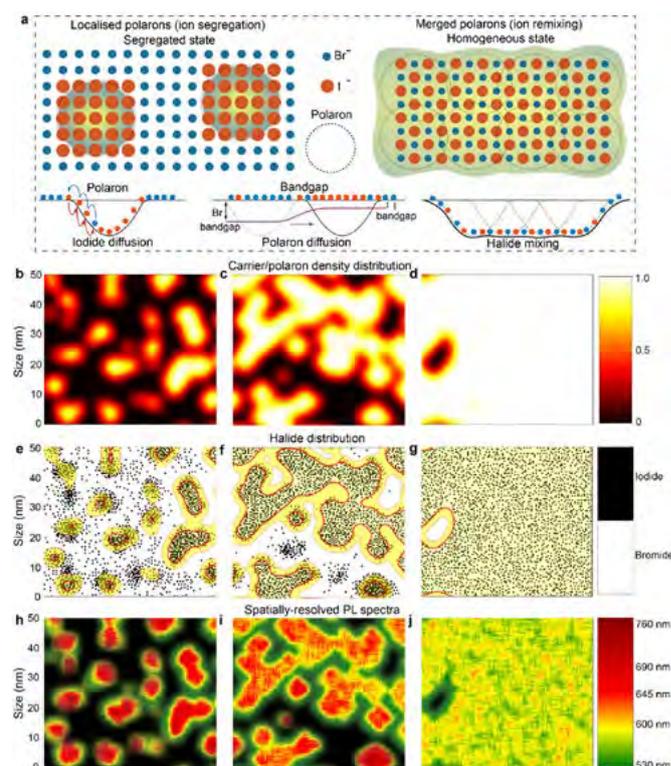


Figure PP2.5.6: Photo-induced halide-ion segregation (PHS) and mixing (PHM) within a $MAPb(Br_{0.8}I_{0.2})_3$ single crystal microplatelet. (a) Normalised PL emission spectra recorded upon illumination with a pulsed laser with low excitation intensity ($10 W cm^{-2}$) over 60 s, followed by high intensity ($200 W cm^{-2}$) over 20 s, and back to low intensity ($10 W cm^{-2}$) over 80 s. (b) Normalised power-dependent PL emission spectra recorded with a range of excitation powers. The arrow indicates the shift in peak position as the excitation power increases. Each steady-state spectrum, recorded at the same crystal position, is reached after 20 s of laser illumination. The excitation intensity was sequentially increased from 5 to 200 $W cm^{-2}$. (c) Schematic of the confocal photoluminescence (PL) microspectroscopy system. (Monash)

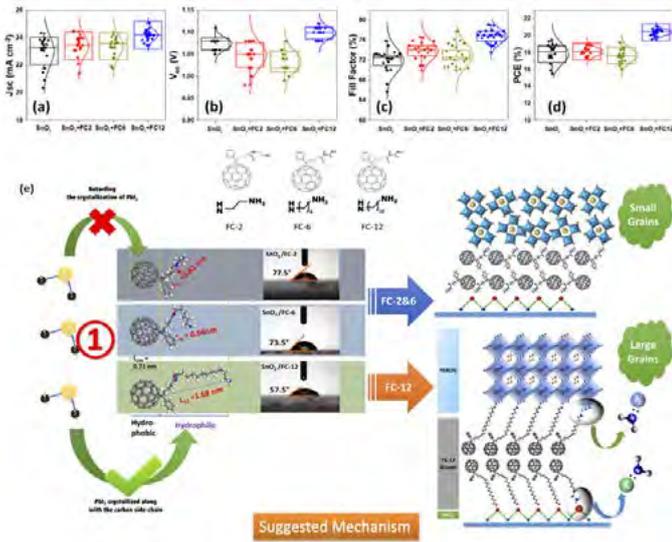


Figure PP2.5.7: Modelling of halide segregation and mixing in response to polaron density (steady state). (a) Illustration of halide ion distribution for a $\text{MAPb}(\text{Br}_{0.8}\text{I}_{0.2})_3$ perovskite lattice in response to low carrier density (left) and high carrier density (right). The lattice model includes three driving mechanisms: (i) iodide diffusion along polaron strain gradients; (ii) polaron diffusion along iodide concentration gradients; and (iii) halide mixing in the absence of strong strain gradients. (b)–(j) Simulation results for the lattice model: (b)–(d), polaron distributions at different carrier densities (b–low, c–medium, d–high); (e)–(g), halide distributions in (b), (c) and (d), respectively; (h)–(j), corresponding spatially resolved PL emission peak wavelength. The model shows how the local halide composition and bandgap can be controlled by the carrier density (Monash).

In terms of device structure engineering, it has been suggested that control of the interfaces between perovskites and the electron transport layer (ETL) or hole transport layer (HTL) can significantly impact the overall perovskite solar cell (PSC) efficiency by reducing interfacial charge recombination, improving ohmic contacts and reducing moisture or air ingress preventing cell degradation. At the University of Melbourne (UoM), the group has examined the impact of amine modified fullerenes on the perovskite cell performance through modifying the linker length between the amine and the n-type fullerene ETL material, FC-1, FC-6 and FC-12 in Figure PP2.5.8. Only the ETL with the longer linker promotes consistent cell performance improvement shown in Figure PP2.5.8, with an improved J_{sc} , V_{oc} , FF and overall PCE. It is suggested that the longer chain length allows better packing of the amine-functionalised fullerenes forming a bilayer chemically anchored to the underlying tin oxide and presenting an amine layer to the deposited lead iodide allowing the crystallisation to be influenced. This leads to larger perovskite crystallites being formed and a better interface, Figure PP2.5.8(e).

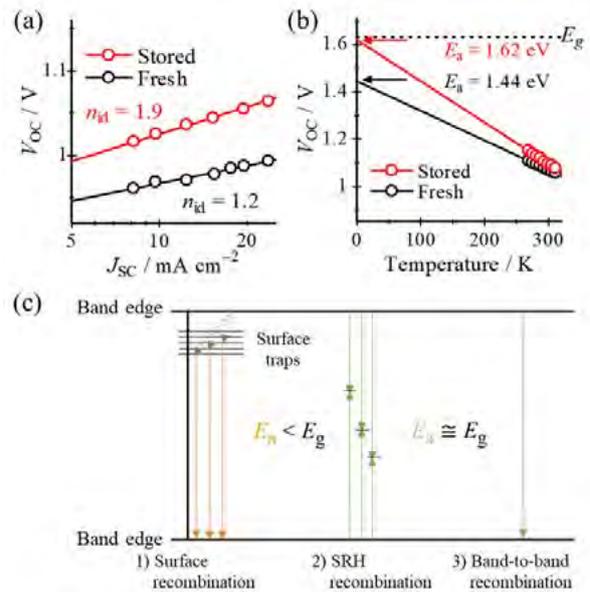


Figure PP2.5.8: Statistical distribution curves for PSC devices made with and without the amine-functionalised fullerene interface layers. (a) J_{sc} , (b) V_{oc} , (c) FF, and (d) PCE each showing a statistically significant improvement when the longer linker is employed. (e) Suggested mechanism of action of the long chain amine-functionalised fullerenes. (1) the longer chain allows better interaction with the underlying tin oxide forming a double layer, (2) a secondary amine layer forms changing the surface energy (contact angle decreases), which (3) impacted crystallite formation of the overlying lead iodide and subsequently formed a perovskite layer (UoM).

Temporal device performance, that is, “storage effect”, the efficiency improvement during early ambient storage is often seen in perovskite solar cells. However, the underlying mechanisms for such temporal efficiency improvement are not yet fully understood. The UNSW group has systematically investigated the mechanisms under controlled ambient conditions and found that ambient storage affects both the perovskite film and hole transport material (HTM) Spiro-OMeTAD. For the perovskite layer, ambient storage improves carrier lifetime and reduces trap density in the first two days confirmed by time-resolved photoluminescence and space-charge-limited current analyses, respectively. By analysing results of temperature- and light intensity-dependent V_{oc} measurements, it is found that the dominant recombination process changes from surface dominated to bulk dominated upon storage and trap-mediated recombinations reduce after storage (Figure PP2.5.9). Therefore, it is the reduction of surface recombination in stored devices that contributes to the initial improvement of V_{oc} for stored devices. For the HTM, it is found for the first time that ambient storage improves its conductivity and reduces its HOMO level facilitating better band alignment with the perovskite confirmed by EQE analysis, four-point probe measurements, and photoelectron yield spectroscopy.

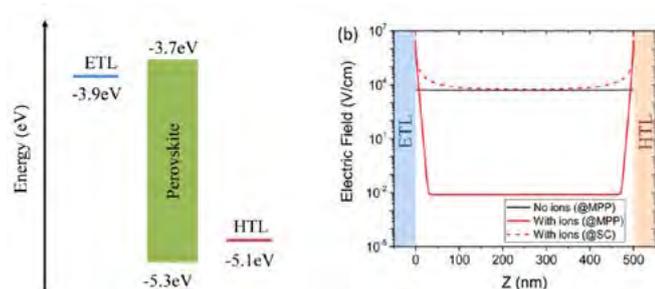


Figure PP2.5.9: (a) Intensity-dependent V_{oc} for a perovskite solar cell before (black curve) and after (red curve) ambient storage.

From the slope, n_{id} was evaluated to be 1.2 and 1.8 for the device before and after the ambient storage, respectively.

(b) Temperature-dependent V_{oc} for a perovskite solar cell before (black curve) and after (red curve) the ambient storage. From the extrapolation of V_{oc} to 0 K, E_g was evaluated to be 1.44 and 1.62 eV for the device before and after ambient storage, respectively. (c) Illustration of energy diagrams for (1) recombination at the surface, (2) SRH recombination, and (3) band-to-band recombination (UNSW).

Mobile ions in perovskite solar cells induce many unique transient phenomena, the study of which has received intense interest. In contrast, their influence under steady state, the primary operating condition of solar cells, has received little attention. ANU employed ionic-drift diffusion models to assess how the steady-state distribution of mobile ions affects the photogenerated carrier collection and the solar cell output characteristics more broadly (Wu et al. 2020).

Figure PP2.5.10(a) shows the structure that was modelled, with transport layers that have fixed work functions. This highly simplified model allows us to focus on the properties of the perovskite film, and in particular, the mobile ions. A key impact of mobile ions is that they tend to arrange themselves in such a way as to screen the perovskite bulk from the electric field, as can be seen in Figure PP2.5.10(b). This screening means that no electric field is present to help extract carriers from the cell. Figure PP2.5.11 shows the possible consequence of the lack of an internal electric field. Figure PP2.5.11(a) shows the I-V curves of a cell with only radiative recombination (black), a cell with additional defect-assisted recombination but no mobile ions (blue) and a cell with defect-assisted recombination and mobile ions (red). Since defect-assisted recombination dominates in real devices, the blue and red curves are more representative of actual devices. It can be seen that the presence of mobile ions results in a reduction in the cell current at a forward bias of ~ 0.4 V, which is the voltage at which the internal electric field vanishes for this cell so that, for higher forward bias voltages, carrier transport is by diffusion only. The presence of mobile ions therefore results in a reduction in cell performance.

Figure PP2.5.11(b) shows the carrier density distributions at maximum power point for each of the three cells. This shows that electron and hole distributions tend to be more equal across the width of the cell when mobile ions are present. Unfortunately, roughly equal carrier concentrations also tend to lead to higher rates of recombination, which is a further factor reducing the cell's power output. Finally, Figure PP2.5.11(c) shows that the impact of mobile ions becomes more acute the larger the defect concentration in the cell is (and therefore the higher the rate of defect-assisted recombination).

The good news is that, provided the defect density in the material can be kept low, then cell performance can remain unaffected by the presence of mobile ions.

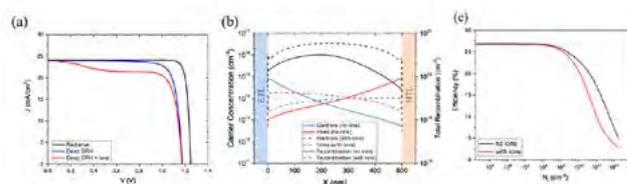


Figure PP2.5.10: (a) Band energy alignment of the simulated perovskite device, (b) Variation of the electric field strength in the perovskite absorber of the cells with or without mobile ions at the maximum power point (MPP) (ANU).

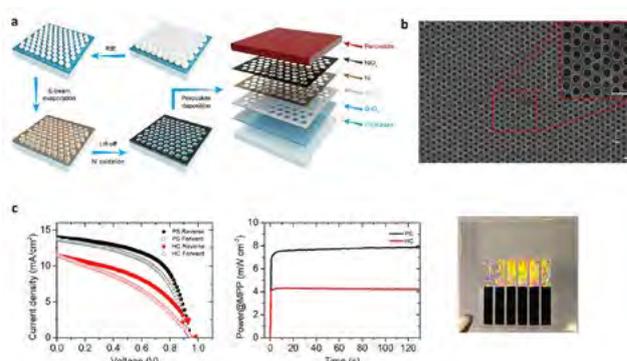


Figure 2.5.11: (a) Simulated I-V curves of the devices with trap-assisted recombination with or without ions, in comparison to the device with only radiative recombination. The maximum power point of the device with ions is denoted by the red dot. (b) Carrier concentration profiles of the trap-dominated devices and their total recombination rate at the maximum power point. (c) Impact of defect density on the efficiency of cells with and without ions, with a carrier mobility of $1 \text{ cm}^2/\text{Vs}$ (ANU).

With regard to cell design, the Monash group has developed a novel self-assembled microsphere patterning technique as a cost-effective replacement of the traditional photolithography method for back contact perovskite solar cells. It was demonstrated that the self-assembled microsphere can easily form a compact motif with high aspect ratio, which is suitable for the ETL and HTL fabrication by RIE etching/lift-off processes (Figure PP2.5.12(a), (b)). The perovskite solar cells based on such electrodes have higher solar cell performance than photolithography (Figure PP2.5.12(c)). Various ETL and HTL materials and fabrication methods were explored to achieve improved device performance. The effect of different ETL/HTL area ratios were studied to investigate the carrier generation and extraction in perovskite materials. This lateral carrier transport configuration also enables the investigations of the ion migrations under electrical and optical bias conditions.

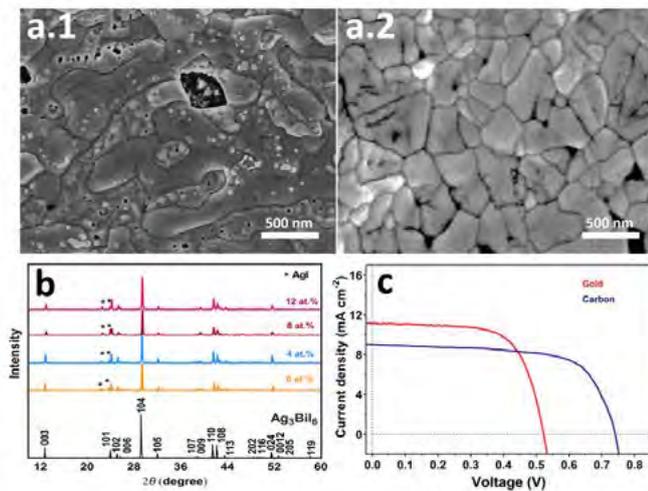


Figure PP2.5.12: Microsphere lithography for back contact perovskite solar cells: (a) Photolithography-free back contact electrode fabrication, (b) SEM image of electrode patterns, (c) Back contact perovskite solar cell I-V curves and stability test with the front image of the micro back contacts fabricated on ITO glass. Note, PS stands for microsphere lithography and HC for photolithography (Monash).

Lead-free perovskites

Monash researchers' collective efforts for finding a reliable and stable lead-free system, eventuated the team to introduce $A_bBiI_{6-a+3b-2x}S_x$ (where A is normally group-11 monovalent cation and X being halide anion), a ruddorffite family of sulfohalide bismuthates that outperform conventional bismuth iodide perovskites. By modifying thiolates' synthesis strategy and employing hot-casting methods, the group was able to increase the amount of S^{2-} in $Ag_bBiI_{6-a+3b-2x}S_x$ to $x = 0.12$ and demonstrated a narrower bandgap of ca 1.7 eV along with a further increase in the absorption coefficient. These changes follow the groups published predictions (Pai et al. 2019) and open up possibilities for setting new performance world records for lead-free photovoltaics. The film quality and interfacial contact were further improved by employing solvent vapour-assisted post-annealing (Figure PP2.5.13(a)), utilisation of an energetically favourable (band-aligned) hole transport layer (PTB7), and carbon as a counter electrode. While the developed phase segregation free sulfide modification with the morphological and architectural advancements (Figure PP2.5.13(b)) significantly improved the open-circuit voltage by ~200 mV, a proportionate increase in current was not achieved (4.2 vs 4.5%) (Figure PP2.5.13c).

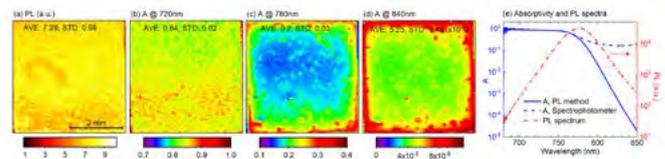


Figure PP2.5.13: Top view of Ag_3BiI_6 film before (a.1) and after (a.2) solvent modification. (b) XRD of the Ag_3BiI_6 at different sulfide modification concentrations; and (c) photovoltaic performance of the PTB7/ Ag_3BiI_6 + m-TiO₂/c-TiO₂/FTO with gold and carbon as counter electrodes (aperture 0.16 cm²) under one-sun irradiation (Monash).

Device durability

Lack of long-term stability in perovskite solar cells is a critical challenge for the commercialisation of this technology. In order to tackle this challenge, it is critical to develop processes that enable the early detection of degradation and facilitate a better understanding of degradation pathways. ANU developed a contactless, nondestructive approach to study degradation across perovskite and perovskite/silicon tandem solar cells (Nguyen et al. 2019). The technique utilises the generalised Planck law (Wüffel 1982) to convert luminescence spectra to absorptivity spectra, enabling the sensitive determination of spectrally and spatially resolved absorptivity at sub-bandgap wavelengths of perovskite materials. Figure PP2.5.14(a)–(d) shows the photoluminescence (PL) intensity map and the absorptivity maps at various wavelengths for a perovskite cell. It can be seen that at long wavelengths (780 nm and 840 nm) new features emerge, particularly around the cell edges. This red “frame” is associated with decomposition of the perovskite material due to moisture ingress. The method can be seen to provide a sensitive approach to monitor cell degradation at early stages, when the degradation does not yet have an obvious impact on material quality (as seen by the PL intensity image in Figure PP2.5.14(a)). Such a tool is invaluable to facilitate a better understanding of degradation pathways and processes, and as a process diagnostic tool. Figure PP2.5.14() shows an example of a PL spectrum and absorptivity spectrum extracted it. In addition, it shows the absorptivity measurement obtained using a standard spectrophotometer. The dramatic discrepancy in the absorptivity at long wavelengths obtained by the two methods illustrates the utility of the luminescence-based approach: the spectrum obtained from a spectrophotometer is influenced by parasitic absorption from other layers which renders it unusable for the purpose of investigating perovskite degradation.

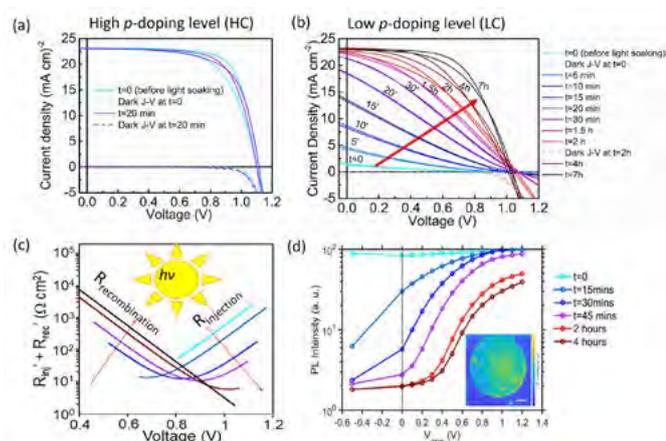


Figure PP2.5.14: (a) PL intensity map and (b)–(d) extracted absorptivity maps at various wavelengths from a PSC. Mean and standard deviation values are also included for each map. (e) Comparison of spectrophotometer-based and PL-based absorptivity spectra. The spectrophotometer-based curve was captured at the centre of the cell with a spot size of ≈ 2 mm in diameter. The PL-based curve was averaged from the centre of the PL map (2 mm \times 2 mm) (ANU).

Stabilising hole transport layers (HTLs) have been continued at Monash University in terms of research on device stability. Spiro-OMeTAD has been widely recognised as the most effective HTL used in perovskite solar cells to achieve high efficiencies. However, the stability issues from the dopants and the unknown complex doping effects of Spiro-OMeTAD are the main hindrances for commercialisation of perovskite technology. The team at Monash have been focused on the detailed mechanisms of doping in Spiro-OMeTAD. It was found that Spiro-OMeTAD with a very low doping level can show improved carrier transfer under long enough light soaking (Figure PP2.5.15). This effect can be attributed to the reduction of injection resistance, indicating the improved Spiro-OMeTAD conductivity and perovskite/Spiro-OMeTAD interface.

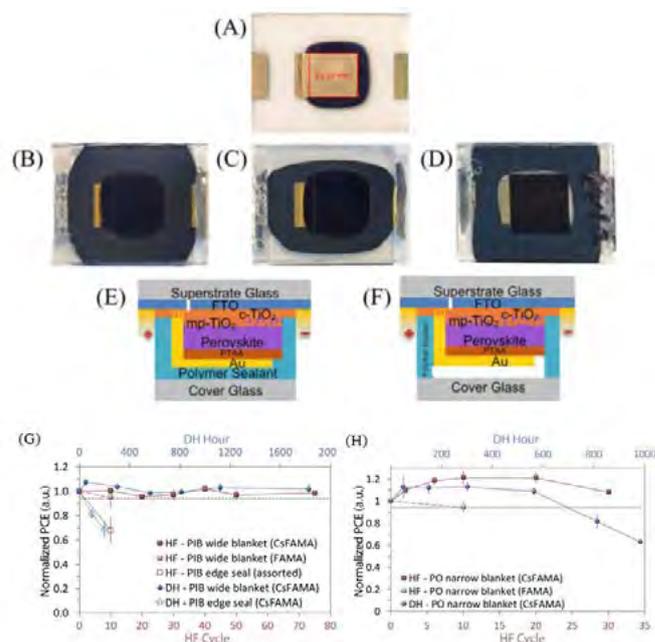


Figure PP2.5.15: IV characteristics of perovskite solar cells using highly doped (a) and low doped Spiro-OMeTAD under light soaking without oxygen (b). The injection resistance is present at the perovskite and HTL interface due to low doping levels of Spiro-OMeTAD and is gradually diminished during light soaking due to the photo-doping effect as shown in (c) impedance measurement of Spiro-OMeTAD. (d) Photoluminescence under various device biases after light soaking (Monash).

In terms of encapsulation approach, the UNSW group has developed a highly effective low-cost encapsulation method for improving the durability of perovskite solar cells using polyisobutylene (PIB, HeliSeal PVS 101) or polyolefin (PO)-based polymers as edge-seals or encapsulants (Figure PP2.5.16(a)–(f)) (Shi et al. 2020). It was unambiguously demonstrated by gas chromatography–mass spectrometry (GC–MS) that this pressure-tight encapsulation suppresses the outgassing of methylammonium (MA)-containing $\text{Cs}_{0.05}\text{FA}_{0.6}\text{MA}_{0.15}\text{Pb}(\text{I}_{0.85}\text{Br}_{0.15})_3$ or $(\text{FAPbI}_3)_{0.85}(\text{MAPbBr}_3)_{0.15}\text{Pb}(\text{I}_{0.85}\text{Br}_{0.15})_3$ perovskites. Results from GC–MS reveal the signature volatile products of decomposition of organic hybrid perovskites such as CH_3I , CH_3Br and NH_3 . These findings are informative for understanding the mechanisms of decomposition of these films. For the first time, MA-containing perovskite cells were able to exceed the requirement of the IEC61215:2016 standard: survived more than 1800 hours of a Damp Heat (DH) test and 75 cycles of a Humidity Freeze (HF) test (Figure PP2.5.16(g) and (f)).

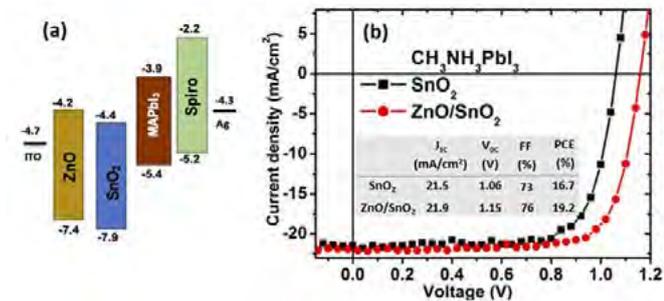


Figure PP2.5.16: Solar cells for IEC61215:2016 Damp Heat and Thermal Cycling tests. (a) "Rear" or metal-side view of perovskite cell before encapsulation (red square denotes the active area). "Front" view (from the superstrate side) of cells after (b) PIB blanket encapsulation, (c) PO blanket encapsulation and (d) PIB edge-seal. (e) and (f) Illustrations of the cross-sections of the respective encapsulation schemes. Results of the IEC61215:2016 tests for (g) PIB encapsulated or edge-sealed and (h) PO encapsulated cells during DH test and HF test. The dashed lines denote 5% relative PCE loss which is maximum allowed by the IEC standard after 1000 hours of DH or 10 cycles of HF (UNSW).

Commercial prospects, upscaling and manufacturing costs

To realise fully printed perovskite solar cells, new solution-processed ETLs need to be accessed. Often individual n-type metal oxides have suboptimal performance. University of Melbourne researchers have examined the impact of the inclusion of double ETLs composed of sequentially deposited zinc oxide / tin oxide (ZnO/SnO₂) shown in Figure PP2.5.17. PSCs containing the low temperature solution-processed double ETLs show a significantly enhanced PCE, with improvements in J_{sc} , V_{oc} and FF.

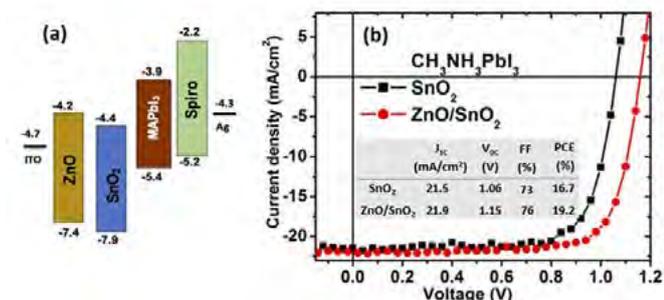


Figure PP2.5.17: PSC device performance with the inclusion of a double electron transport layer (ETL) composed of ZnO and SnO₂. (a) energy level diagram and (b) J-V curves (UoM).

The core research activity at CSIRO this year has been the exploration of dopant-free organic hole transport materials (HTMs) for perovskite solar cells (PSCs) and their scalable deposition via slot-die coating. Through a collaboration with Nanjing Tech University, several novel HTMs with suitable bandgaps have been synthesised at much lower cost in comparison to expensive PTAA and high-performance Spiro-OMeTAD. The molecular structures of the HTMs used in this study, one polymer (PFTPA) and four small molecules (BDT2, BDT4, Cz and fused Cz), are shown in Figure PP2.5.18(a). The narrow bandgap and measured HOMO and LUMO levels indicate most would facilitate efficient energy transfer between the HTM and the perovskites. The

photovoltaic performance of the PSCs based on non-doped HTMs were evaluated. The device fabricated with the PFTPA polymer exhibited the best photovoltaic performance, with a maximum efficiency of 17.06%, compared to 13.5% for the control device fabricated with PEDOT:PSS under the same conditions (Figure PP2.5.18(b)). The PCEs obtained from other HTMs, BDT2, BDT4, Cz and fused Cz, are 16.65%, 13.39%, 15.01% and 16.58%, respectively. PFTPA-based devices show less than 8% decrease in efficiency over 1000 hours of storage under a nitrogen environment. It has been found that the perovskite precursor solution wets the PFTPA surface well during slot-die coating trials, thereby exhibiting desirable characteristics. This indicates it has encouraging potential for the next step of trials in the roll-to-roll (R2R) process. The slot-die coated perovskite devices based on PFTPA, BDT4 and fused Cz exhibit PCEs of 13.08%, 12.23% and 11.95%, respectively. These promising outcomes provide a reference for the future development of highly efficient, stable and R2R-printable PSCs with dopant-free HTMs.

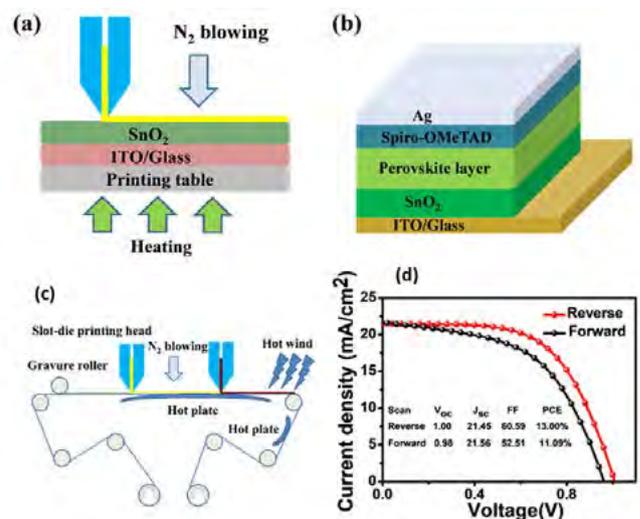


Figure PP2.5.18: (a) Molecular structures of synthesised HTMs with HOMO and LUMO levels. (b) J-V curves of PFTPA and control PEDOT perovskite solar cells prepared by drop-cast in air without using any dopants. The devices have an inverted structure glass/ITO/HTM/MAPbI₃/PCBM/PEIE/Ag (CSIRO).

CSIRO has also developed two-step fully slot-die coated perovskite cells in air. They found that the two-step or sequential deposition method exhibits excellent film morphology and surface coverage (Heo et al. 2017) and is more suitable and reliable for a mass-production process. High performance and stable triple-cation planar heterojunction PSCs have been deposited successfully via a low temperature two-step solution process (Figure PP2.5.19(a) and (b)). The fully slot-die coated solar cells achieved remarkably high PCEs of 18.13% with a cell area of 0.1 cm² on glass-based substrates. Furthermore, devices with 1 cm² area gave a champion PCE of 15.10%. The most promising result was the PSC with a maximum PCE of 13.03% obtained on a flexible PET substrate with an R2R coating process (Figure PP2.5.19(c) and (d)). These results pave the way for improving the performance of large-scale PSCs produced in a benign environment.

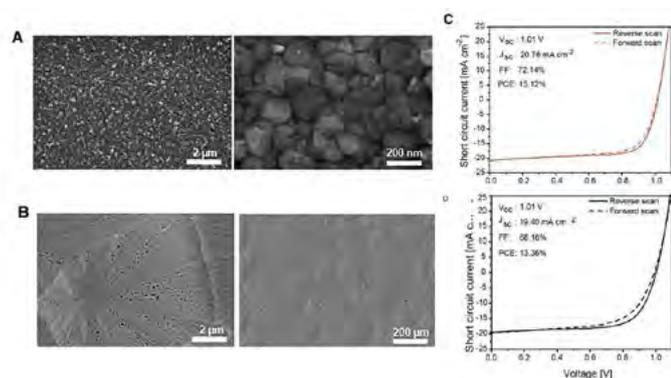


Figure PP2.5.19: (a) Schematic of slot-die coating process. (b) Structure of planar conventional device. (c) Schematic of R2R process for continuous preparation of flexible perovskite solar cells. (d) J-V curves for the champion device fabricated by R2R coating (CSIRO).

In order to improve the stability and reproducibility of device performance fabricated by an R2R process, CSIRO researchers have systematically investigated a crystal growth mechanism of slot-die hot-deposited (130°C) perovskite in comparison with a spin coating process. They found that for spin-coated film, nucleation-driven (ND)-type crystallisation can be driven by an antisolvent treatment or nitrogen blowing, to induce rapid precipitation of the precursor ions and fast solvent evaporation. With the rapid increase in the degree of supersaturation, highly dense, relatively small grains are formed leading to ND-type film growth. While for the slot-die hot-deposition, crystal-growth-driven (CGD) crystallisation dominates the film formation where low supersaturation heterogeneous nucleation occurs at the interface of the perovskite solution and the underlying PEDOT:PSS layer, and then an elevated temperature promotes crystal growth. The generated spherulitic arm grain clusters from CGD are two orders larger than those from ND-type films (Figure PP2.5.20) (Angmo et al. 2021). PL shows faster decay for the CGD-type film on bare glass compared to the ND-type film, which is attributed to more surface and/or bulk defects. It was discovered that these conspicuous differences in highly contrasting morphologies are not reflected in PSC performance, with the PCEs of PSCs comprising a CGD-type perovskite layer only marginally lower than those containing an ND-type perovskite layer (Figure PP2.5.20(c) and (d)).

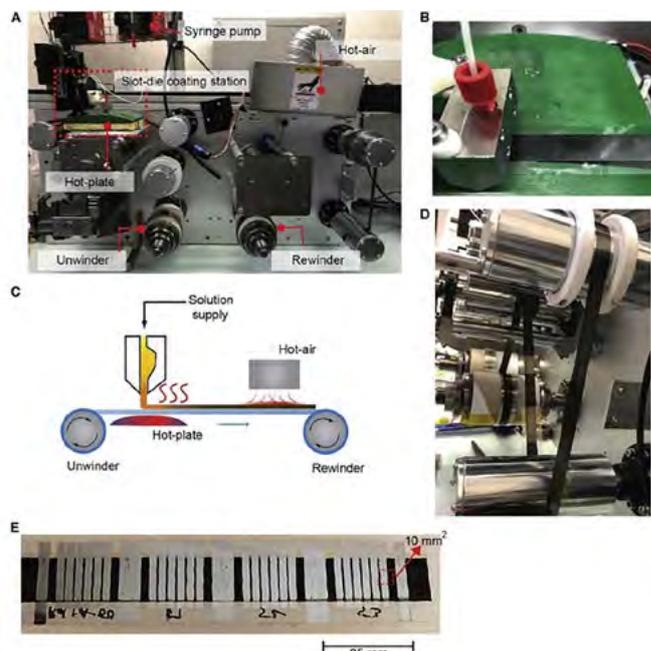


Figure PP2.5.20: SEM images of spin-coated ND-type perovskite film (a) and slot-die hot-deposited CGD-type perovskite film (b) at low and high resolutions. Photovoltaic performance of perovskite solar cells based on (c) ND-type and (d) CGD-type perovskite films. The devices were fabricated in an ambient environment (relative humidity of 30%–45% and temperature of 25°C) (CSIRO).

Based on the above findings, a CGD-type perovskite layer was chosen for R2R production because of its higher operational stability and humidity resistance during fabrication, together with the compatibility of slot-die coating with continuous R2R coating. Heating of the substrate for slot-die coating was easily replicated by passing the substrate film over a customised hotplate directly beneath the slot-die coating head (Figure PP2.5.21). The R2R slot-die coating of each layer was systematically optimised. The addition of surfactant improves the film quality by lowering the surface tension of the perovskite solution and improving its wetting on the underlying layer. A maximum PCE of 11.2% was achieved, with a V_{oc} of 0.94 V, J_{sc} of 20.1 mA cm^{-2} , and FF of 59% (Figure PP2.5.22(b)). The lower FF of the R2R-processed PSCs is attributed to high sheet resistance of ITO on PET ($50 \Omega \square^{-1}$). The similar PCEs of PSCs on both ITO/glass substrate and ITO/PET indicate the successful translation of the slot-die deposition process to the R2R format. The high reproducibility of the flexible R2R-processed PSCs (Figure PP2.5.22) is particularly impressive considering that all layers, apart from the electrodes, were produced by R2R slot-die coating under ambient laboratory conditions. Contrary to two-step deposition, the one-step method allows for precise control of precursor composition, making it compatible with complex perovskite formulations, and is a simpler coating process.

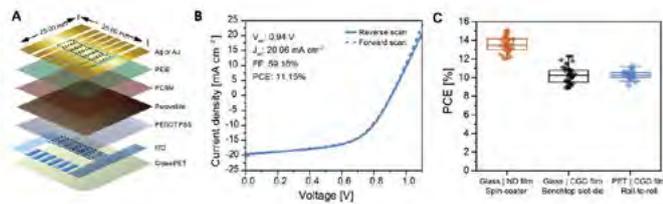


Figure PP2.5.21: (a) R2R equipment used in this study. (b) Magnified view of the R2R slot-die coating station. (c) Schematic of the R2R fabrication setup for CGD-film fabrication. (d) Image of perovskite film on a continuous roll of substrate film during an R2R fabrication experiment. (e) Image of a completed device fabricated on a 10 cm stretch of the R2R-coated film (CSIRO).

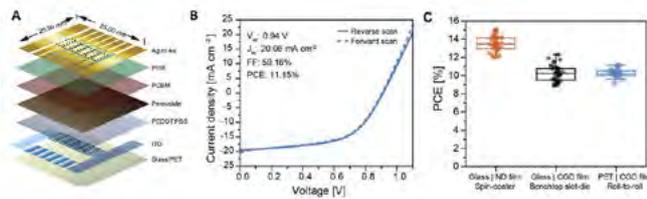


Figure PP2.5.22: (a) Schematics of the inverted device structure and the device pattern used in this study. (b) J-V curve of the best-performing R2R CGD-type device; and (c) statistics of PCE comparing R2R-processed CGD-based PSCs with lab cells based on ND-type and CGD-type films on glass (CSIRO).

Highlights

- A new technique has been developed that enables the early detection of perovskite degradation, thus facilitating an improved understanding of degradation mechanisms.
- I_3^- incorporation in a perovskite precursor can improve perovskite film formation with reduced defect density, hence significantly improving the efficiency of FAPbI₃ cells from 17.5% to 20.6%.
- Great progress has been made in defect passivation to improve device performance and stability. In particular, certified efficiency of 22.6% has been achieved on a 1 cm² cell.
- A better understanding of the temporal storage effect on a perovskite defect property and HTM energy level is achieved, guiding future research to improve device efficiency.
- A clearer picture has been obtained of the impact of mobile ions in perovskite materials on steady-state efficiency. In general, the better the quality of the perovskite material and its interfaces, the smaller the efficiency penalty due to the presence of mobile ions.
- Champion photoconversion efficiencies of 22% achieved for laboratory-scale inverted solar cells.
- A new photolithography-free patterning process using a self-assembled microsphere has been developed for back contact perovskite cells, enabling large-area uniform patterning and significantly improving device performance.
- Significant improvement in open-circuit voltage for sulfoiodobismuthate lead-free devices.
- The oxygen-free photo-doping effect in Spiro-OMeTAD under light soaking has been discovered, which is potentially more stable than the conventional doping methods.

- The ability to control ion segregation could become key to solving the issue of halide de-mixing and to harness the exceptional opportunities associated with a bandgap tunable semiconductor material.
- Simulations confirmed the driving force for photo-induced phase segregation is dependent on carrier-induced strain gradients that vanish at sufficiently high carrier densities.
- A highly effective low-cost encapsulation method has been developed for improving the durability of perovskite solar cells using polyisobutylene.
- For the first time, MA containing perovskite cells exceeded the requirement of the IEC61215:2016 durability standard.
- For scale-up technology, PCE of 18.3% has been achieved for fully slot-die coated devices in an inverted device structure.
- A highly reproducible one-step hot-deposition method has been developed using an upscaling R2R process.

Future Work

Despite the great research effort in developing passivation strategies leading to improved efficiency and stability for small cells, the defect formation in the large-scale perovskite films is not uniform and defects are difficult to passivate. This is particularly detrimental for large cell and module performance. Moreover, the solution processes for the fabrication of perovskite cells are not as controllable as c-Si PV. Batch-by-batch variations in film and defect formation add another hurdle for module development. Therefore, future research efforts are required in further identifying and understanding the defect mechanisms as well as developing more controllable processes to mitigate the ununiformed film and defect formation.

Large-cation 2D materials have been proven effective in improving device performance and stability. Further studies revealing the reasons why such materials can improve efficiency and durability are required so as to guide the development of more effective new 2D materials.

It has been discovered that photo-induced halide-ion segregation can be reversed back into a homogeneous phase in a mixed-halide single crystal by concentrated excitation. Further investigation on single crystalline device performance under concentrated light illumination may solve the phase segregation issue and harness the exceptional opportunities associated with a bandgap tunable semiconductor material.

In terms of Pb-free perovskites, the thiolate precursor and modification of the synthesis strategy may be feasible to achieve >15 at.% sulphur in $Ag_bBi_bI_{a+3b-2x}S_x$ that could lead to an ideal bandgap aligning with the calculations. An extensive study on the origin of lower dimensionality, non-ideal band structures, and other optoelectronic properties would certainly resolve major constraints in these materials and pave novel pathways to higher efficiencies. Also, it is anticipated that the new fabrication and bandgap-tuning methods introduced should also apply to other halides/chalcogenides, such as copper(I)-based systems, caesium titanium double perovskites, antimony-based perovskites and others that, theoretically, can be engineered as efficient and very cheap photovoltaic materials.

We have developed an effective and low-cost encapsulation method for single-junction perovskite devices that, for the first time, exceeded the requirements of the IEC durability standard. Similar technology can be applied to perovskite tandem devices.

In terms of scaling-up technology, there is still much room for improving lab-to-fab translation by the optimisation of R2R fabrication processes. The stability and durability of slot-die and R2R-fabricated devices need to be further investigated. This is of particular importance for the commercialisation of perovskite technology.

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PP3

OPTICS AND CHARACTERISATION

OVERVIEW

Program Package 3 (PP3), “Optics and Characterisation”, aims to utilise and manipulate the fundamental interactions between light and matter to develop high efficiency, low-cost photovoltaic (PV) devices. This includes, but is not limited to, thin-film organic and Earth-abundant solar cells. These devices rely on special optical properties – imparted either by their constituent materials or by structural modifications – to enhance energy conversion efficiency well beyond what would be expected for a conventional PV device of comparable thickness. However, the characterisation of such devices can be much more challenging than for standard devices, requiring the development of a range of new characterisation techniques.

Previous reports for this Program Package have outlined our achievements in these areas. In this report we present our recent progress and suggest promising new directions for the work. In PP3.1, ANU and Monash present a number of critical advances in the development of methods for characterising perovskite and perovskite/silicon tandem solar cells, which help understand the time and spatially varying recombination processes, charge transport and degradation in these materials. These innovative methods provide a new perspective for probing the relationship between film properties and device performance, and are expected to deliver significant insights. Included in PP3.1, the Monash team also reports a prototype of a high-throughput current-voltage (I-V) testing system for laboratory level small-area thin-film solar cells. Meanwhile, the ANU team reports their recent process in the quantification and engineering of the maximum potential of novel two-dimensional (2D) transition metal dichalcogenides (TMDs).

Under PP3.3, ANU and UNSW describe their advances in the understanding of microscopic structural and optoelectronic properties of various components across different silicon solar cell technologies, as well as the development and optimisation of fast and reliable techniques to monitor these properties. Particularly, the UNSW team reports a wide range of applications of their fast imaging methods for the characterisation of defects and impurities in silicon materials and solar cells, including magnetic field imaging, spatially non-uniform illumination photoluminescence, impacts of gettering and hydrogenation on temperature coefficients of silicon solar cells, and trap precursors in Czochralski silicon wafers. Meanwhile, the ANU team focuses on understanding microstructures and optoelectronic properties of doped polycrystalline silicon passivating contacts and their degradation mechanisms.

PP3.1 METHODS TO CHARACTERISE THE OPTICAL AND ELECTRICAL PROPERTIES OF ORGANIC AND OTHER THIN-FILM EARTH-ABUNDANT SOLAR CELLS

PP3.1A NEW APPROACH FOR DEGRADATION STUDY OF PEROVSKITE AND PEROVSKITE/SILICON TANDEM SOLAR CELLS

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Funding Support
ACAP, ARENA, ANU

Aim

Instability of perovskite solar cells is the main challenge for the commercialisation of this solar technology and for their integration in tandem configurations. The groups involved in this work aim to deepen the understanding of the complex degradation mechanisms observed in perovskite materials, with the objective of bringing this very promising technology to a high technology readiness level. Rapid, non-destructive, reliable methods for characterising these materials and devices will be critical for their commercial deployment.

Progress

The team at ANU, led by Dr Hieu Nguyen, has developed a new contactless, non-destructive approach to study degradation across perovskite and perovskite/silicon tandem solar cells. The technique employs spectrally and spatially resolved absorptivity at sub-bandgap wavelengths of perovskite materials, extracted from their photoluminescence (PL) spectra. Parasitic absorption in other layers, carrier diffusion, and photon smearing phenomena are all demonstrated to have negligible effects on the extracted absorptivity.

The absorptivity is demonstrated to reflect real degradation in the perovskite film and is much more robust and sensitive than its luminescence spectral peak position, representing its optical bandgap and intensity.

In Figure PP3.1.1, the sub-bandgap absorptivity map (row 4) clearly shows that the air slowly invades the solar cell through the edge of the gold contact when the cell is exposed in the atmosphere. Various pinholes through the gold contact can also be observed, as indicated by the white circles (row 4, absorptivity at 800 nm). The technique is also applied to study other common factors which induce and accelerate degradation in perovskite solar cells including heat exposure and light soaking. Finally, it is employed to extract the individual absorptivity component from the perovskite layer in a monolithic perovskite/silicon tandem structure (Figure PP3.1.2). The results demonstrate the value of this approach for monitoring degradation mechanisms in perovskite and perovskite/silicon tandem cells at early stages of degradation and various fabrication stages. This work was published in *Advanced Energy Materials* and selected as an issue's inside back cover (Nguyen et al. 2020).

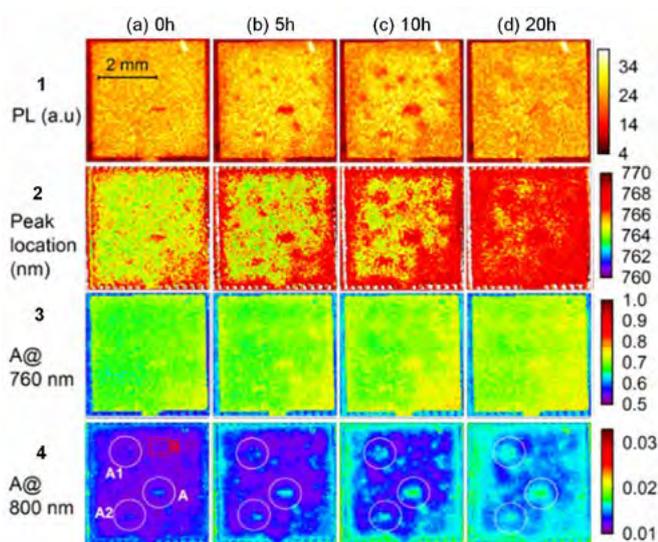


Figure PP3.1.1: PL intensity, spectral peak location, and extracted absorptivity maps of a perovskite solar cell versus exposure time in a room atmospheric environment.

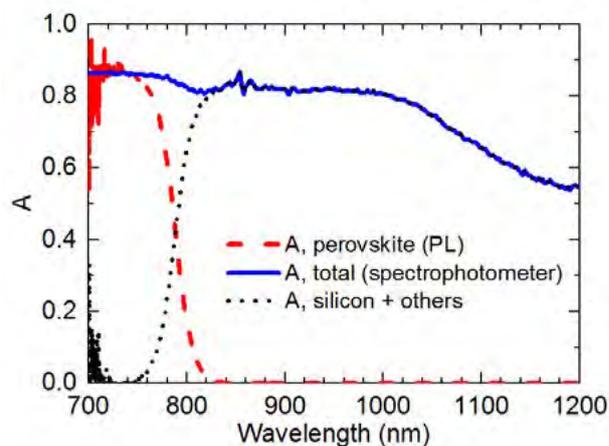


Figure PP3.1.2: Various absorptivity components from a monolithic perovskite/silicon tandem solar cell.

Highlights

- Spectrally and spatially resolved absorptivity for perovskite solar cells.
- Degradation studies (heat, air, light) of perovskite solar cells using sub-bandgap absorptivity.
- Sub-bandgap absorptivity is more sensitive to early stages of degradation than luminescence intensity.
- Separation of absorptivity in perovskite layers from other layers in monolithic perovskite/silicon tandem cells.
- Powerful way to study degradation in top perovskite cells in tandem configurations.

Future Work

The team will continue to refine their technique to support the drive to near-term commercial viability of perovskite solar cells. Particularly, the technique will be thoroughly quantified and its use for characterisation of single-junction and tandem cells under various conditions will be explored.

PP3.1B UNLOCKING AND ENGINEERING THE POTENTIAL OF EMERGING 2D MATERIALS

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Funding Support

ACAP, ARENA, ANU

Aim

Two-dimensional (2D) transition metal dichalcogenides (TMDs) are currently receiving enormous attention for photovoltaic applications due to their very strong light-matter interaction, atomic thickness and naturally occurring surface passivation. Also, there has been a rapid improvement in their large-scale material processing capability and quality. This signals that in the next few years, large-area (square millimetres to square centimetres) solar cells based on TMDs could be fabricated. Therefore, this work aims to understand and quantify the potential of these future solar cells using experimental and/or theoretical means in early days.

Progress

One of the most fundamental parameters of any photovoltaic material is its quasi-Fermi level splitting under illumination. This quantity represents the maximum open circuit voltage (V_{oc}) that a solar cell fabricated from that material can achieve. However, no study of TMD materials has focused on quantifying this limitation either experimentally or theoretically, although thousands of works on other aspects of TMDs have been published. By quantifying light absorbed and emitted from the TMDs, the ANU team, led by Dr Hieu Nguyen, has developed a method to predict the possible V_{oc} that could be achieved from TMD-based solar cells, at the material stage.

The team applied the technique to quantify the upper limits of V_{oc} that could possibly be achieved from monolayer WS_2 , MoS_2 , WSe_2 and $MoSe_2$ -based solar cells, and compared them with other thin-film technologies. Their results showed that V_{oc} values of ~ 1.4 , ~ 1.12 , ~ 1.06 and ~ 0.93 V could be potentially achieved from solar cells fabricated from WS_2 , MoS_2 , WSe_2 and $MoSe_2$ monolayers at one-sun illumination, respectively, as shown in Figure PP3.1.3. The results suggested that the requirements of high-voltage, flexibility, ultralight, transparency, and stability for future solar cells were possible with 2D TMDs. More significantly, the established limits could be a reference for future works on fabricating TMD-based photovoltaic devices.

The team also observed that the predicted V_{oc} values were inhomogeneous across different regions of these monolayers. Therefore, they attempted to engineer the observed V_{oc} heterogeneity by electrically gating the TMD monolayers in a metal-oxide-semiconductor (MOS) structure which effectively changed the

doping level of the monolayers electrostatically and improved their V_{oc} heterogeneity (Figure PP3.1.4). These preliminary results demonstrated that indeed both the predicted V_{oc} and its homogeneity could be manipulated by the doping levels inside monolayer TMDs. This work was published in *Advanced Materials* and selected as an issue's frontispiece (Tebyetekerwa et al. 2019).

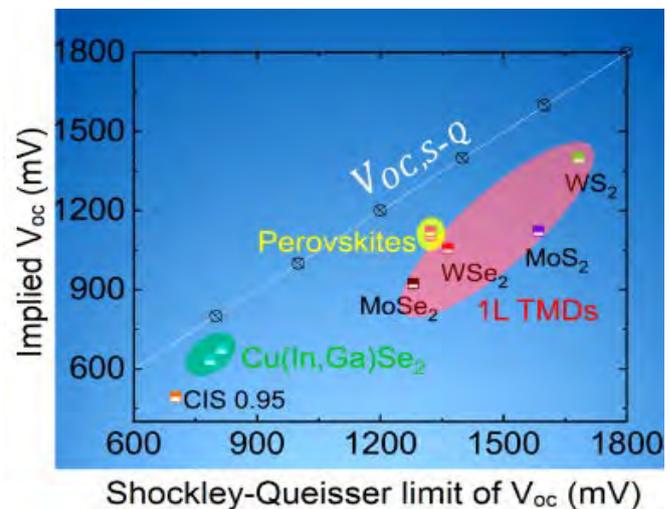


Figure PP3.1.3: 2D TMD-based solar cells could potentially yield high voltages, very competitive to other thin-film technologies.

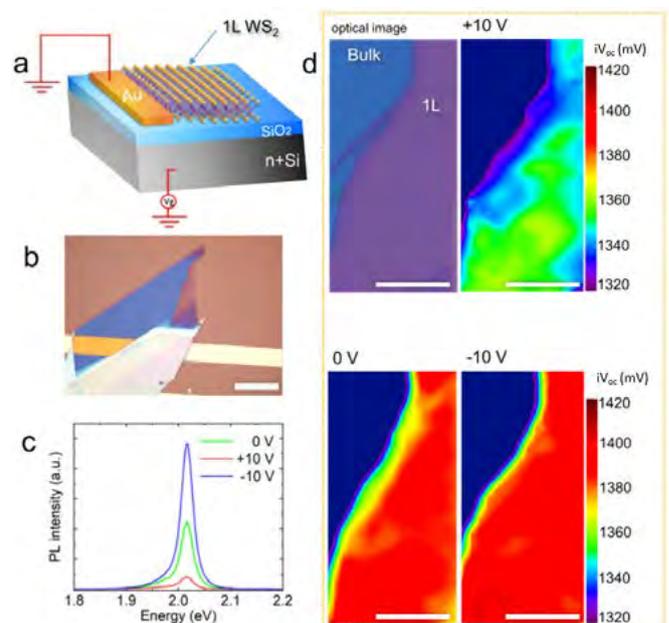


Figure PP3.1.4: Effects of electrical gating on predicted V_{oc} of the monolayer WS_2 . (a) Schematic assembly of the monolayer-based MOS structure with electrical connections. (b) Optical microscope image of the analysed monolayer on the MOS setup (scale bar $50 \mu\text{m}$). (c) Photoluminescence spectra obtained from the monolayer WS_2 with back gate voltages of -10 , 0 and $+10$ V. (d) The corresponding mapping of predicted V_{oc} across the monolayer WS_2 (scale bar $10 \mu\text{m}$).

Furthermore, the team developed a class of air-stable vertical organic-inorganic (O-I) heterostructures comprising of a monolayer of TMDs, including WS₂, WSe₂ and MoSe₂, on top of tetraphenylethylene (TPE) core-based aggregation-induced emission (AIE) molecular rotors. This class of O-I heterostructures presented synergistic and enhanced optoelectronic properties with a high tunability. The created O-I heterostructures yielded a photoluminescence (PL) enhancement of up to ~950%, ~500% and ~330% in the top monolayer WS₂, MoSe₂ and WSe₂, as compared to PL in their pristine monolayers, respectively. The strong PL enhancement was mainly attributed to the efficient photo-generated carrier process in the AIE luminogens (courtesy of their restricted intermolecular motions in the solid state) and the charge transfer process in the created type-I O-I heterostructures. Moreover, they observed an improvement in photovoltaic properties of the TMDs in the heterostructures including the quasi-Fermi level splitting $\Delta\mu$, minority carrier lifetime and light absorption (Figure PP3.1.5). This work presented an inspiring example of combining stable, highly luminescent AIE-based molecules, with rich photochemistry and versatile applications, with atomically thin inorganic semiconductors for multifunctional and efficient optoelectronic devices. The results were published in *ACS Nano* (Tebyetekerwa et al. 2020).

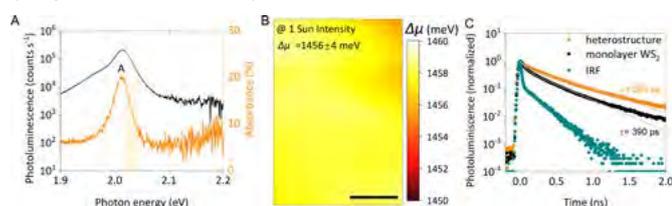


Figure PP3.1.5: Photovoltaic properties of the AIEgen-WS₂-based O-I heterostructure. (a) Representative PL and absorption spectra from the heterostructure at room temperature. Using the generalised Planck law, the quasi-Fermi level splitting $\Delta\mu$ under excitation can be extracted. "A" denotes the A-excitonic peak. (b) The resultant $\Delta\mu$ map of an AIEgen-WS₂ heterostructure-based solar cell. The scale bar is 2.5 μm . (c) Lifetime measurements of the heterostructure and pristine WS₂ regions, excited with a 522-nm femto-second laser.

Highlights

- 2D TMDs could yield very high implied open circuit voltages of more than 1 V.
- 2D TMDs can be engineered by doping to improve their uniformity and implied open circuit voltages.
- Development of a class of air-stable vertical organic-inorganic heterostructures comprising of a monolayer of TMDs on top of tetraphenylethylene core-based aggregation-induced emission molecular rotors.

Future Work

The team will continue to explore various surface treatment and doping techniques to improve the quality of the 2D TMDs. The team will also move to the next steps to demonstrate proof-of-concept solar cells, aiming to achieve a 2D TMD-based cell with reasonably high V_{oc} values.

PP3.1C IDEALITY FACTOR MAPPING OF PEROVSKITE BACK CONTACT SOLAR CELLS

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Funding Support

ACAP, Monash University, Exciton Science

Aim

Perovskite back contact solar cells are an exciting, emerging technology that offers a wide range of advantages over the conventional design including buried contacts, flexibility in substrate choices and capacity for operando studies, and has a power conversion efficiency (PCE) of 12%. However, these devices exhibit a strong hysteresis during current-voltage analysis and suffer from temporal changes in operation over time scales of up to 1–2 minutes. Understanding the origins of this long-term transient behaviour is critical to understanding current limitations in the contemporary designs and to improve device performance reproducibility and ultimately, the PCE. Such transient behaviour has been observed in conventional perovskite cells and is generally attributed to ion migration. In order to directly observe the impact of the transient behaviour on the operation of back contact solar cells, the Monash team employed a novel time and light intensity-dependent photoluminescence (PL) imaging approach at a micron scale to resolve the electrode arrays. The aim of the work is to monitor the time evolution in photoluminescence intensity and ideality factor of different back contact devices to gain insights to the time and spatially varying recombination processes.

Progress

A technique for mapping ideality factors has been established by adapting an approach based on the method developed by Calado et al. (Calado et al. 2019) for a single pixel analysis. It is inherently straightforward to perform, non-destructive and can track the time evolution of an ideality factor map with a resolution ~ 1 s at length scales from centimetres down to one micron. Initially the cell is shorted, to precondition the device, for typically 30 s, then switched to open circuit and the PL signal is measured periodically using a camera. This process is repeated at six different light intensities spanning from 0.01 to one-sun equivalent intensities. At each time step, a linear regression of the logarithm of the PL intensity Φ and incident light intensity I_L is determined to provide the ideality factor at each pixel:

$$n_i = \frac{d \ln(\Phi_i)}{d \ln(I_{L_i})}$$

To demonstrate the capability of the technique, maps of PL and ideality factor for a quasi-interdigitated perovskite solar cell are given in Figure PP3.1.6. Upon switching from short circuit (-5 s) to open

circuit at 0 s, the mean intensity drops significantly but interestingly the change is much greater for the NiO layer which now exhibits a higher PL than near TiO₂, causing a reversal in the local relative intensity. With time the intensity reduces, the dominant electrode swaps back to being TiO₂, during the transition at t = 5 s, there being very little variation in the PL between the electrodes. The ideality factor shows a gradual increase with time without any significant variation in the modulation. The stark changes of these parameters reveal the impact of the ion migration on the operation of back contact solar cells.

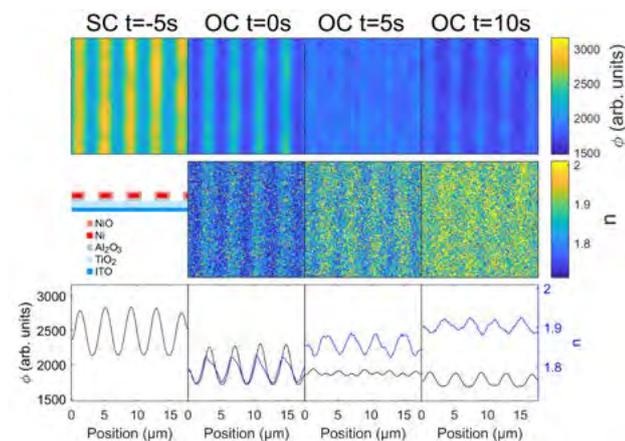


Figure PP3.1.6: Evolution in the photoluminescence (top row) and ideality factor (bottom) for a quasi-interdigitated perovskite solar cell. The pitch size of the device is 4 μm and the image size is 19 μm \times 19 μm . Note: OC = open circuit, SC = short circuit, n = ideality factor.

Highlights

- Produce the first ever ideality factor maps of perovskite back contact solar cells of various designs.
- Demonstrate that the ideality factors of back contact cells indeed vary spatially and temporally.
- Evolution in the photoluminescence determined ideality factors can be directly compared to those determined from open-circuit voltage.

Future Work

The team will develop photocurrent mapping capabilities within the same apparatus to provide insights into the transport behaviour of the devices that will complement the current study into recombination processes. This work is currently being prepared for a manuscript.

PP3.1D HIGH-THROUGHPUT SOLAR CELLS I-V AND LONG-TERM STABILITY CHARACTERISATION

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Monash Student

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Funding Support

ACAP, Monash University, Exciton Science

Aim

The fast developments of robotic automation, machine learning, data science now is enabling the revolution of the scientific research and the acceleration of research progress. The aim of this program is to build the prototype of a high-throughput current-voltage (I-V) testing system for laboratory level small-area thin-film solar cells. The prototype systems will enable researchers to increase the research quality and output.

Progress

In early 2020, the Monash team launched the high-throughput I-V solar cell testing system (Surmiak et al. 2020). More than 40 researchers in Monash node have measured thousands of batches of solar cells with this high-throughput testing system throughout the year. With the carefully designed device protocol, once the fabricated device is placed inside the characterisation jig, it moves to the illumination area and this automated measurement system will complete the routine measurement or custom sequential I-V testing programs. The system can measure a unit of 16 solar cells in a parallel mode by making all electrical connections separated, which can be expanded easily by duplicating the measurement units to automatically handle hundreds of cells. It employs a 4-wire sense technique to reduce series resistance effects from contacts and connection wires. The data is being produced and visualised in a real-time mode to the user who can immediately assess and identify the feature, trend and quality of the devices, with the raw file exported in the background for follow-up analysis as well. In the mid-year review of the system, it was decided to further expand the measurement routine to multiple iterations of parallel 16 devices for additional improvement of the system, and also to introduce temperature recording, dehumidifier to reduce impact of the humidity on devices and active cooling below room temperature. With experience of the I-V testing stage, another 24-channel testing prototype system for parallel real-time measurement was built to accommodate the same device protocol in the environment chamber, which enables high-throughput aging and long-term stability testing.

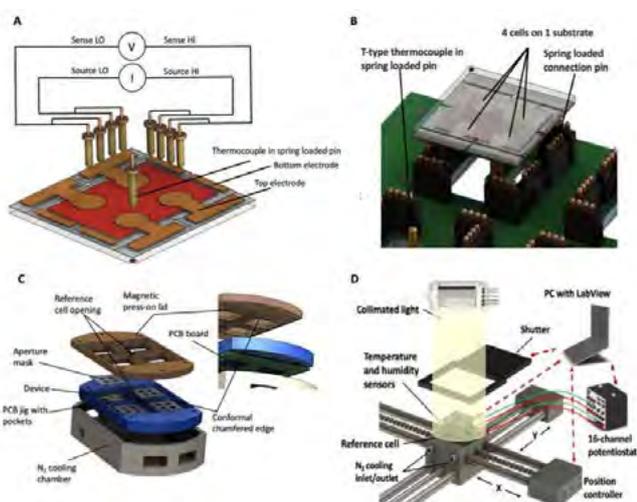


Figure PP3.1.7: Evolution schematic diagram of the high-throughput solar cell characterisation system. (a) A schematic showing a custom-designed pre-patterned FTO substrate that is being probed in a 4-wire sense configuration with spring-loaded pins. (b) Close-up of a single substrate slot, where each cell is connected with eight spring-loaded pins, and measured with a 4-wire sense technique. (c) Single measurement module consists of positioning jig where the substrates are mounted, the design allows the room for a thin 0.08 mm black dyed stainless-steel apertures mask. The mask is pressed against the solar cells by a magnetic force and the chamfered protrusion guides the magnetic lid in place restricting the movement of the cells and ensuring electrical connection between solar cells and spring-loaded probes. (d) Sample holder consists of a printed circuit board (PCB) equipped with spring-loaded gold pins that provide electrical connection between the 16 solar cells and the potentiostat. The red dashed lines denote communication routes between the PCB and system parts.

Highlights

- The prototype of expandable high-throughput laboratory level solar cell IV testing system.
- Parallel 16 solar cells measurement, automated measurement stage changing and sequential IV testing programs.
- The 24 channels parallel IV measurement embedded with an environment chamber.

Future Work

- Increase device count from 16 to 144 in a singular measurement routine.
- Support novel back-contact solar cell devices and top-down monolithic tandem solar cells.
- Completion and testing of the multi-channel stability system in a Climate Simulation Environmental Chamber.

PP3.3 ADVANCED CHARACTERISATION OF SILICON

Understanding material properties, carrier dynamics, defects and impurities in starting silicon materials and during device fabrication helps identify potential problems for final devices and their root causes in early stages. Also, advances in characterisation metrologies have been critical for historical development of more efficient silicon solar cells. Therefore, the groups involved in this work aim to continue advancing the understanding of microscopic structural and optoelectronic properties of various components across different silicon solar cell technologies, as well as to develop fast and reliable techniques to monitor these properties.

PP3.3A DEGRADATION IN SILICON

Lead Partner

ANU

ANU Team

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ANU Student

Di Kang

Funding Support

ACAP, ARENA, ANU

A. Light and elevated temperature induced degradation

Aim

Light and elevated temperature induced degradation (LeTID) can cause significant performance loss in photovoltaic modules. The aim of this work is to evaluate LeTID in different types of silicon (Si) materials, and develop a model to describe LeTID behaviours and correspondingly identify the root causes of the underlying mechanism.

Progress

The ANU team, led by Dr Hang Sio, studied LeTID activities in four different silicon substrates, namely p-type boron-doped and n-type phosphorus-doped mono-like silicon and float zone silicon (FZ-Si) wafers, and investigated the dependence of the degradation behaviours on silicon nitride (SiN_x) film properties and diffusions. As shown in Figure PP3.3.1(a), all studied materials were found to exhibit different extents of degradation. P-type materials generally suffered higher degradation extent than their n-type counterparts, whereas mono-like Si wafers degraded more severely than FZ-Si samples. It is observed that the degradation is strongly correlated to the Si-N bond density and the refractive index of the SiN_x films, measured using Fourier-transform infrared spectroscopy (FTIR) and ellipsometry. The degradation behaviours were found also to be affected by diffusions, with the degree of degradation decreasing as the gettering efficiency improves.

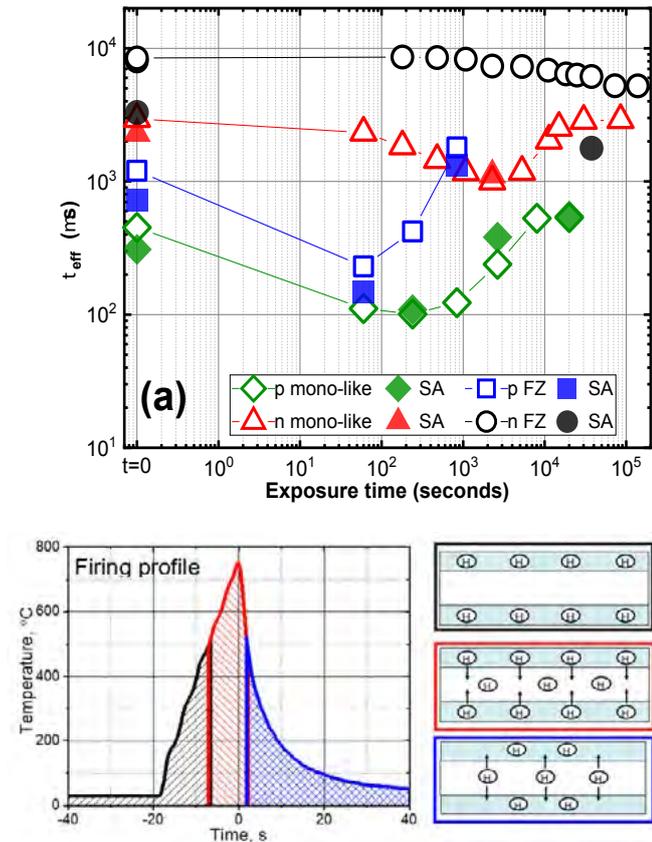


Figure PP3.3.1: (a) Evolution of t_{eff} upon light soaking test performed under one-sun at 140°C . The lifetimes were measured at 10% of the background dopant density. Samples were all gettered by phosphorus diffusion and coated with SiN_x capping during firing treatment. Also shown are the effective lifetimes measured by superacid (SA) treatment on samples collected at various degradation stages, with SiN_x and diffusion layers removed by HF dip and TMAH etch. (b) A model correlating LeTID, firing and hydrogen.

A model for LeTID is developed based on the team's experimental findings, correlating hydrogen, firing and LeTID. In the model, as demonstrated in Figure PP3.3.1(b), it is proposed that hydrogen atoms originally bound in the SiN_x layer are released into the Si bulk above a certain firing temperature, which then interact with some other species in the Si bulk under illumination, causing the LeTID degradation. During the cooling ramp of the firing process or extended annealing, hydrogen in the Si bulk starts to out-diffuse into the ambient, altering the amount of hydrogen remaining in the Si bulk. The amount of hydrogen remaining in the Si bulk, and the resulting LeTID behaviour, then depends on the properties of the dielectric films, the peak firing temperature, the cooling rate and also the sample thickness and dopant type, which govern the balance between in-diffusion and effusion of hydrogen.

Highlights

- First observation of LeTID behaviours in n-type FZ-Si.
- Development of a new model to explain complex LeTID characteristic.

Future Work

Verify the proposed LeTID model with experimental data.

B. Firing and long-term stability of doped poly-Si passivating contacts

Aim

Passivating selective contacts based on polycrystalline silicon (poly-Si) films are considered one of the most promising technologies for the next generation of silicon solar cells, and are currently under development at several companies and institutes. Conversion efficiencies above 25% have been achieved by multiple research institutes on laboratory-scale small-area devices using photolithography technology. However, the average efficiency in production is still around 23%. One major challenge for the industrial uptake of the poly-Si passivating contacts technology is its compatibility with the high temperature screen-printing metallisation process. This project aims to investigate the impacts of the firing process to the passivation quality and the long-term stability of poly-Si passivating contact structures.

Progress

The ANU team, led by Dr Hang Sio, investigated the change in the passivating quality of the poly-Si structures upon firing. As shown in Figure PP3.3.2(a), samples passivated with n^+ poly-Si layers showed a stable J_0 when fired at 700°C or below, but had its surface passivation quality deteriorated severely when fired at 800°C and 850°C . As typical screen-printed solar cells are fired at a peak temperature in a range from 750°C to 800°C , the result implies that the high temperature firing treatment used in screen-printing silicon solar cells could potentially impact the performance of poly-Si passivating contact-based devices. It was found that the dielectric coating layer plays a significant role on the performance of the poly-Si passivation layers after firing. The hydrogen profiles measured by Secondary Ion Mass Spectrometer (SIMS) suggest that the impact of firing on n^+ poly-Si passivation layers could be related to the changes of hydrogen concentration in the poly-Si/ SiO_x /c-Si structure. Surprisingly, the quality of surface passivation does not solely increase with the hydrogen content in poly-Si layers.

They have also investigated the long-term stability of poly-Si passivation layers under illumination. It was found that the surface passivation quality of the n^+ phosphorus doped poly-Si structures experiences a degradation and regeneration process upon light soaking at elevated temperature, as demonstrated in Figure PP3.3.2(b). The degradation and regeneration behaviours depend strongly on temperature and light intensity, and the presence of silicon nitride (SiN_x) capping layers during the light soaking. It is speculated that hydrogen is involved in the observed degradation or regeneration phenomena.

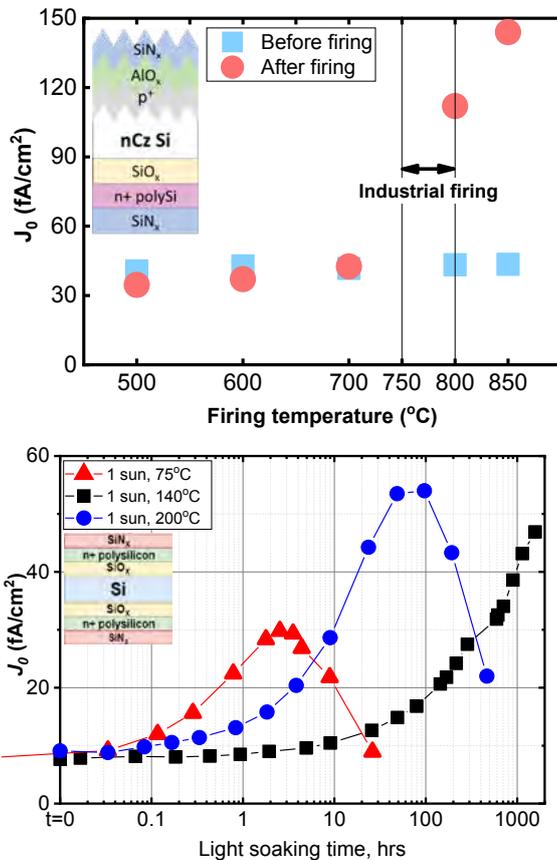


Figure PP3.3.2: (a) Changes of J_0 in poly-Si passivating contact cell precursors before and after firing. (b) Evolution of J_0 values upon one-sun illumination at different temperatures.

Highlights

- Report of the change in the passivating quality of poly-Si passivating contact structures upon different firing conditions.
- Report of the long-term stability of poly-Si passivation layers under illumination.

Future Work

The team will extend the studies to cover different types of poly-Si passivating contact structures, including passivation layers deposited by different deposition methods and both phosphorus-doped and boron-doped poly-Si. Another objective is to identify the role of hydrogen in poly-Si layers, which can potentially provide an explanation for the observed instability phenomena. They will apply advanced characterisation techniques including FTIR, SIMS and high-resolution micro-photoluminescence spectroscopy (μ -PL) to measure hydrogen in the poly-Si layers, and correlate the hydrogen measurement with the surface passivation quality.

PP3.3B OPTOELECTRONIC PROPERTIES OF POLY-SI PASSIVATING CONTACTS

Lead Partner

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ANU Student

Thien Truong

Academic Partners

National Renewable Energy Laboratory (NREL), UNSW

Funding Support

ACAP, ARENA, ANU

Aim

The objective of this project is to explore optoelectronic properties of doped polycrystalline silicon (poly-Si) films employed in passivating contact Si solar cells, and their applications to the development of high quality passivation films.

Progress

In 2018, the ANU team, led by Dr Hieu Nguyen, found that their doped poly-Si films contained both amorphous and crystalline phases, each of which yielded distinct luminescence peaks at low temperatures (Figure PP3.3.3). In 2019, they also discovered that after high temperature diffusion processes to form the doped poly-Si films, most of the hydrogen content had effused out of the films, leaving them un-hydrogenated. Un-hydrogenated amorphous Si (a-Si) contained a very high density of non-radiative defects, yielding no PL signal. Once hydrogenated, the a-Si:H phase emitted a strong PL peak in which the intensity was proportional to the hydrogen content inside the films. Tracking the a-Si:H PL emission, the team could study the effectiveness and mechanisms of various hydrogenation techniques on different poly-Si films. Their findings and the various applications of their method were reported in a series of four journal papers (Nguyen et al. 2018; Truong et al. 2019a and b; Truong et al. 2020a). Also, the work in Truong et al. 2020a was selected as an issue's frontispiece.

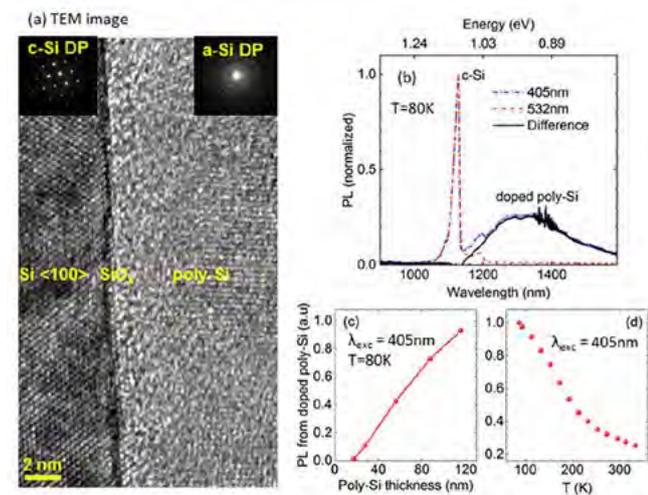


Figure PP3.3.3: (a) Cross-sectional transmission electron microscope (TEM) image of a phosphorus-doped poly-Si/SiO_x/c-Si structure reveals both amorphous and crystalline phases in the poly-Si layer. (b) Normalised PL spectra with various excitation wavelengths at 80K. (c) Integrated PL intensity from poly-Si films versus their thicknesses. (d) Temperature dependence of the poly-Si film's PL intensity.

In 2020, the team combined the PL-based method with various optical and microscopy techniques to unlock the structural and optoelectronic characteristics of ex-situ boron-doped poly-Si/SiO_x passivating contacts, formed from sputtered intrinsic a-Si deposited at different pressures on top of SiO_x/c-Si substrates and subjected to a high temperature boron-diffusion step. They found that the deposition rate and density of the as-deposited a-Si films increased with reducing pressure. Low temperature PL spectra captured from the as-deposited samples at different pressures did not show typical emissions from hydrogenated a-Si. Meanwhile, their Fourier-transform infrared absorption spectra all showed Si–H stretching modes, indicating that hydrogen had been initially incorporated into the chemical SiO_x layers and eventually hydrogenated the a-Si/SiO_x interfaces during the sputtering process. After the high temperature boron-diffusion step, all hydrogen-related peaks disappeared. The team also found that lower pressure films (1.5 and 2.5 mTorr) showed more consistent improved performance after hydrogen treatments, compared to higher pressure films (4 and 5 mTorr). The resultant passivating contacts at 2.5 mTorr achieved a low single-side recombination current density J_0 of ~ 9 fAcm⁻² (Figure PP3.3.4), whereas their contact resistivity was still low at 15 mΩ cm². These results were then published in *Solar Energy Materials & Solar Cells* (Truong et al. 2020b).

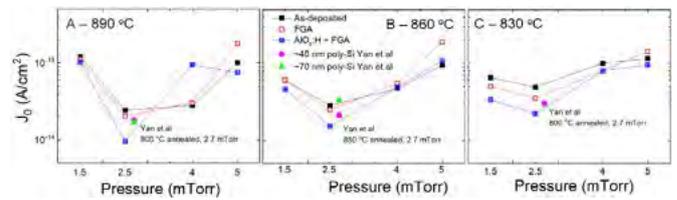


Figure PP3.3.4: Recombination current density J_0 of different poly-Si samples diffused at 890°C (A), 860°C (B), and 830°C (C), with various a-Si deposition pressures, and before and after hydrogen treatments. The J_0 was measured using a quasi-steady state photoconductance (QSSPC) technique. Reference J_0 results from Yan et al. (*Appl. Phys. Lett.* 2018, 113, 061603) for in-situ boron doped samples with the poly-Si layer thicknesses of ~ 40 nm and ~ 70 nm, sputtered at 2.7 mTorr and annealed at 800°C, 850°C and 900°C, are also given. The legends are the same for all figures.

Highlights

- Poly-Si films contain both amorphous and crystalline phases, each of which yields distinct luminescence peaks at low temperatures.
- The luminescence signatures can be used to understand the behaviour of poly-Si/SiO_x passivating contacts in terms of carrier recombination and transport.
- Luminescence from the amorphous Si phase in poly-Si films can be used to track the hydrogen content inside the films.
- High quality ex-situ boron-doped poly-Si/SiO_x passivating contacts based on sputtered amorphous silicon films.

Future Work

The team will consolidate their techniques and scientific findings to support high efficiency silicon solar cell teams at ANU and UNSW.

PP3.3C MAGNETIC FIELD IMAGING FOR PHOTOVOLTAIC CELLS AND MODULES

Lead Partner

UNSW

UNSW Team

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Industry partner

BT Imaging Pty Ltd

Aim

Magnetic field imaging is a characterisation technique where the current flow patterns in a device are estimated by measuring the magnetic field on a plane above/below the device under test. The magnetic field (MF) created by the current that flows within the solar cell is a vector field with values in all three directions. Such an MF map is measured using a linear array of magnetometer sensors and performing a line scan over the solar cell at fixed height.

In solar cells, early measurements using a super conducting quantum interference device (SQUID)-based magnetometer were done to measure the magnetic fields. However, such measurements require large and expensive setups for the SQUIDs. Recent developments have led to manufacturing of highly sensitive magneto-resistance-based sensors (anisotropic magneto-resistance (AMR) sensors and giant magneto-resistance (GMR) sensors), which have made MF imaging-based characterisation of solar cells into a viable method to measure the current flows in solar cells in a fast and inexpensive way. This project aims to use such AMR sensors to measure the MF images. With the best sensors available and a robust measurement system, the team aims to use this technique to provide much higher resolution images of solar cells and modules. These resultant images can then be used to extract detailed current flow maps and highlight series resistance features in the solar cell.

Additionally, this project aims to develop techniques to provide the actual 2D current flow patterns and magnitude in the whole device. Using 2D arrays of these sensors it is now possible to visualise 2D and possibly even 3D current flows in solar cells at sub-mm resolution and at speeds of tens to hundreds of samples per second. The fundamental principle behind this is that moving charges (J) are causing magnetic fields (B) as described by Ampère–Maxwell's law. The magnetic field created when current flows through an infinitesimal length of wire some distance away can conveniently be calculated using the Biot–Savart law. Subsequently, a magnetic field strength can be calculated at any point in space originating from an arbitrary 3D current flow. There are a lot of unexplored applications, such as highlighting soldering problems and bypass diode failures (Kunz 2019, Paduthol 2019).

Progress

1. Development of high sensitivity MF imaging setup

As the basis of this work a measurement system needed to be established at UNSW labs to perform magnetic field imaging (MFI) and to be able to develop this technology and to compare it to the team's in-house photoluminescence (PL) and electroluminescence (EL) capabilities. This deliverable has been achieved.

Further enhancement of the measurement capabilities has been achieved via using a high performance magnetic field sensor (Memsic - MMC5883MA) that has an approximate 50 times improved magnetic measurement sensitivity compared to the team's linear sensor arrays. This point sensor can be used where for example very small currents in solar grid lines need to be detected or for precise imaging of regions of interest that were previously identified with the standard line sensor array.

Figure PP3.3.5 depicts the imaging system and a 3D robotic measuring system with a linear magnetic sensor array attached to it. The UNSW team is using this tool now to routinely perform high speed, high sensitivity MFI measurements. The system can reliably measure magnetic fields down to 50 nT magnetic resolution.

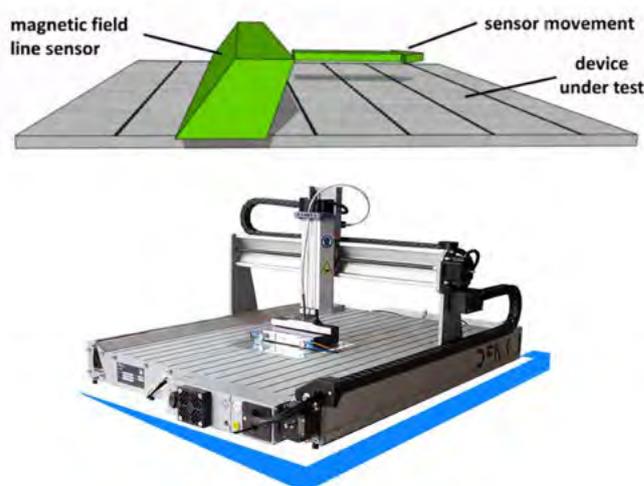


Figure PP3.3.5: Schematic of an MFI system and a 3D robotic measuring system.

2. High resolution MFI of solar cells

High resolution MF images of solar cells with many types of defects were taken and studied. This section shows two examples of the types of features that can be extracted using MF images.

First, a solar cell with a broken busbar is shown (Figure PP3.3.6). The solar cell is p-type with a PERC structure and four busbars. The solar cell was kept under forward bias at 5 A and then EL and MF images were taken. The cell was contacted only on the left-hand side of the front busbars. On the rear side, it was contacted only on the right-hand side edge. The front side busbars of the cell were not tabbed. The MF image was measured at 2 mm away from the solar cell. The EL image in Figure PP3.3.6(a) shows two sets of cracks. The current map along the direction of the busbars, calculated from the MF image is shown in Figure PP3.3.6(b). It shows mainly the current through the busbars. As the solar cell is considered a thin sheet in this first order approximation, the results shown in Figure PP3.3.6(b), show the sum of the currents flowing on the front and rear side of the cell. For the first three busbars, the current is not interrupted. But the current flow in the fourth busbar gradually reduces and goes to zero where the crack meets the busbar. This is because the contact on the bottom right-hand corner is partially isolated by the crack and so the current flows into the adjacent busbar. This highlights that some features relating to the current flow on the solar cell can be highlighted easily using MF images.

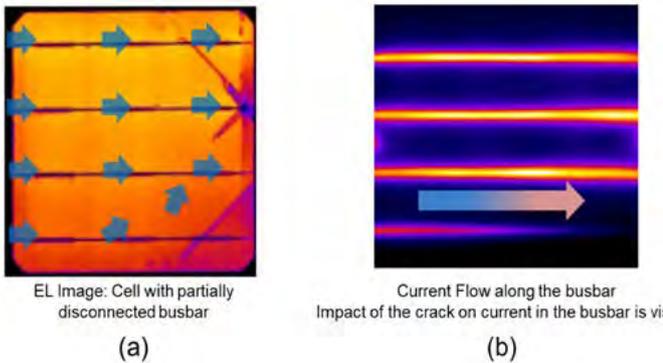


Figure PP3.3.6: (a) EL image of a PERC silicon solar cell with four busbars under 5 A current injection. (b) MF image of the same cell under 5 A forward bias. The current flow along the busbar is shown which highlights the impact of the crack on the current in the busbar.

In this next example, a multi-crystalline solar cell with a prominent crack is shown (Figure PP3.3.7). In this figure the MF image showing the current in the direction perpendicular to the busbar is shown. As mentioned earlier, the MF image is a vector quantity. The image of the current flowing in the direction parallel to the busbar can highlight partially disconnections within the busbars. Conversely, the current flow in the direction perpendicular to the busbar highlights the soldering points on each of the busbars (Figure PP3.3.7b). The current can be seen to be leaving and entering the busbar through the solder points and such an image can be used to visually identify any problems in the soldering.

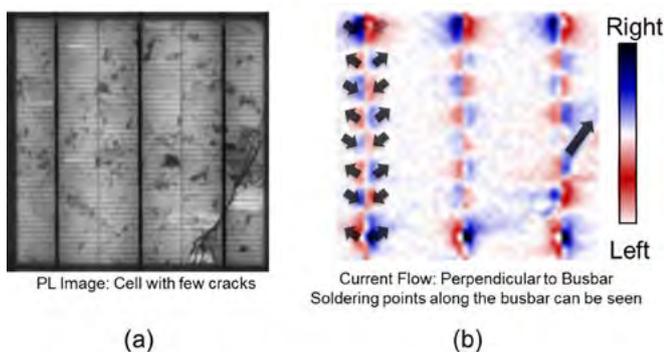


Figure PP3.3.7: (a) EL image of a multi-crystalline silicon solar cell with three busbars under 5 A current injection. (b) MF image of the same cell under 5 A forward bias. The current flow perpendicular to the busbar is shown, which highlights the soldering points along the busbars. Such MF images can be used to characterise the quality of soldering in high-throughput solar cell production.

Highlights

High sensitivity MFI setups with the capability of measuring silicon solar cells and modules were developed. This technique was shown to be useful at identification of issues in front/rear contacting structures and to quantify contacting quality in cells with newer contacting schemes. Resulting images showing features such as broken busbars and soldering points are highlighted.

Future Work

- One journal publication is currently in preparation and expected to be submitted beginning of 2021. The paper discusses the basic theory of magnetic field imaging for solar applications, its strengths and weaknesses and is supported by measurement results from the course of this project.
- Progress the work with higher sensitivity sensor array and local laser illumination, which leads to magnetic field images with significantly improved spatial resolution and sensitivity.

PP3.3D INVESTIGATION OF LIGHT-INDUCED DEGRADATION USING PHOTOCONDUCTANCE DECAY MEASUREMENTS

Lead Partner

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Academic Partner

University of Manchester

Aim

Light-induced degradation (LID) in boron-doped Czochralski (Cz)-grown wafers is considered a substantial problem for the cells made with this type of wafer. Numerous studies have investigated the defect causing this degradation as well as its precursor. In these studies, photoconductance (PC)-based lifetime measurement has been widely used to investigate the correlation between the interstitial oxygen and boron concentration with degradation rate and extent. They have shown that the degradation extent is correlated with [B] and [O] in uncompensated wafers. Thus, it is suggested that a boron complex in the form of $B_{\text{O}}O_2$ is responsible for this degradation.

However, the typically used PC-based lifetime measurement method is not capable of detecting the precursor directly. Since the lifetime measurement is sensitive to the defects limiting the lifetime, it is not a suitable method to investigate the non-recombination active form (precursor) of the defects. This means that the sample degradation extent can only be exactly determined after the full degradation process. It also means that the precursor of the defects cannot be characterised in a direct manner.

In this project, the team aims to utilise the photoconductance decay (PCD) measurement method to study the precursor of the defect causing LID in B-doped Cz wafers using a modified lifetime tester. Moreover, they demonstrate the abilities of their tool which improves measurement quality and certainty (Jarafi 2020).

Progress

1. Measurement tool

The measurement has been done using a modified lifetime tester. A schematic of the system is shown in Figure PP3.3.8. With this system, it is possible to measure the PC and photoluminescence (PL) transients of a sample for up to hundreds of seconds. The system uses a flash (identical to the flash used in WCT-120 lifetime tester) as an excitation source. Measurement can be done at different temperatures using a temperature-controlled stage. Acquisition time, acquisition rate, and time between consecutive excitations during averaging are also tunable. In the final section, "Modified lifetime tester for trap studies", the importance of PL measurement and temperature-dependent measurements for this study will be discussed in more detail.

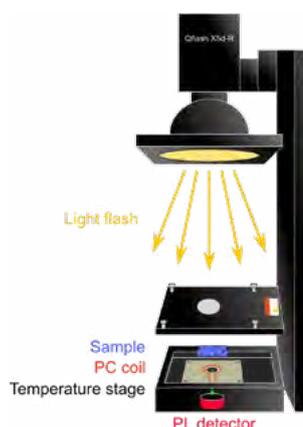


Figure PP3.3.8: A schematic of the modified lifetime tester.

1. Transformation of traps to LID-related defects

Figure PP3.3.9(a) presents the lifetime curves of a representative wafer throughout the dark annealing (DA)-degradation cycles. As expected, the two states can be easily identified. The lifetime is decreased clearly by the degradation, while DA recovers the lifetime curve to its initial values. Further degradation/DA processes result in cycling the lifetime between these two states.

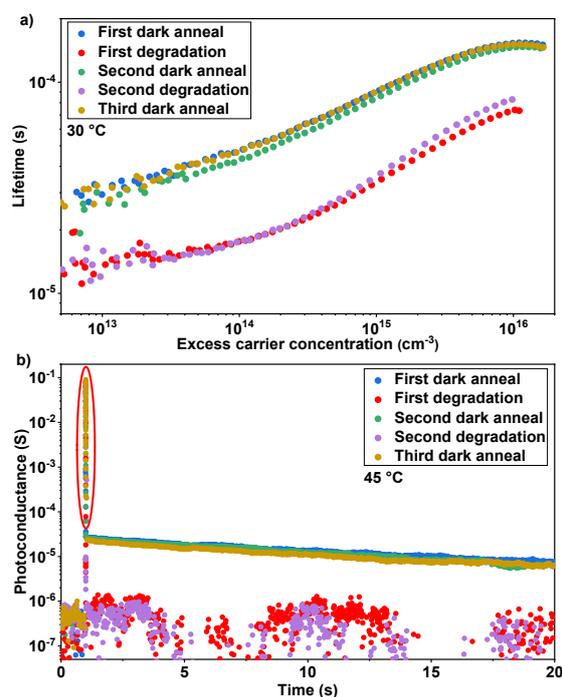


Figure PP3.3.9: (a) Lifetime curves at 30°C. (b) PCD curves at 45°C for a sample going through DA-degradation-DA-degradation-DA cycle.

Figure PP3.3.9(b) shows the PCD curves (at 45°C) as a function of time for the same wafer. In the DA state, the initial fast decay after the flash (marked with red ellipse) is due to the recombination of excess carriers. This fast decay is followed by a second slow decay. Since the chosen passivation method has a negative fixed charge and the samples do not have a junction, this slow decay cannot be explained by a depletion region modulation (DRM) mechanism and is most likely related to minority carrier trapping centres. After the degradation, the fast decay is still visible, however, the second slow decay has disappeared, and the PC signal returns to its dark conductance background value within a few hundred microseconds. This suggests that the trapping centres are annihilated by the degradation process. Repeating the DA process results in the recovery of the traps again, while the degradation process eliminates them again. Additional cycles of degradation and DA confirms that these transitions are fully reproducible after any number of cycles and are strongly correlated with the change of lifetime observed in Figure PP3.3.9(a). From fitting the slow decay of the PCD curves (DA states), an average PCD time constant of 13.7 ± 0.9 s is determined at 45°C.

Figure PP3.3.10 shows the change in the normalised trap density and normalised defect density (NDD – at $0.1 \times p_0$ cm⁻³ where p_0 is the bulk doping) with light soaking time.

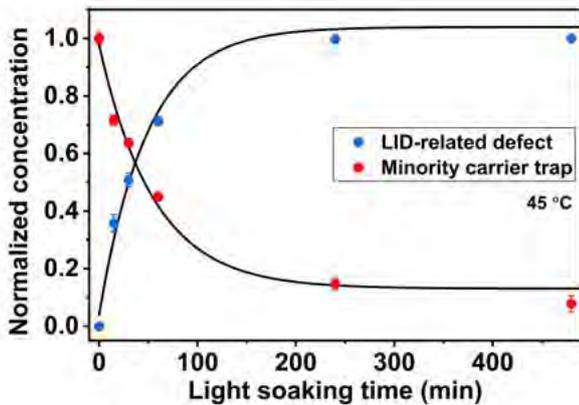


Figure PP3.3.10: Change in the normalised trap and defect density of a wafer with BO-related traps after various light soaking times under one-sun illumination at 60°C. The fitted curves have exponential functions with a time constant of 55 ± 5 minutes.

Both values show an exponential dependency on the light soaking duration. The trap density is reduced with light soaking duration, while the normalised density of LID-related defects increases. A time constant of 55 ± 5 minutes is determined for both curves. This time constant matches well with the reported time constant for the generation of the slow-formed recombination centres in a similar wafer. These results suggest that the traps act as a precursor for the recombination active BO defect. It also demonstrates the unique potential of PCD measurement to study defects in their non-recombination active form.

3. Modified lifetime tester for trap studies

As mentioned previously, the possibility of simultaneous PL and PC measurement as well as temperature-dependent measurements are highly beneficial for trap studies. Previously, it was shown that while PC-based measurements are affected by the traps, PL-based measurements are not affected by this phenomenon. This is shown in Figure PP3.3.11. While the PL signal returns to the dark signal immediately after the flash, the PC signal continues for tens of seconds. Such a characteristic difference between PC and PL signals is helpful to better identify the source of the long PCD tail in such measurements.

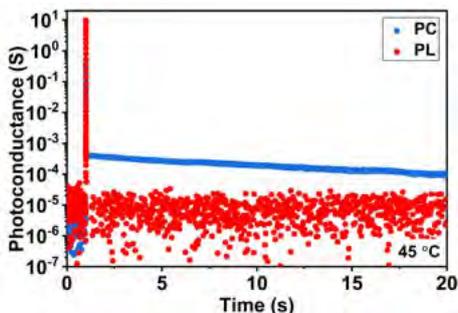


Figure PP3.3.11: PC and PL signal of a sample with BO-related traps measured at 45°C.

The possibility of PCD measurement at different temperatures is helpful in, for instance, improving the signal-to-noise (SNR) ratio. Figure PP3.3.12 presents the PCD curves of a sample with BO-related traps at different temperatures. It should be noted that the graph has a log x-log y scale. With increasing temperature, the initial conductance decreases. This is due to a decrease in carrier mobility with temperature. Additionally, since de-trapping is a thermally activated process, at higher temperatures the PC signal returns to the dark value much sooner compared to a lower temperature. Thus, high averaging is possible at a shorter time scale. Considering the trade-offs between lower conductance and the possibility of high averaging at higher temperatures, the right temperature for optimum SNR can be chosen for the measurements.

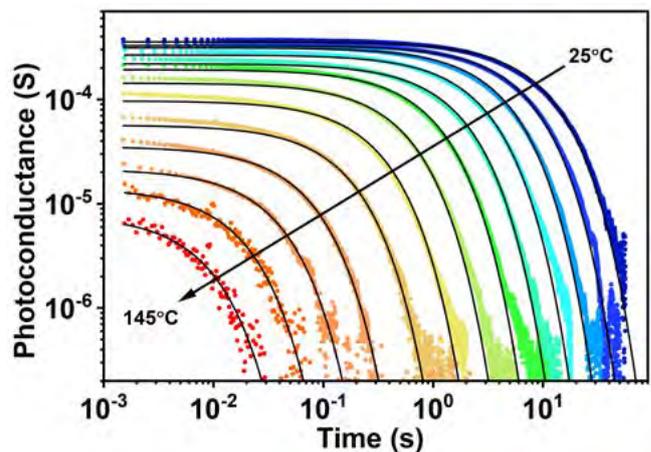


Figure PP3.3.12: Temperature-dependent PCD measurement of a sample with BO-related traps.

Highlights

- The connection between minority carrier traps and BO-related defects is shown using PCD measurement method.
- It is shown that simultaneous PL measurement and temperature-dependent measurement increases the certainty of the results.
- PCD measurement method is suggested as a tool for prediction of LID without any degradation step.

Future Work

Improvement of measurement sensitivity is needed to reduce the measurement time (number of averaging) for wafers with low trap density. Also, the exact correlation between trap density and $[B]$ and $[O]$ should be studied to further confirm the results. Finally, the method can also be applied to other well-known defects that have non-recombination active and recombination active states.

PP3.3E TEMPERATURE-DEPENDENT PERFORMANCE OF SILICON WAFERS: THE IMPACT OF GETTERING AND HYDROGENATION PASSIVATION

Lead Partner

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UNSW Team

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UNSW Student

Shuai Nie

Aim

The performance of silicon (Si) solar cells is usually tested and optimised under standard test conditions (STC). However, STC does not represent the actual operating conditions of photovoltaic (PV) devices in the field. In order to allow a reliable prediction of energy production and optimisation of solar cells for field operation, it is vital to investigate the impact of temperature on the electrical properties of silicon solar cells.

Solar cells' operating temperatures have a strong impact on their instantaneous output, with the highest influence recorded on the open-circuit voltage (V_{oc}) (Green 2003). Besides the changes in the intrinsic carrier concentration and bandgap at elevated temperatures, the charge carrier recombination within the device affects its temperature sensitivity via the gamma factor (γ) (Dupré et al. 2017). In the PV industry, processing steps, such as gettering, firing and hydrogenation, are commonly used to reduce carrier recombination, therefore, they are expected to have a considerable impact on the temperature coefficient (TC). Moreover, TC of non-uniform materials can also differ significantly across the sample area. This study aims to improve the understanding regarding the temperature-dependent performance of Si solar cells by investigating the influence of different fabrication processes on the spatially resolved TC using photoluminescence (PL) imaging.

Progress

This project investigates the temperature-dependent performance of p-type cast-mono wafers from different ingot heights and n-type mc-Si wafers after different fabrication processes, including gettering, firing and advanced hydrogenation (Hallam et al. 2020). After each processing step, the wafers were characterised using the team's novel temperature-dependent PL imaging system (Nie 2019). The PL images were calibrated into implied open-circuit voltage (iV_{oc}) images using the calibration procedure in Nie et al. 2020. The subsequent local absolute TC(iV_{oc}) is obtained from the slope of a linear fit to each pixel.

Figure PP3.3.13 shows the iV_{oc} maps at 25°C and the corresponding histograms (the lines represent the harmonic average) of p-type cast-mono wafers from the top of the ingot and n-type wafers before and after gettering, after firing and after advanced hydrogenation.

For the p-type cast-mono wafers in the ungettered state, the dislocation clusters are highly recombination-active. Gettering further increases the recombination strength of the dislocations, while no significant change is observed at the mono-like regions. After firing, a significant improvement of iV_{oc} in the mono-like regions is realised, possibly due to the diffusion of hydrogen from the SiN_x into the bulk, while dislocation clusters remain recombination-active. There is no significant variation in the overall recombination activity of the dislocated regions after the first two processes, although the mono-like regions are significantly improved by the firing process. The overall effect of gettering and firing is negligible in the case of cast-mono wafers obtained from the top of the ingot, as the change in the global iV_{oc} is within 5 mV. Advanced hydrogenation passivates the entire wafer, with stronger improvement in the mono-like regions. It is noticeable that wafers from different ingot heights respond differently from these different processes. For wafers from the bottom and middle of the ingot, all three processes improve the overall performance, while gettering is more beneficial for the bottom wafers. The n-type mc-Si wafers behave similarly to the cast-mono wafers, except that the grain boundaries (GBs) in mc-Si wafers are activated by gettering and are then passivated by the firing process. Firing is a critical process for improving the performance of mc-Si wafers as evidenced by a shift of the distribution to higher iV_{oc} . Moreover, the advanced hydrogenation implemented in this study seems to be more effective to passivate n-type mc-Si wafers compared to cast-mono wafers.

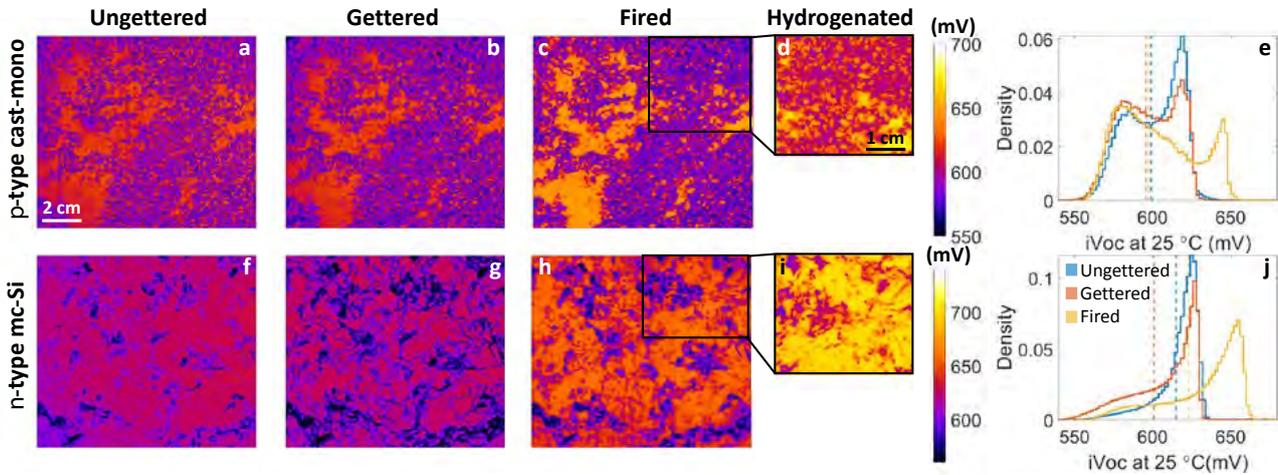


Figure PP3.3.13: iV_{oc} maps at 25C obtained at an illumination intensity of approximately 0.5-sun and their respective histograms after different processes (please note the different colour scales).

Figures PP3.3.14(a)-(e) present the measured $TC(iV_{oc})$ for the top cast-mono wafer after different processes and their respective histograms (the dashed lines represent the averages). Gettering reduces the temperature sensitivity of the mono-like regions and some dislocation clusters [to less negative $TC(iV_{oc})$]. This reduction is less significant for wafers from the middle of the ingot. Interestingly, firing does not have a significant impact on $TC(iV_{oc})$, regardless of the ingot height. The hydrogenation process significantly reduces the temperature sensitivity across the entire wafer. It is noted that the dislocated regions remain the least temperature-sensitive regions after all the processes.

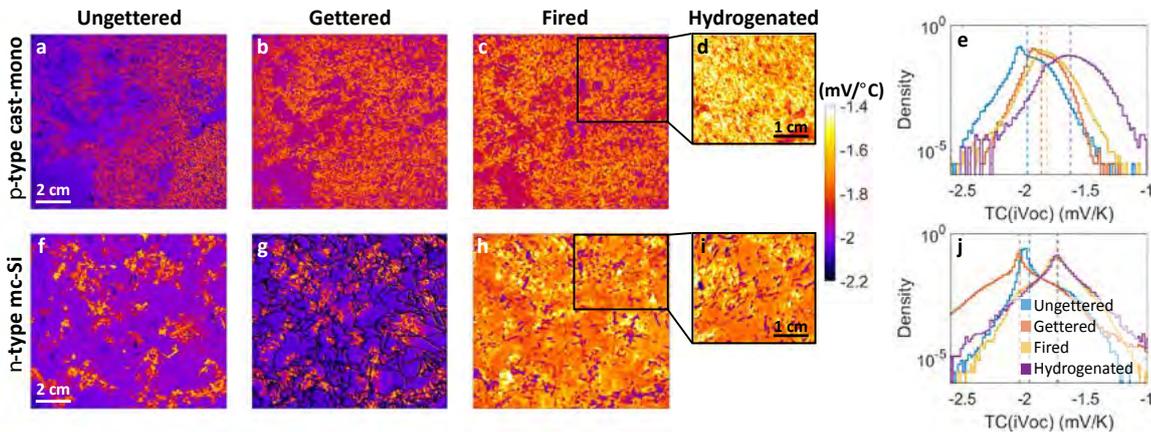


Figure PP3.3.14: $TC(iV_{oc})$ obtained at an illumination intensity of approximately 0.-sSun and their respective histograms after different processes for cast-mono and mc-Si wafers.

For the mc-Si wafers (Figures PP3.3.14(f)-(j)), $TC(iV_{oc})$ is not strongly affected by gettering, except for the GBs which interestingly exhibit increased temperature sensitivity. In contrast to the cast-mono wafers, firing significantly reduces the temperature sensitivity of the investigated mc-Si wafers (see Figure PP3.3.14j). Surprisingly, there is no significant change in the temperature sensitivity upon hydrogenation, despite the significant improvement of iV_{oc} .

Notably, the initial iV_{oc} and γ have a critical impact on $TC(iV_{oc})$, as $TC(iV_{oc})$ is theoretically expected to reduce with increasing iV_{oc} if γ remains unchanged. Figure PP3.3.15 presents the sole impact of the iV_{oc} on the $\Delta TC(iV_{oc})$ maps, which is defined as the relative difference between measured and expected $TC(iV_{oc})$ of the hydrogenated wafers. The expected $TC(iV_{oc})$ was calculated assuming no temperature dependence of the recombination ($\gamma = 0$) (Dupré et al. 2017). This $\Delta TC(iV_{oc})$ could be explained by the presence of recombination-active defects. Interestingly, the hydrogenation process not only improved the iV_{oc} but also reduced the $TC(iV_{oc})$ on the mono-cast wafers; most regions of the wafer are less sensitive to change of temperature

than expected. For both materials, it is noticeable that most of the dislocated clusters show lower than expected temperature sensitivity. One possibility lies in the temperature characteristics of the metal impurities decorating dislocations.

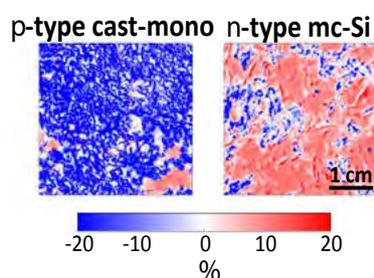


Figure PP3.3.15: $\Delta TC(iV_{oc})$ between measured and expected temperature sensitivity for hydrogenated wafers (blue areas indicate lower temperature sensitivity than expected).

Highlights

- This work highlighted the advantages of performing spatially resolved analysis to assess the $TC(iV_{oc})$ of silicon wafers, which provides more detailed information about the materials' electrical properties and their temperature dependence in comparison to global measurements.
- It is shown that advanced hydrogenation significantly reduces the temperature sensitivity of p-type cast-mono silicon wafers, while firing effectively reduces the temperature sensitivity of n-type multicrystalline wafers.
- Dislocation clusters in both materials show low temperature sensitivity, indicating their detrimental impact is less severe at high operating temperatures.

Future Work

- To assess whether the benefit of the advanced hydrogenation process on temperature coefficient is also applicable to solar cell structures.
- To further investigate the root cause of low temperature sensitivity of dislocation clusters.

PP3.3F PHOTOLUMINESCENCE IMAGING OF SILICON WAFERS AND SOLAR CELLS WITH SPATIALLY NON-UNIFORM ILLUMINATION

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Aim

Photoluminescence (PL) imaging is a characterisation technique widely used for obtaining the spatial non-uniformity of silicon bricks, wafers, solar cells and modules. One of the main advantages of PL imaging is that no electrical contact is required. This reduces the potential damage of samples and also makes PL imaging suitable for in-line inspection. In conventional PL imaging measurement, uniform illumination light is used, for example the entire sample area is laterally excited under the same generation rate. As PL is directly correlated to the excess charge carrier concentration, lower counts in a PL image usually indicate regions with lower local electrical quality, such as lower minority carrier lifetime or local shunts.

However, resistance information is usually difficult to be extracted from conventional PL imaging. The resistance information such as series resistance is also important metric for quantifying the performance of solar cells. To get the resistance information, stimulation of lateral carrier flow is required, which is usually done by techniques that require electrical contact, such as electroluminescence (EL) imaging or PL imaging with current extraction. Lateral carrier flow can also be stimulated by using spatially non-uniform illumination, where no electrical contact is required. Therefore, in this project, they explore the potential of using spatially non-uniform illumination in PL imaging to extend its characterisation capability in silicon photovoltaics.

Additionally, this project aims to improve quantitative analysis of PL images by using non-uniform illumination. In conventional PL imaging where uniform illumination is used, any non-uniformity in the sample quality will lead to a gradient of the quasi-Fermi level splitting. This gradient induces a net lateral carrier flow in the sample. It should be noted that this lateral carrier flow is usually not enough for resolving the resistance information mentioned above. On the contrary, this lateral carrier flow smears the resulted PL image and impedes an accurate quantitative analysis of PL images. By using spatially non-uniform illumination, it is possible to compensate the non-uniform quality of the sample and reach a uniform injection level in PL imaging. The spatially resolved sample quality information can be retrieved from the applied non-uniform illumination image (Heinz et al. 2018; Zhu et al. 2017; Zhu et al. 2018).

Progress

1. Development of PL imaging setup with non-uniform illumination

The PL image setups with spatially non-uniform illumination have been developed by the UNSW team (Figure PP3.3.16). The spatially non-uniform illumination is achieved by using a uniform light source and a digital micromirror device (DMD) chip or a liquid crystal display (LCD) chip. The DMD chip allows a higher contrast ratio than the LCD chip. However, the LCD chip allows pure steady state illumination which is required for certain applications.

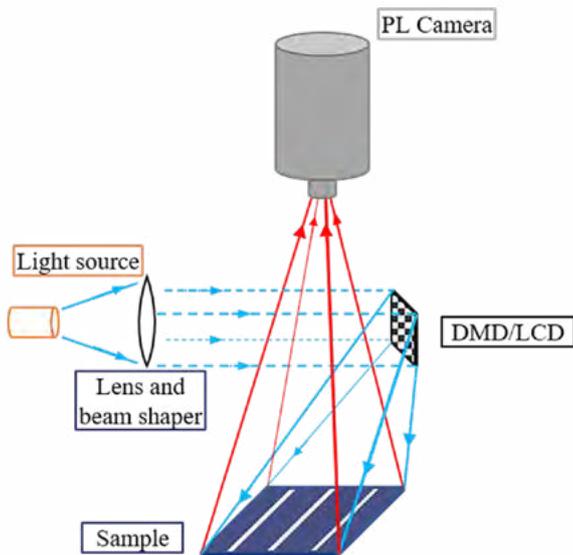


Figure PP3.3.16: Sketch of the developed PL imaging setup with spatially non-uniform illumination.

1. PL imaging with contactless induced lateral carrier flow

The developed DMD-based PL imaging with non-uniform illumination setup was first applied to induce lateral carrier flow into the samples while keeping the contactless feature of PL imaging.

For a silicon solar cell, the lateral carrier flow leads to local voltage drop across local series resistance. The local voltage drop can be reflected from PL imaging. Therefore, by using spatially non-uniform illumination to induce lateral carrier flow, it is possible to obtain a series resistance image in a contactless manner. In Figure PP3.3.17, a demonstration of the contactless series resistance imaging method is shown for a six-inch silicon solar cell (only half of the cell is shown). Two PL images of the sample with partial illumination are obtained with the DMD-based setup (Figure PP3.3.17(b) and (c)). The division of these two partially illuminated PL images yields a qualitative series resistance image of the sample (Figure PP3.3.17(e)). As can be seen, the high series resistance regions due to broken fingers are clearly shown. The resulting image also shows good agreement to the quantitative series resistance image obtained using a method by Kampwerth et al. (Kampwerth et al. 2008) (Figure PP3.3.17(f)). However, the method by Kampwerth et al. is based on a PL image with current extraction, which requires electrical contact. Another series resistance image obtained by the method of Kasemann et al. (Kasemann et al. 2012) is also shown (Figure PP3.3.17(d)). The method of Kasemann et al. is also based on non-uniform illumination

PL imaging. However, the non-uniform illumination is achieved by putting an opaque buffer on the sample. The physical contact adds the potential risk of damaging the samples. Furthermore, the PL beneath the buffer is not available. The DMD-based PL imaging setup in this project allows the PL from the non-illuminated area also to be captured by the camera and this information helps to increase the quality of the resulting PL image. As can be seen, the local low lifetime region marked by a red circle in Figure PP3.3.17(a) is still observable in the series resistance image obtained by the method of Kasemann et al., whereas the series resistance image obtained by the team's DMD-based PL imaging setup does not show this impact of local non-uniformity of lifetime.

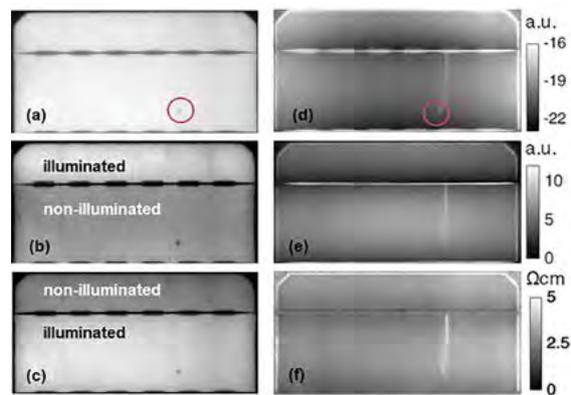


Figure PP3.3.17: Contactless series resistance image of a silicon solar cell using non-uniform illumination PL imaging. (a) Conventional PL image with uniform illumination; (b) and (c) PL images of the sample with partial illumination; (d) contactless series resistance image using a method by Kasemann et al.; (e) contactless series resistance image using non-uniform illumination PL imaging method; and (f) series resistance image obtained with current extraction using the method of Kampwerth et al.

The non-uniform illumination can also be used to stimulate lateral carrier flow in silicon wafers. For a diffused silicon wafer, the lateral carrier flow is impacted by the emitter sheet resistance ρ_{she} . The developed DMD-based PL imaging setup has thus also been used to extract emitter sheet resistance of diffused silicon wafers. The non-uniform illumination pattern used is simply a uniform large-area illumination with a dark circular mask in the centre. A series of samples with various emitter sheet resistances were measured. The rear surfaces of the samples were full-area metallised to remove the impact of bulk conductivity on the measurement. A theoretical correlation between the maximum to minimal PL ratio and the product of ρ_{she} and photo-generated current was previously established by Juhl (Juhl 2013) via simulation. The measurement results by the team's DMD-based setup are compared to the theoretical correlation and good agreement is achieved (Figure PP3.3.18).

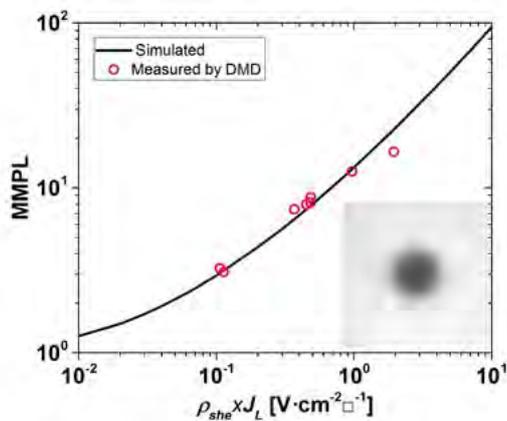


Figure PP3.3.18: Extraction of emitter sheet resistance ρ_{she} from PL imaging with non-uniform illumination. The solid line indicates the theoretical correlation between maximum to minimal PL ratio (MMPL) and the product of ρ_{she} and photo-generated current J_L obtained by simulation. The circles indicate the experimental results.

For non-diffused silicon wafers, the lateral carrier flow is primarily dominated by diffusion. Therefore, it is possible to extract the diffusion length of a non-diffused silicon wafer with non-uniform illumination. The team has demonstrated a proof-of-concept measurement of diffusion length using non-uniform illumination PL imaging for a high lifetime silicon wafer. Good agreement between the obtained result and the calculated diffusion length using charge carrier lifetime measured by photoconductive decay was obtained.

1. PL imaging at uniform excess carrier concentration

A different application of non-uniform illumination in PL imaging is to mitigate the lateral carrier flow due to the spatial non-uniform lifetime of the sample. The lateral carrier flow leads to inaccuracies in PL imaging-based quantitative analysis. For example, in carrier lifetime imaging, when lateral carrier flow is present, the lifetime is not simply the ratio of excess carrier concentration and generation rate, an additional term of the lateral carrier flow needs to be considered. This lateral carrier flow is difficult to quantify in practice. By using non-uniform illumination, they can minimise the lateral carrier flow in the sample by illuminating the low lifetime region with higher light intensity and illuminating the high lifetime region with lower light intensity. The modulation frequency of the DMD chip is not suitable for this application. Therefore, the team uses an LCD chip to achieve non-uniform illumination.

A proof-of-concept measurement is made on a silicon sample with non-uniform lifetime. To achieve PL image at uniform excess carrier concentration (thus no lateral carrier flow), an adaptive iteration procedure is required. The iteration starts from the PL image with uniform illumination (conventional PL imaging). From the resulted PL image, a non-uniform illumination image can be calculated and applied to the next iteration. The iteration continues until a uniform PL image is obtained. This procedure is shown in Figure PP3.3.19a. As can be seen, a reasonably uniform PL image is obtained in the last iteration. The lifetime image of the sample can be obtained from the non-uniform illumination image in the last iteration. The lifetime profiles

of the sample obtained from this adaptive PL imaging procedure and from conventional PL images are compared in Figure PP3.3.19(b). As can be seen, the lifetime profile obtained from the adaptive PL imaging shows a much sharper transition. This is expected as there is no smearing effect due to the lateral carrier flow. Moreover, the resulted lifetime image is under the same injection level across the whole sample.

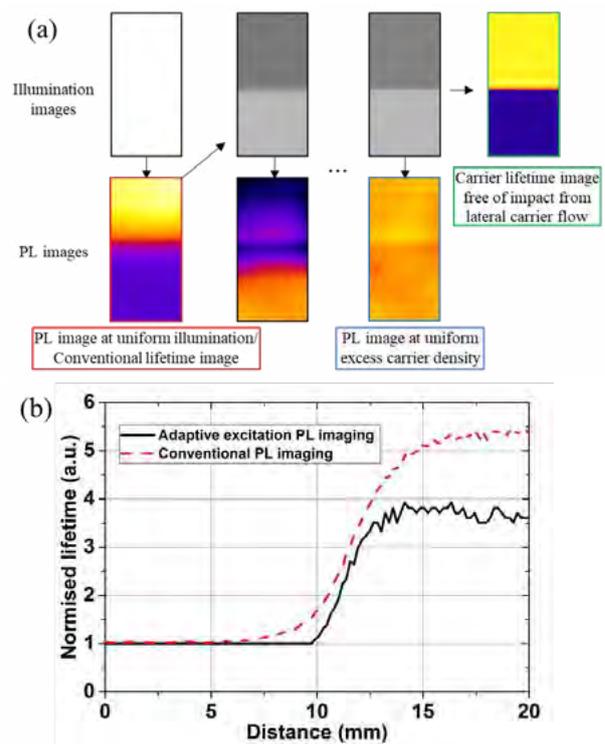


Figure PP3.3.19: Demonstration of PL imaging at uniform excess carrier concentration on a non-uniform silicon wafer. (a) The adaptive iteration procedure; (b) the resulted normalised lifetime profile from the PL imaging at uniform excess carrier and the conventional PL imaging.

Highlights

- PL imaging setups with the capability of arbitrary spatially non-uniform illumination is developed.
- Contactless series resistance imaging of silicon solar cells, emitter sheet resistance of diffused silicon wafers, and diffusion length of non-diffused silicon wafers were achieved using PL imaging with non-uniform illumination.
- PL image at uniform excess carrier concentration is achieved for a silicon wafer with spatially non-uniform quality.

Future Work

The current setup of PL imaging with non-uniform illumination will be updated featuring higher illumination intensity (above one-sun) and better mapping between the PL image and illumination image. Meanwhile, a few new applications of the developed methods will be made including: (1) the series resistance components in silicon

heterojunction solar cells; (2) advanced parameterisation for solar cells; and (3) improved recombination analysis of ring defects in Czochralski-grown silicon.

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PP4

MANUFACTURING ISSUES

OVERVIEW

PP4, entitled “Manufacturing Issues” concentrates on costs, both financial (PP4.1) and environmental (PP4.2). The methods in each have a great deal of similarity since both rely heavily on inventories of estimates and measurements of inputs and outputs of manufacturing processes.

Work under PP4.1 has produced a methodology for assessing manufacturing costs for the different technologies under investigation in the ACAP program. This is a resource for assessing the cost of different processes with a view to informing research efforts on the key cost drivers and opportunities, and to understand how the technology fits in roadmaps for photovoltaics. The methods are tolerant of uncertainty in the data and, so, permit rapid assessment of emerging technologies. In 2020, the cost methodology has been applied to different PV technologies and end-of-life processes, notably: (i) first known cost studies around CZTS technology; (ii) new developments in ITO organic cells and their potential cost reduction; (iii) comparison among virgin, reused and recycled silicon wafers; (iv) solar energy and storage in the Association of Southeast Asian Nations and energy costing forecasts; and (v) costing and ideal locations for off-river pumped hydro technology.

Similarly, in PP4.2, the initial focus was on using the life cycle assessment (LCA) methodology to assess the life cycle environmental costs, to inform research directions and policymakers by documenting the costs for a set of key environmental impacts of different ways of manufacturing cells and modules. Interest in extending the boundaries of these studies has now led to an inclusion of end-of-life (EoL), to “close the loop”. EoL products have traditionally been excluded from manufacturing costs estimates but some jurisdictions globally are already requiring “stewardship” or other responsibility measures for certain types of products, including photovoltaic modules, so it is becoming necessary to incorporate it into costs models. In this context, LCA studies have been extended to include EoL and to apply LCA to alternative EoL pathways, along with exploring new technology pathways for recycling. Three outputs relating to LCA and EoL issues were produced in 2020: (i) the development of an EoL recycling process and the use of LCA to compare it to the baseline option of landfill disposal; (ii) the environmental impact comparison of two proposed recycling processes for EoL PV through LCA; and (iii) the analysis of the amount of the EoL waste arising from PV according to the upper bound installation of PV and its relative size in comparison to similar waste already being generated.

PP4.1 FINANCIAL COST

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Aims

ACAP's Program Package 4 (PP4) aims to assess the financial cost related to the manufacturing and life management of different photovoltaic technologies. The financial analysis may involve the proposal of models, the actual modelling of cost, competitiveness assessment, financial decision-making tools, etc. This assists in guiding the direction of future research and industry developments, as well as quantifies the financial advantages a given process (or technology) has over another. Additionally, it aims to highlight the main processes that should be addressed to reduce cost, as well as to point out the specific actions that can be taken to enable the implementation of a new endeavour.

Progress

A key outcome of the efforts under PP4.1 is to provide a resource for assessing the cost of different processes with a view to informing research efforts on the key cost drivers and opportunities and to understand how the technology fits on the costs and marketing roadmaps for photovoltaics.

Over 2020, the cost methodology previously developed through ACAP and presented in previous reports has been applied to different PV technologies and end-of-life processes, notably: (i) first known cost

studies around CZTS technology; (ii) new developments in ITO organic cells and their potential cost reduction; (iii) comparison among virgin, reused and recycled silicon wafers; (iv) solar energy and storage in the Association of Southeast Asian Nations and energy costing forecasts; and (v) costing and ideal locations for off-river pumped hydro technology.

A. CZTS Costing analysis (UNSW)

There have not been any detailed cost studies of the CZTS thin-film technology, which is very similar to CIGS, but with the potential for lower cost. In this work, UNSW adapted a CIGS cost study to investigate the possible cost range for CZTS on glass, steel and plastic (Figure PP4.1.1).

The study shows there is a potential to lower the cost using the same cell structure as the CIGS, but that even cheaper costs could be achieved by using stainless steel substrates (Figure PP4.1.2). The study also investigated possible markets for these products and shows a levelised cost of energy analysis (Figure PP4.1.3). Results were published in the journal *Sustainable Energy & Fuels* (Wang 2021).

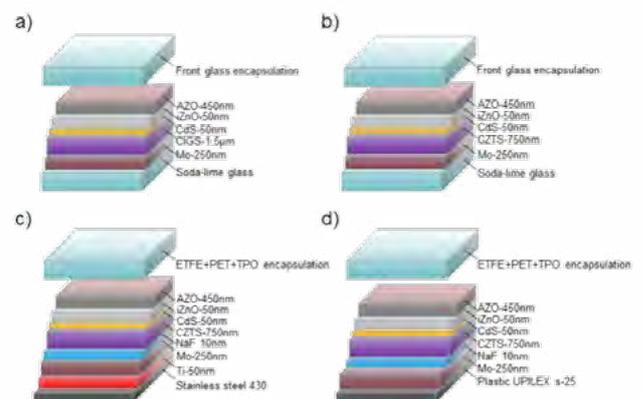


Figure PP4.1.1: Possible cell configurations.

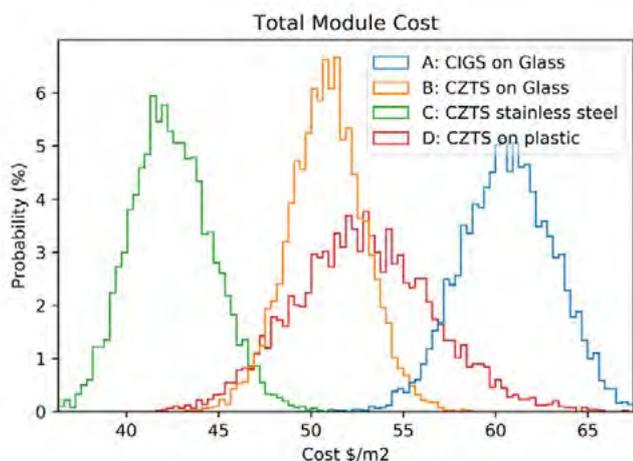


Figure PP4.1.2: Cost model of the possible cell configurations.

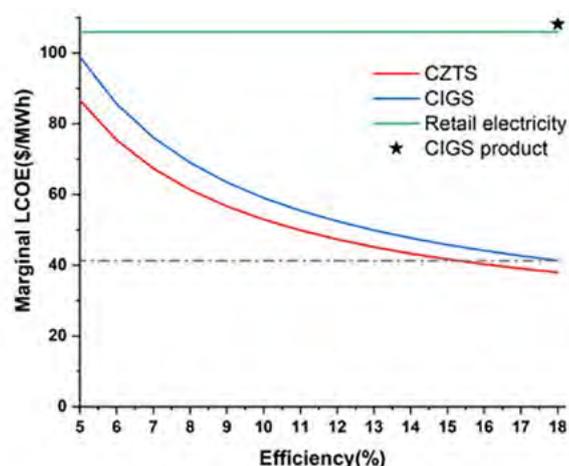


Figure PP4.1.3: Levelised cost of energy analysis.

B. ITO-free printed organic solar cells costing analysis (CSIRO, UNSW)

The CSIRO have been developing the organic and perovskite PV technology using potentially low-cost roll-to-roll (R2R) processing. Building on previous work analysing R2R perovskite modules, CSIRO and UNSW have analysed recent developments in R2R OPV modules. The first is a low-cost ITO-free plastic substrate, which is aimed at reducing cost without sacrificing performance. The second is a higher efficiency photo-active layer, which uses more expensive materials, but is potentially cheaper overall when considering the cost per watt metric.

The cost results for four alternatives are shown in Figure PP4.1.4. This shows the cost reduction of the ITO-free substrate (Seq B) compared to the standard ITO substrate (Seq A). Also shown is the cost advantage (in \$/W) of the two higher efficiency photo-active layers (Seq C and Seq D). The arrangement of these layers and the estimated cost of materials for each layer are shown for the overall lowest cost Seq D in Figure PP4.1.5.

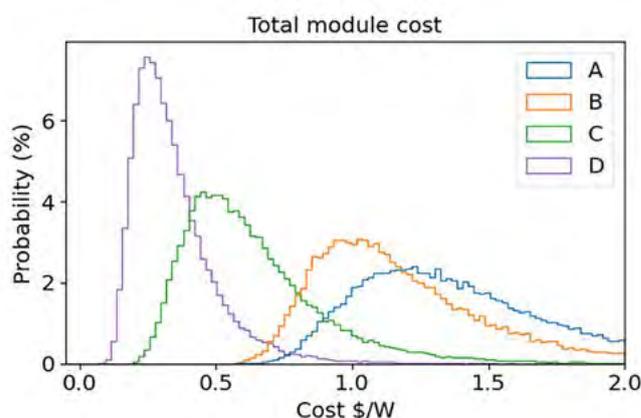


Figure PP4.1.4: Cost model. Seq A is standard OPV with ITO-based substrate. Seq B is standard OPV with lower cost ITO-free substrate. Seq C and Seq D both use the lower cost ITO-free substrate but each also includes a higher efficiency photo-active layer.

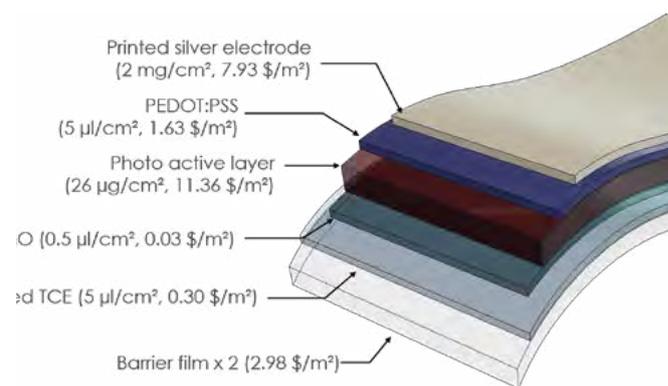


Figure PP4.1.5: Layers of the ITO-free printed organic solar cells (Seq D), showing the median estimated cost of materials for each layer.

C. Reuse of silicon wafers – financial analysis (UNSW)

Silicon can be recovered from PV modules in different forms: metallurgical grade silicon, solar grade silicon, intact solar wafer. Each of these requires different recycling processes and has a different value. This work explores the financial side of silicon recovery and maps the trade-off between cost and the expected drop in (absolute) efficiency.

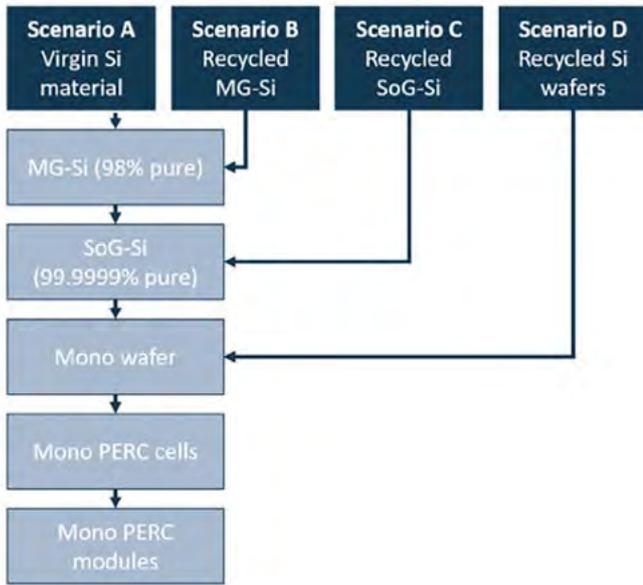


Figure PP4.1.6: Different silicon recovery forms and scenarios.

Results show how recovering intact wafers has the greatest economic potential, as it can be justified even with efficiency drops of 4% (absolute) in comparison to wafers created using virgin materials. The mapping of the different forms of recovered silicon relating to cost and efficiency difference is shown in Figure PP4.1.6. Results were published in early view format in the journal Progress in Photovoltaics (Deng et al. 2020).

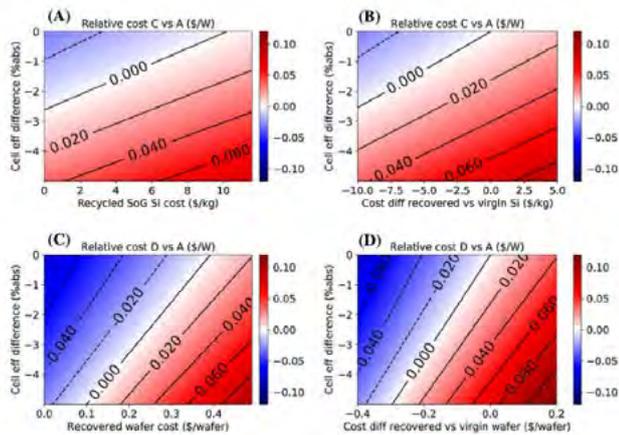


Figure PP4.1.7: Pairwise analyses of (A,B) scenario C versus scenario A and (C,D) scenario D versus Scenario A.

D. Solar energy and storage in ASEAN (ANU)

Southeast Asia has one of the highest growth rates of electricity consumption in the world, driven by the economic and population growth, urbanisation and industrialisation. Rapid increases in electricity consumption raise significant concerns about energy security, affordability and environmental sustainability. In this study, low-emission and sustainable electricity scenarios in Southeast Asia are modelled primarily on solar PV and off-river pumped hydro storage. A high-voltage direct-current super grid across Southeast Asia is analysed, with further extensions to north Australia, southwest China and northeast India.



Figure PP4.1.8: The Asia-Pacific Super Grid: a high-voltage direct-current backbone across Southeast Asia.

The modelling results show that solar PV will be the major source of electricity in Southeast Asia's renewable energy futures. A US\$1–5 trillion PV market is expected in Southeast Asia by 2050. Solar PV plus off-river pumped hydro storage can effectively support the future electricity growth, avoiding the catastrophic damage to the environment due to the burning of fossil fuels. The levelised costs of electricity, including the costs of energy generation, storage and transmission, range from US\$55–115 per megawatt-hour (\$/MWh) based on 2020 costs, compared with: (i) Australian electricity export \$100/MWh; and (ii) Australian hydrogen export \$200/MWh.

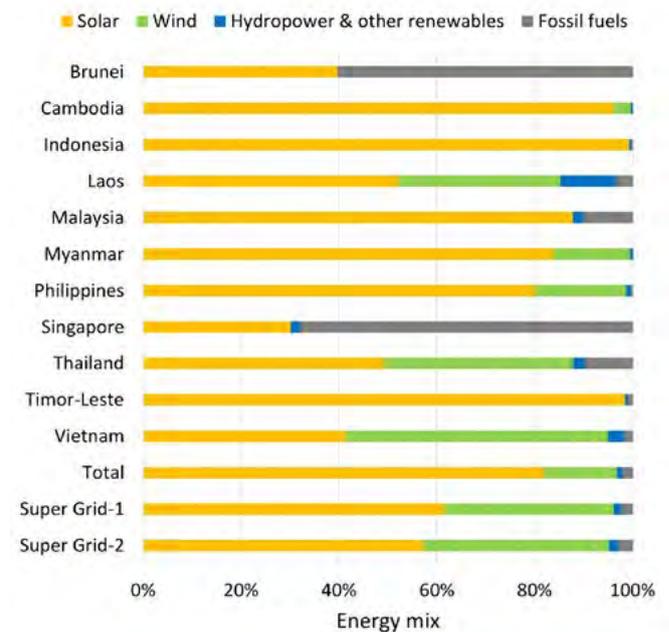


Figure PP4.1.9: Electricity generation mix in the high electricity consumption scenarios.

E. Off-river pumped hydro costing (ANU)

Pumped hydro energy storage is the largest source of energy storage, with more than 95% and 99% of global installed power and energy capacity. It is a technically mature technology that demonstrates low storage costs, however, the choice of suitable sites is critical to delivering the lowest cost. Difficulties in identifying suitable sites has led to assumptions that the role for pumped hydro in future electricity systems is small.

GIS analysis has been used to identify virtual reservoirs as can be seen in Figure PP4.1.10. This enables key cost parameters to be identified comprising head, tunnel length and the dam wall volumes (Figure PP4.1.11). These enable the cost of a particular size scheme to be identified. Sites that meet cost criteria are retained in the database and ranked with the best class A sites approximately double the cost of the lowest class E sites. Importantly, the best sites are very well suited to providing low-cost storage for firming photovoltaics. Class A sites with 300 cycles per year (approximately daily cycling) have a levelised cost of storage of \$40/MWh. Results were published in *Joule* journal (Stocks et al. 2020).



Figure PP4.1.10: GIS image of identified virtual reservoirs.

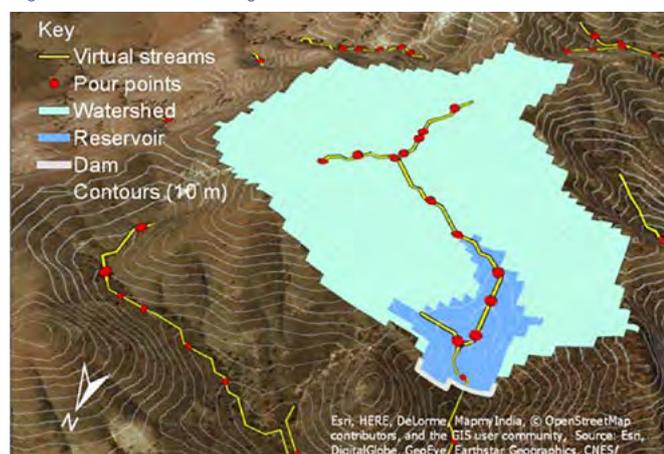


Figure PP4.1.11: GIS image identifying key parameters of pumped hydro installation.

Summary

Cost analysis continues to be an important task within ACAP, and the scope of technologies being considered is increasing over time as ACAP researchers value the insights into the commercial viability of these important renewable energy developments.

Technologies analysed include the manufacturing cost of specific PV technologies (CZTS, OPV), the economics of recycling silicon and methods of addressing PV deployment issues, such as pumped hydro storage and high-voltage transmission lines.

Highlights

- First CZTS cost evaluation and projection of possible cost reduction.
- Collaboration with domestic and international institutions.
- Detailed cost comparison among using virgin, reused or recycled wafers in PV manufacturing.
- Cost evaluation of off-river pumped hydro technology.

Future Work

- Analysis of additional PV technologies, such as perovskite, III-V, silicon-based and CIGS.
- Cost analysis of module recycling alternatives such as electrostatic sorting.
- Cost analysis and projections related to electricity consumption and supply.

References

Deng, R., Chang, N., Lunardi, M. M., Dias, P., Bilbao, J., Ji, J. & Chong, C. M. 2020 Remanufacturing end-of-life silicon photovoltaics: Feasibility and viability analysis. *Prog. Photovolt. Res. Appl.* <https://doi.org/10.1002/pip.3376>.

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WANG, A., CHANG, N.L., SUN, K., XUE, C., EGAN, R.J., LI, J., YAN, C., HUANG, J., RONG, H., RAMSDEN, C. and HAO, X. 2021 Analysis of manufacturing cost and market niches for Cu₂ZnSnS₄ (CZTS) solar cells. *Sustainable Energy & Fuels*. <https://doi.org/10.1039/D0SE01734E>

PP4.2 ENVIRONMENTAL COST

Lead Partners

UNSW, ANU

UNSW Team

Dr Nathan Chang, Dr Pablo Dias, Dr Marina Lunardi, Dr Jose Bilbao, Dr Richard Corkish, A/Prof. Renate Egan, Prof. Martin Green

ANU Team

Prof. Andrew Blakers

Academic Partners

Universidade Federal do Rio Grande do Sul (UFRGS):
Prof. Hugo Marcelo Veit

Students

Rong Deng, Lucas Schmidt, Gustavo Spier

Aims

The PP4.2 program aims to address environmental manufacturing costs and end-of-life issues. It mainly uses life cycle assessment (LCA) but is also concerned with end-of-life management analysis, development of recycling processes and creation of decision-making tools concerning environmental impacts. This allows the photovoltaic technology to grow with minimum environmental impact, which assists in achieving its goal of being a reliable and renewable source of energy that is eco-friendly and less harmful to the environment than competing technologies.

Progress

The PP4.2 outputs should provide guidance around environmental impact of PV technologies. An important outcome is arriving at conclusions in respect to competing manufacturing and end-of-life processes so as to inform the ideal option in terms of environmental impact.

The year of 2020 has allowed the PP4.2 teams to overdeliver in accordance with ACAP's original schedule. Three outputs relating to life cycle assessment and end-of-life issues were produced. Specifically: (i) the development of an end-of-life recycling process and the use of life cycle assessment to compare it to the (widely chosen) baseline option of landfill disposal; (ii) the environmental impact comparison of two proposed recycling processes for end-of-life PV through life cycle assessment; and (iii) the analysis of the amount of the end-of-life waste arising from PV according to the upper bound installation of PV and its relative size in comparison to similar waste already being generated.

A. PV toluene recycling (UNSW, UFRGS – Brazil)

In the interest of promoting PV recycling, a method using organic solvents has been proposed and carried forward experimentally. The process included frame and junction box removal, delamination using toluene immersion, thermal decomposition and metal extraction through leaching. The research also involved evaluating the economic and environmental costs and impacts associated with such recycling processes.

The results showed that the proposed route was capable of separating and recovering the main components of silicon PV, including the intact front glass, aluminium frame, the copper tabbing, junction box, silver and metallurgical-grade silicon. Life cycle costing showed that the process done at large scale would not result in a net positive outcome, but environmental analysis showed that such a process done at large scale has a positive impact due to the recovery of materials. Results were published in the Resources, Conservation & Recycling journal and dubbed "Comprehensive recycling of silicon photovoltaic modules incorporating organic solvent delamination – technical, environmental and economic analyses" (Dias et al. 2021).

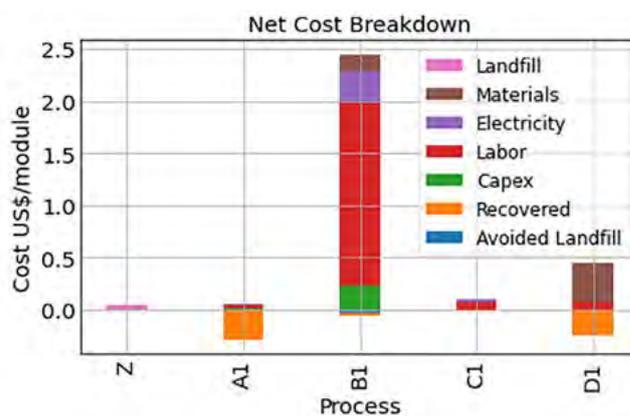


Figure PP4.2.1: Net cost breakdown of the large-scale processing using the proposed toluene recycling route.

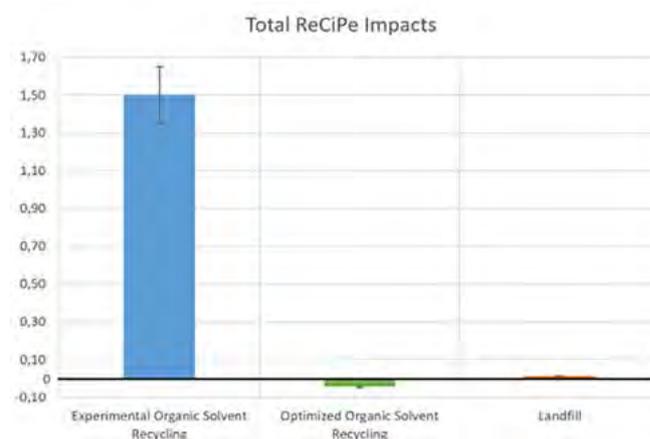


Figure PP4.2.2: Summary of environmental impacts for proposed toluene recycling route (at laboratory and industry scale) and for PV module landfilling.

B. Comparative LCA of two experimental PV recycling processes (UNSW, UFRGS – Brazil)

The rapid growth of the solar photovoltaic (PV) industry offers a solution to the challenging issue produced by emissions from fossil fuel combustion. But, when the PV modules reach their end of life, it generates a considerable amount of waste. This report presents a novel environmental comparison between thermal and chemical (toluene and $\text{AgNO}_3 + \text{HNO}_3$) experimental silicon-based PV module recycling approaches.

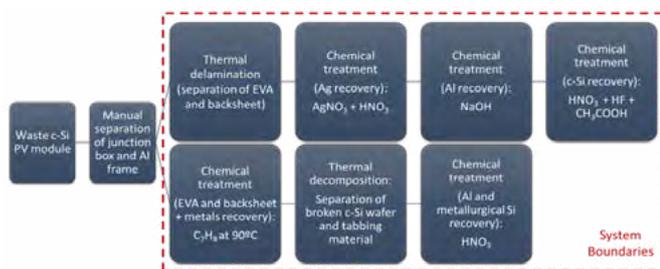


Figure PP4.2.3: Diagram showing the two recycling routes that were compared in this study.

The results show that the use of electricity causes the main ecological impacts for all categories analysed, but also that attention must be paid to the use of chemicals. Lower impacts might be achieved by using renewable energies as input for all processes. Further improvement in the ecological performance could be achieved by replacing chemicals with less hazardous substances, increasing treatment capacities, and improving the efficiency of the processes.

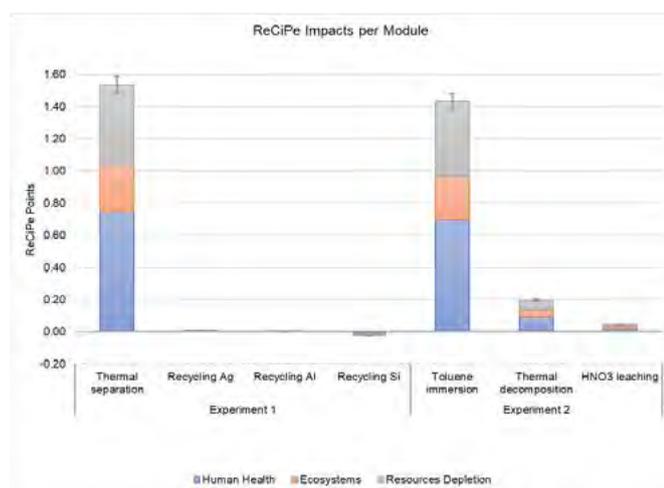


Figure PP4.2.4: Summary of environmental impacts for both recycling routes, distinguishing human health, ecosystems and resources depletion impacts.

C. Upper bound analysis of the potential end-of-life problem (ANU)

This analysis looks at the Australian end-of-life PV problem from the perspective of a best-case installation scenario, that is, one in which complete renewable electrification is achieved and 500 TWh (two-thirds of total energy generation) is from solar energy. The study investigates the amount of additional waste the PV industry would generate and finds it would be about 2 m² per person (20 kg).

At this upper bound limit (best-case renewable scenario, which would incur the highest waste generation), the addition of waste to the existing Australian waste generation scenario would be minimal (Table PP4.2.1), since the use of known techniques such as thermo decomposition can remove the plastic materials and recover glass and the aluminium frames. In the case of non-recovery of silicon and

glass, both are non-toxic. Therefore, the addition of waste arising from PV would not be an intolerable problem, even at the upper bound limit. Detailed calculations were published on the RenewEconomy website (Blakers 2020).

Table PP4.2.1: Australian waste and the relative impact of PV waste on it.

Material	Existing (Mega tonnes)	Extra from PV panels
Glass	1.1	0.4
Metals	5.5	0.09
Silicon	small	0.01
Masonry	17	0

Summary

The PP4.2 program has started to deliver its first significant work concerning environmental costs of PV manufacturing and usage. The ACAP schedule required the output of one work within the program and this year the team, through inter-institutional collaboration, has been able to deliver three. These studies are paramount to evaluate and minimise the environmental impact of photovoltaic technologies so as to ensure they are strongly aligned with their primary goal of being an eco-friendly means of obtaining clean energy.

The studies presented show that the amount of waste arising from end-of-life photovoltaic panels is not significant when compared to the waste generated by other industries, even considering an upper bound scenario of high PV installation in the future. Moreover, they show the development of possible recycling routes for end-of-life PVs and the impact these routes have on the environment, allowing to choose the greener option and to focus attention on the phases that are responsible for the main impacts along the recycling process.

Highlights

- Development of a PV recycling route using organic solvents.
- Evaluation of the developed method in terms of environmental impact.
- Life cycle assessment evaluating different recycling processes.
- Upper bound analysis of the PV waste generation.

Future Work

- Development of additional recycling processes.
- Evaluation of material trend and recycling possibilities.
- Environmental assessment of new technologies being developed in PV industry.

References

BLAKERS, A. 2020. Solar PV panel waste will not become a significant problem. *RenewEconomy*. <https://reneweconomy.com.au/solar-pv-panel-waste-will-not-become-a-significant-problem-98181/> (accessed 1.4.21).

DIAS, P., SCHMIDT, L., MONTEIRO LUNARDI, M., CHANG, N. L., SPIER, G., CORKISH, R. & VEIT, H. 2021. Comprehensive recycling of silicon photovoltaic modules incorporating organic solvent delamination – technical, environmental and economic analyses. *Resour. Conserv. Recycl.* 165, 105241. <https://doi.org/10.1016/j.resconrec.2020.105241>

PP5

EDUCATION, TRAINING AND OUTREACH

Nodes Involved

All nodes involved

Industry Partners

Australian Photovoltaic Institute (APVI)

Funding Support

All nodes, ACAP

Overview

Within the PP5 Education, Training and Outreach package, ACAP has specific targets for high-quality publications and for the number of researchers in different categories who benefit from the infrastructural support it provides, as well as for the number and length of researcher exchanges. A significant number of outreach events are also targeted for each year. As well as major events such as those reported in the PP5 section of this annual report, other outreach activities in 2020 included public lectures on material relevant to ACAP's activities, newspaper and magazine articles, and visits, information papers and presentations for policy developers and their advisors.

Again in 2020, there was very strong international interest in the articles by ACAP researchers in leading journals. A remarkably high number of these were "Hot Papers" and "Highly Cited Papers", as identified by Clarivate Analytics Web of Science. See Chapter 2 of this report for further information. In general, interest in and citations of ACAP's work continues to grow.

The ACAP nodes continue to educate future investors, industry partners, practitioners, researchers and educators to support the necessary rapid expansion of the national and global photovoltaics (PV) industry and to develop more effective educational tools. This was advanced considerably in 2020 through the uptake of seventeen ACAP Fellowships and additional Collaboration Grants.

Aim

The work described here is about promoting knowledge of the opportunities and successes of Australian photovoltaics research, adding to the global body of knowledge, engaging the next generation of researchers and sharing knowledge with the broader community including industry, government and the general public.

Progress

ACAP holds an annual research conference near the end of each year in order to keep ARENA and its National Steering Committee informed, and to exchange research results, enhance collaboration and reinforce face-to-face contacts between students and staff from the different nodes. The program typically includes an oral summary of progress and plans for each Program Package as well as oral and poster presentations of technical progress from staff and student researchers, and a situation summary presentation by ARENA.

The 8th ACAP annual conference in 2020 ran over two days, with Day One as an online stream on the final day of the 7th Asia-Pacific Solar Research Conference (APSRC), organised by the Australian PV Institute (APVI).

Dr Richard Corkish (ACAP/UNSW) chaired the online Keynote session with the plenary speaker, Professor Paul Bern (UQ), presenting his topic, "2D or not 2D – that is the perovskite question".

This was followed by a joint ACAP/APSRC poster session, which was then followed by a series of speakers from all the ACAP nodes and one concurrent workshop.

On Day Two the director's welcome, presented by Professor Martin Green was followed by ACAP PP1–PP5 summaries and a CZTS update by Associate Professor Xiaojing Hao (ACAP/UNSW).

The 14th ACAP National Steering Committee meeting and the 26th Management Committee meeting were held online on the afternoon of the second day of the conference.

The APVI's APSRC, mentioned above, aims to provide a forum for development and discussion of content specific to Australia and its region, allow an opportunity to foster collaboration between institutes, and promote engagement between industry and academics. ACAP partners with the APVI to support the development of the conference program through financial sponsorship, participation in its organisation and through scheduling ACAP presentations as a stream of the conference.

The 7th APSRC was held from 30 November to 2 December 2020 online with Day One having optional physical attendance at two venues: the Melbourne Bayview Eden, Melbourne or the Sydney Boulevard Hotel, Sydney.

Representatives from the UNSW and ACAP nodes served on the organising committee. Staff and students from all the nodes participated in academic review committees and contributed papers and posters to the conference.

The conference drew 254 participants from academia, government and industry, and ran parallel streams including: Characterisation of PV Devices; Building Integrated PV & Solar Thermal Systems; Concentrating Solar Thermal (CST) Receivers; Distribution Networks and EVs; Passivation Contacts and Defects; Building Solar Heating and Cooling and Data Analysis; CST – Materials and Heat Exchangers; Solar Farms – Practical Solutions; PV – Module Testing and Performance; and, CST – Optics, Storage and System Analysis.

The list of invited plenary speakers included Sarah Barker (MinterEllison) with “Climate change through a finance and liability lens: how developments in the EU may shape Australian markets”; Professor Andrew Blakers (ANU Node Leader) with “Australia, the global renewable energy pathfinder”; Dr Dietmar Toubier (ASTRI-CSIRO) with “Advancements in Concentrated Solar Thermal”; Professor Paul Cooper (SBRC-UoW) with “Enhanced solar energy exploitation in buildings with advanced HVAC and storage systems”; Associate Professor Xiaojing Hao (ACAP/UNSW) with “Recent development in high bandgap chalcogenide thin-film PV materials and devices”; and Dr Philipp Furler (Synhelion) with “Solar thermal pathways for sustainable fuels”.

Professional bodies

In addition to involvement in the APSRC, ACAP has continuing strong engagement with the APVI, one of the more effective vehicles for Australian policy development through its focus on data, analysis and collaborative research. ACAP was a founding “Large Organisation” member of the APVI and ACAP partners were active members of APVI throughout 2020. ACAP collaborators contributed to and participated in Australian representation on the Executive Committee for the International Energy Agency, Photovoltaic Power Systems.



Figure PP5.1: UNSW first-year undergraduates competing in the “Solar Cable Car” project of ENGG1000.

Education and training

All the nodes are involved in undergraduate and/or postgraduate education as capacity building for the next generation of photovoltaics researchers. Of particular note in 2020, ACAP nodes were involved as follows:

UNSW reviewed course learning outcomes and assessments of all relevant courses and the (Undergraduate) Renewable Energy Engineering program and updated them where necessary.

The revised structure:

- Accreditation of Master of Renewable Energy degree. Provisional accreditation by Engineers Australia (June 2020) effective from T1 2020 uptake. This is a 96 UOC, 2-year full-time equivalent degree.
- Bachelor of Engineering/Bachelor of Engineering Science dual degrees. Double degrees in PV & Solar and Electrical Engineering and Renewable Energy and Electrical Engineering are available. They are 240 UOC, 5-year full-time degrees.
- Graduate certificates in Engineering Science: PV and Solar Engineering and Renewable Engineering established.

There have been additions or revisions in the teaching structure for the following:

- Core subjects: SOLA1070 Sustainable Energy; ELEC1111 Electrical and Telecommunications Engineering; and SOLA4012 Photovoltaic Systems Design.
- New course ELEC2911 Power Engineering for Renewable Energy (developed in collaboration with UNSW School of Electrical Engineering and Telecommunications) as a core subject.
- A small but strong set of core courses – offers flexibility in the set of core/elective courses (8 courses).
- Three “Strands” – humanitarian engineering, low energy systems and RE Systems.

These revisions are effective in 2021 with a transitional arrangement for current students.

ACAP is a strong driver in education. Overall, to date, ACAP has supported at least 141 early career researchers, at least 234 Honours and 125 Masters students, and over 326 PhD students and graduated more than 182 PhD graduates. See Chapter 8 for additional theses added in 2020.

ACAP Postdoctoral Fellowships

Through 2020, seventeen ARENA-funded ACAP Postdoctoral Fellowships were taken up by outstanding young researchers in cutting-edge projects across the nodes.

The recipients (host node) and projects are:

- Hieu Nguyen (ANU) “Poly-Si passivating contacts: structures, optoelectronic properties, and defect engineering”
- Narendra Pai Kalapparambath Rajendra (Monash) “High performing lead-free earth abundant solar cells via physical vapour deposition”
- Yiliang Wu (ANU) “Stable and scalable perovskite films using industrially relevant processes”
- The Duong (ANU) “Towards 30% efficiency for four-terminal perovskite-silicon tandem solar cells”
- Daniel Chen (UNSW) “Investigating the Impact of Hydrogen-induced Defects on the Reliability and Stability of Emerging Solar Cell Technologies”
- Nadja Giesbrecht (Monash) “Applications of Stable Lead-Free Absorber Layers in Photovoltaics”
- Sagar Masoomi-Godarzi (UoM) “2 excitons for the price of one photon: Towards better understanding of singlet fission”
- Aaron Raynor (UQ) “Non-fullerene acceptor-based tandem perovskite: OPV devices”
- Moonyong Kim (UNSW) “Development of accelerated LID testing methods with in-situ PL characterization and numerical model to improve the understanding of degradation mechanisms in silicon solar cells”

- Yan Zhu (UNSW) “Photoluminescence Imaging with Spatially Non-Uniform Illumination for the Characterization of Silicon Wafers and Solar Cells”
- Navid Haghdadi (UNSW) “Characterising the performance, contribution and impact of distributed PV systems in Australia’s electricity grids”
- Michelle Vaqueiro Contreras (UNSW) “Low-temperature graphene oxide film properties and applications for advanced and high-performance photovoltaics”
- Teng Choon Kho (ANU) “Pathways to achieve a solar cell efficiency above 26%”
- Weijian Chen (UNSW) “Development of 3-dimensional optical characterization techniques and recombination analysis routines for understanding carrier dynamics of emerging photovoltaic materials and devices”
- Sudhaker Reddy Saripally (Monash) “Polysilicon Tunnel Junctions for Si based Tandem Solar Cells”
- Calvin Lee (UoM) “Beyond the theoretical limit: silicon photovoltaic efficiencies through singlet fission augmentation”
- Jianjun Li (UNSW) “In-situ back surface field enhanced high efficiency $\text{Cu}_2\text{ZnSn}(\text{S},\text{Se})_4$ solar cells with surface passivation”.

Researcher exchanges

An additional educational and training aspect supported by ACAP is researcher exchange. Exchange activity is supported by core ACAP activities as well as the Collaboration Grants reported in Chapter 6.

Researcher exchanges provide a broader experience to ACAP researchers and strengthen collaborations, through secondments to international laboratories. COVID-19 restricted international travel worldwide during 2020; however, Dr Bonna Newman (Senior Scientist with TNO Energy Transition – PP4), Professor Hugo Marcelo Veit (Mestrado & Doutorado Acadêmico – PP4), Dr Gianluca Coletti (Senior Scientist with TNO Energy Transition – PP1) and Professor Albert Polman (Program director LMPV program at AMOLF – PP2) were able to exchange to UNSW. Additionally, Dr David McMeekin (Monash) visited Professor Henry Snaith’s group at the University of Oxford.



Figure PP5.2: University of Oxford Physics Wolfson Cleanroom – photo taken during Dr David McMeekin’s international collaboration visit with Professor Snaith’s group in Oxford, designing and fabricating novel organic-inorganic hybrid perovskite absorbers for multi-junction solar cell application.

Outreach and external engagement



Figure PP5.3: The CSIRO’s Flexible Electronics Laboratory showroom tours and other ACAP affiliated areas were affected by COVID-19 lockdowns.

ACAP was again very active in the areas of outreach and external engagement in 2020 with most events being online though many events were live. The CSIRO’s Flexible Electronics Laboratory showroom tours were affected by COVID-19 lockdowns. However, before the lockdown, there were visits from the Defence Science Institute, Department of Industry, Innovation and Science as well as the local companies, Smart Option Solar, Melbourne Convention and Exhibition Centre and KISKO. All ACAP node facilities were affected by the shutdown to varying degrees.

ACAP researchers were involved in a range of technical, industry and public presentations throughout 2020. ACAP members made many presentations at leading photovoltaics devices conferences around the world (see Chapter 8) with some of the highlights in the conference, industry and public space being:

- 47th IEEE PVSC – Tutorial 1 “Fundamentals of Photovoltaics” – N.J. Ekins-Daukes (UNSW)
<https://ieeepvsc.org/PVSC47/program-tutorials.php>
- 47th IEEE PVSC – Tutorial 3 “Silicon PV Technology: from Cradle to Grave” – Udo Romer (UNSW), Anastasia Hertanti Soeriyadi (UNSW)
<https://ieeepvsc.org/PVSC47/program-tutorials.php>
- 47th IEEE PVSC – Tutorial 9 “100% Renewable Future” – Andrew Blakers (ANU)
<https://ieeepvsc.org/PVSC47/program-tutorials.php>
- CRC 1073 Summer School on Energy Conversion – September 2020 “Advanced Photovoltaic Solar Power Conversion – Concepts, Present Status and Future Prospects” – N.J. Ekins-Daukes (UNSW) – 60-minute invited presentation, September 2020
<https://www.uni-goettingen.de/de/437142.html>
- Cyberport, Hong Kong300 “Solar energy generation, what is in store for the future?” – N.J. Ekins-Daukes (UNSW) – 20-minute invited presentation, November 2020
<https://www.cyberport.hk/en>
- Solar Mobility Forum, September 2020 “VIPV in Australia: Availability of Sunlight and Consumer Attitudes” – N.J. Ekins-Daukes (UNSW) – 20-minute invited presentation, September 2020
<https://solarindustryforum.com/program/>
- Kylie Catchpole (ANU) – “The Bright Future of Solar Energy – a Solar Revolution” – Smart Energy Conference & Exhibition, May 2020
- Martin Green (UNSW) – “Can Solar PV save the World?” – Smart Energy Conference & Exhibition, [month?] 2020



Figure PP5.4: ACAP Director Professor Martin Green and speakers at the Making Solar Powered Transport a Reality seminars organised by Dr Bonna Newman (ACAP research exchange) and Associate Professor N.J. Ekins-Daukes and the Digital Grid Futures Institute.

- UNSW – Making Solar Transport a Reality, Dr Bonna Newman, Associate Professor Ned Ekins-Daukes (UNSW) with Professor Martin Green (UNSW) and others. The Driven Podcast: How close are we to solar cars? (40 minutes) <https://thedriven.io/2020/02/24/the-driven-podcast-how-close-are-we-to-solar-cars>

- How Cheap Can Solar Photovoltaics Become? – Professor Martin Green – UNSW SPREE and the Australian Centre for Advanced Photovoltaics <http://www2.pv.unsw.edu.au/videos/Martin-Green-18December2020/>
- The Grand History and Future of Silicon Solar Cells – Professor Martin Green – UNSW SPREE and the Australian Centre for Advanced Photovoltaics (Edmond Becquerel Symposium, 7 December 2020, Paris) <http://www2.pv.unsw.edu.au/videos/martin-green-7december2020/>

There are over 200 seminars on file with downloadable PDF files of the presenters' slides available for download at:

<http://www2.pv.unsw.edu.au/pvseminars/>

– via the YouTube

<https://www.google.com/l?sa=t&rct=j&q=&esrc=s&source=web&cad=rja&uact=8&ved=2ahUKew1rKWTpunvAhUHxzgGHbp3Bs8QFJAHEgQICxAD&url=https%3A%2F%2Fwww.youtube.m%2Fuser%2FUNSWSPREE&usq=AOvVaw1X7cge7JbCre3JMhvoerBV>

or by searching for "YouTube UNSWSPREE".

ACAP in the media

ACAP researchers were again prominent in media channels. Some of their contributions were:

Really Australia, it's not that hard: 10 reasons why renewable energy is the future

Australia's latest greenhouse gas figures released on Friday show national emissions fell slightly last year. This was by no means an economy-wide effort – solar and wind energy did most of the heavy lifting.

MAY 30, 2020 PAUL ZUBRINICH

CRDS & INTEGRATION MARKETS POLICY AUSTRALIA



Image: Public Domain

Figure PP5.6: Andrew Blakers' PV Magazine article.

- Andrew Blakers (ANU), "Really Australia, it's not that hard: 10 reasons why renewable energy is the future" <https://theconversation.com/really-australia-its-not-that-hard-10-reasons-why-renewable-energy-is-the-future-130459>
- Reprinted: <https://www.pv-magazine-australia.com/2020/05/30/really-australia-its-not-that-hard-10-reasons-why-renewable-energy-is-the-future>
- Reprinted: <https://reneweconomy.com.au/really-australia-its-not-that-hard-10-reasons-why-renewable-energy-is-the-future-80354/>

Figure PP5.5: Pierre Verlinden's seminar – Future challenges for photovoltaic manufacturing at the terawatt level.

Additionally, the UNSW node has a series of public lectures by internationally renowned researchers, that are recorded and made available to the public. Three notable seminars from 2020 are:

- Future challenges for photovoltaic manufacturing at the terawatt level – Pierre Verlinden – AMROCK Pty Ltd – Trina Solar – Sun Yat-Sun University – UNSW <http://www2.pv.unsw.edu.au/videos/pierre-verlinden-19november2020/>

- Renate Egan (UNSW), “Green Jobs Now! What are they and where are they?”
<https://www.eventbrite.com.au/e/green-jobs-now-what-are-they-and-where-are-they-tickets-110236075068>
- Andrew Blakers (ANU), “Australia leading the world in deploying renewable energy”
<https://www.anu.edu.au/news/all-news/australia-leading-the-world-in-deploying-renewable-energy>
- Andrew Blakers (ANU), “Off-river pumped hydro could provide lower costs for energy storage”
<https://reneweconomy.com.au/off-river-pumped-hydro-could-provide-lower-costs-for-energy-storage-31629/>
- “UNSW Sydney: Preventing LID in a 23.83% efficient Longi PERC cell”, PV Magazine
<https://www.pv-magazine-australia.com/2020/02/04/unsw-sydney-preventing-lid-in-a-23-83-efficient-longi-perc-cell/>
- Andrew Blakers (ANU), “Solar PV panel waste will not become a significant problem”
<https://reneweconomy.com.au/solar-pv-panel-waste-will-not-become-a-significant-problem-98181/>
- “2020 Malcolm McIntosh Prize for Physical Scientist of the Year: UNSW Associate Prof. Xiaojing Hao”
<https://www.industry.gov.au/data-and-publications/prime-ministers-prizes-for-science-2020/2020-malcolm-mcintosh-prize-for-physical-scientist-of-the-year>

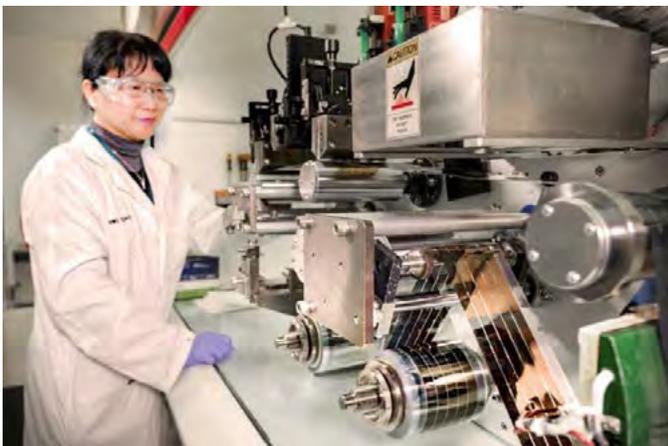


Figure PP5.7: Dr. Mei Gao (above) and others from the CSIRO were featured in PV Magazine.

- “The decade of perovskite PV” (CSIRO)
<https://www.pv-magazine.com/magazine-archive/2020-the-decade-of-perovskite-pv/>

Education Outreach



Figure PP5.8: Fairfield Patrician Brothers’ College was the venue for the UNSW SunSprint, MiniSprint & Solar Boats events.

The UNSW SunSprint (for years 6–12) is a set of solar races that are age-appropriate and fun. The event is comprised of SunSprint, a 100-metre figure-eight track (the SunSprint race cars are built to the Australian–International Model Solar Challenge specifications);

MiniSprint (for years K–12), (raced on a 20-metre straight track, these cars are built from kit materials, consisting of a solar module, motor, gears, wheels and corflute chassis); and Solar Boats (for years K–12).

MiniSprint & Solar Boats were held at Fairfield Patrician Brothers’ College with 130 students from nine schools and 62 teams:
<https://youtu.be/bG-Mqq5Twx>

Unfortunately, the SunSprint event (with the 100-metre track due to be held two weeks after MiniSprint) was cancelled at the last moment due to COVID-19.

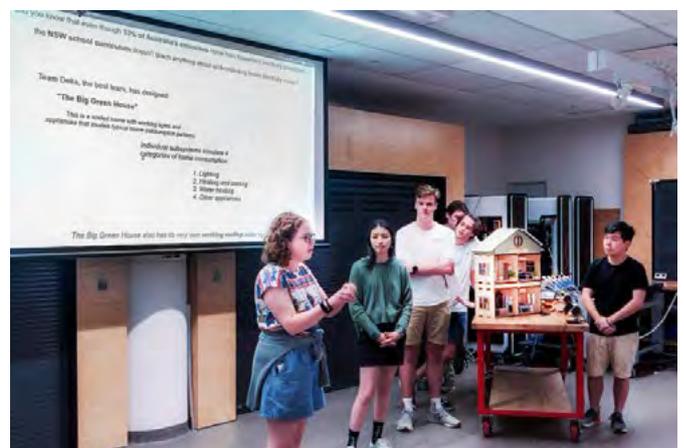


Figure PP5.9: DESN2000 team showing The Big Green House.

As part of the UNSW DESN2000 class, students formed teams and over the teaching term produced projects specifically aimed at developing teaching aids for renewable energy education. The Big Green House (pictured) is a sample of their project work. ACAP has since provided funding for The Big Green House to be developed as a teaching resource that will be available for display and for loan to schools and teaching events.



Figure PP5.10: Women in Renewable Energy hosted social and networking events.

UNSW's Women in Renewable Energy (WIRE) is a society that aims to create a platform to support and connect the women who aim to become engineers in the field of renewable energy. In 2020, WIRE was supported in part by ACAP to organise both social and networking events including:

- an International Women's Day brunch in collaboration with the Women in Technology and Women in Science societies
- continuing WIRE's tradition of hosting an introductory picnic for all members
- an industry networking event in collaboration with RESOC featuring various industry representatives from companies including Evergen, AEMO and Tesla
- a range of social online events, to help transition to online socialising during the pandemic, including Pictionary, Trivia and an online scavenger hunt.



Figure PP5.11: Members of the UNSW Renewable Energy Society (RESOC).

UNSW's Renewable Energy Society (RESOC) supports undergraduate and postgraduate students in the School of Photovoltaic and Renewable Energy Engineering (SPREE). RESOC is a student-run society that aims to create a strong sense of community and expose students to a wide range of networking opportunities.

In 2020, unfortunately, many social and networking events were limited by COVID-19 restrictions. However, with the support of ACAP, some events could still be held including:

- RESOC & WIRE Industry Cocktail Night (pre-COVID) featuring representatives from AEMO, AEMC, AGL Energy, GSES, Infigen, Lendlease, Origin, Tesla, WSP and more
- RESOC & Electrical Engineering and Telecommunications Society (ELSOC) First Year Camp (pre-COVID) and Peer Mentoring Program to ease the transition into university for new SPREE students
- Upskilling Sessions to focus on professional presentation, scientific typesetting, programming and CAD
- Chinese Association for Renewable Energy (CARE) & RESOC joint Webinar on technologies for the renewable energy transition.

RESOC will continue hosting more of their usual events in the coming year with the continued support of ACAP. These include site visits, BBQs on campus and networking events to reconnect with industry after a difficult 2020.

UNSW's Sunswift Solar Racing Team continued the refinement of their solar racing car in preparation for the 2021 Bridgestone World Solar Challenge. Unfortunately, the 2021 World Solar Challenge has been cancelled due to COVID-19.

ACAP 2020 Highlights

- Seventeen new ACAP Fellows started on their postdoctoral research projects.
- The 7th Asia-Pacific Solar Research Conference was held, in conjunction with ACAP annual meetings, bringing the Australian PV research community together with many prominent international guests.
- ACAP was actively involved in education, outreach and external engagement activities with students, industry and the general public.

Future Work

The next ACAP Conference will be held online and in Sydney on Thursday, 16 December 2021, in partnership with APSRC 2021 (14-16 December 2021) and the 31st International PV Science and Engineering Conference (PVSEC-31, 13–15 December 2021). <https://pvsec-31.com/>

Ongoing representation on the Executive Committee for the International Energy Agency, Photovoltaic Power Systems, and growing participation in several tasks, will also continue.

Media and Prominent Events

- Throughout 2020, ACAP, its researchers and its research attracted media attention. Some of the articles, podcasts, reports and events are listed below:
- 4-minUTE interview with ABC radio regional Queensland on renewables and pumped hydro
- 7-minute interview with Fran Kelly on ABC RN about gas and renewables
<https://www.abc.net.au/radionational/programs/breakfast/is-gas-really-clean-energy/12672744>
- A letter from a university lecturer to his students affected by coronavirus: Murad Tayebjee, ABC Life. | Murad on Radio National Canberra.
<https://www.abc.net.au/everyday/letter-from-university-lecturer-to-students-coronavirus-pandemic/12271366>
- ABC interview on the subject of transmission adequacy problems
<https://www.abc.net.au/news/rural/2020-03-04/renewable-profits-slashed-amid-national-transmission-failure/12021082>
- Advice re pumped hydro to Sebastian Reinehr, policy advisor to Ryan Smith, Victorian Opposition spokesperson for energy
- ANU Solar Oration 2020: Professor Mark Z. Jacobson - Transitioning the world to 100% clean, renewable energy, and how the U.S. election will affect the transition
<https://www.youtube.com/watch?v=6aPeigNtKPY>
- ARENA backs start-up SunDrive's next-gen solar cells: Renewables Now
<https://www.renewablesnow.com/news/arena-backs-startup-sundrives-next-gen-solar-cells-716085/>

- Article in May 2020 issue of Energy Informer "Australia, the new pathfinder"
<http://www.menloenergy.com/?p=2130>
- Associate Professor Brett Hallam awarded the Edgeworth David Medal by The Royal Society of NSW
<https://royalsoc.org.au/awards/edgeworth-david-medal>
- "Aussie tech gurus driving local, low-cost solar panel breakthrough", Sydney Morning Herald
<https://www.smh.com.au/politics/federal/aussie-tech-gurus-driving-local-low-cost-solar-panel-breakthrough-20201002-p561j7.html>
- Australia's leading deployment rate - Renewables through the roof, as small-scale solar heads to stunning new highs
<https://reneweconomy.com.au/renewables-through-the-roof-as-small-scale-solar-heads-to-stunning-new-highs-17645/>
- "Australian 'Solar Skin' invention could power cities and vehicles of the future", Renew Economy
<https://reneweconomy.com.au/australian-solar-skin-invention-could-power-cities-and-vehicles-of-the-future-49259/>
- Australian Parliamentary Library research paper series on Australian Electricity options: Photovoltaics (Professor Andrew Blakers and Dr Matthew Stocks)
https://parlinfo.aph.gov.au/parlInfo/download/library/prspub/7451418/upload_binary/7451418.pdf
- Australian Parliamentary Library research paper series on Australian Electricity options: Pumped hydro energy storage (Professor Andrew Blakers and Dr Matthew Stocks)
https://parlinfo.aph.gov.au/parlInfo/download/library/prspub/7451400/upload_binary/7451400.pdf
- "Australian researchers claim world first in global race to develop better solar panels", The Guardian
https://www.theguardian.com/australia-news/2020/may/22/australian-researchers-claim-world-first-in-global-race-to-develop-better-solar-panels?CMP=Share_iOSApp_Other
- "Australian researchers say 'unusual' breakthrough may solve perovskite solar instability", Renew Economy
<https://reneweconomy.com.au/australian-researchers-say-unusual-breakthrough-may-solve-perovskite-solar-instability-29300/>
- "Australian researchers seek cheaper, better and easier to dispose of solar panels", Renew Economy
<https://reneweconomy.com.au/australian-researchers-seek-cheaper-better-and-easier-to-dispose-solar-panels-88507/>
- "Australian scientists 'drastically improve' new solar cell technology", Sydney Morning Herald
<https://www.smh.com.au/environment/climate-change/australian-scientists-drastically-improve-new-solar-cell-technology-20200521-p54v7s.html>

- "Australia's top solar research school snares \$19m in new funding", Sydney Morning Herald, exclusive. | Follow-up to Saturday Herald, page 3 feature on funding future
<https://www.smh.com.au/environment/climate-change/australia-s-top-solar-research-school-snares-19m-in-new-funding-20201213-p56n25.html> and prior article <https://www.smh.com.au/environment/climate-change/major-blow-looms-for-top-sydney-solar-research-unit-as-funds-wither-20200507-p54r3j.html>
- Award-winning renewables engineer says her technology can change the world
<https://www.createdigital.org.au/xiaojing-hao-award-winning-renewables-engineer/>
- "CEFC backs revolutionary eArc panels in next wave of solar innovation for Australia", Mirage News
<https://www.miragenews.com/cefc-backs-revolutionary-earc-panels-in-next-wave-of-solar-innovation-for-australia/>
- Central prominence for ANU's global PHES Atlas in "Role of Pumped Hydro Energy Storage in India's Renewable Transition", a 58-page report produced by the Asia Foundation and Integrated Research and Action for Development
<https://irade.org/Role%20of%20Pumped%20Hydro%20Energy%20Storage%20in%20Indias%20Renewable%20Transition-%20Final%20Report.pdf>
- Climate Conversations podcast
<https://omny.fm/shows/climate-conversations/professor-andrew-blakers-champions-solar-power>
- Comment on AEMO's Integrated System Plan 2020 for EcoGeneration (August edition)
https://www.ecogeneration.com.au/is-aemos-2020-integrated-system-plan-up-to-the-job/?utm_source=Ecogeneration&utm_campaign=afe0d028c4-EMAIL_CAMPAIGN_2017_01_25_COPY_02&utm_medium=email&utm_term=0_cd04baabb5-afe0d028c4-137142021
- Efficient, affordable solar cells born in Sydney garage: ARENA WIRE
https://arena.gov.au/blog/efficient-affordable-solar-cells-born-in-sydney-garage/?utm_medium=email&utm_campaign=ARENAWIRE%20041120&utm_content=ARENAWIRE%20041120+CID_9a96f4fbb43422332db5c1679ac7190e&utm_source=enews&utm_term=Read%20More
- "Five UNSW researchers honoured by Royal Society of NSW", Mirage News
<https://www.miragenews.com/five-unsw-researchers-honoured-by-royal-society-of-nsw/>
- ForwardSlash podcast: The Australian: Solar generation is an Australian success story. Martin Green and Alison Lennon
<https://omny.fm/shows/forward-slash/solar>
- "Global research team sets up database for emerging PV tech", PV Magazine
<https://www.pv-magazine.com/2020/12/11/global-research-team-sets-up-database-for-emerging-pv-tech/>
- Interview in the Canberra Times, "Two Canberra Aldi supermarkets go solar"
<https://www.canberratimes.com.au/story/6902573/two-canberra-aldi-stores-make-switch-to-solar/>
- Interview on Radio Adelaide's Breakfast Program re PERC
<https://radioadelaide.org.au/2020/01/20/the-aussie-invention-fighting-greenhouse-emissions/>
- Interview on SBS TV re energy technology roadmap – "Clean' hydrogen and carbon capture: Will the government's energy roadmap drive down emissions?"
<https://www.sbs.com.au/news/clean-hydrogen-and-carbon-capture-will-the-government-s-energy-roadmap-drive-down-emissions>
- Interview on SBS TV about Government's energy technology roadmap
- Interview with 2SER on climate change and COVID (5 minutes)
- Invited talk at the "Renewable Energy in the Central West" Forum
- Item in Renew Economy, "Australia deploying new renewables at ten times global average"
<https://reneweconomy.com.au/australia-deploying-new-renewables-at-ten-times-global-average-11689/>
- Item in Renew Economy on the rapid decline in PV prices, "Technology leaps driving cost of solar PV electricity in Australia to just A\$30/MWh"
<https://reneweconomy.com.au/technology-leaps-driving-cost-of-solar-pv-electricity-in-australia-to-just-a30-mwh-42052/>
- "Next-generation solar cells pass strict international tests", Nature Science. | In SBS Mandarin
<https://science.sciencemag.org/content/368/6497/eaba2412> and in Chinese <https://www.sbs.com.au/chinese/mandarin/zh-hans/audio/australian-experimental-perovskite-solar-cells-pass-strict-international-tests>
- Organised a public evening "Imagining Australia with 100% renewable energy: how do we get there?" attended by 210 people
<https://www.anu.edu.au/events/imagining-australia-with-100-renewable-energy-how-do-we-get-there>
- Organised a response by senior academics from ANU and UNSW to the Government energy technology roadmap: "Solar PV and wind – the heart of an energy technology roadmap"
- Organiser of and speaker at a workshop on 100% renewable energy futures at ANU attended by 60 specialists
- Participation in a high-profile public webinar on the topic of Australia, renewable energy pathfinder (150 in the audience)
<https://www.youtube.com/watch?v=l6pdwxelZUo&feature=youtu.be>
- PERC cells – The Conversation, "How an Aussie invention could soon cut 5% of the world's greenhouse gas emissions"
<http://theconversation.com/how-an-aussie-invention-could-soon-cut-5-of-the-worlds-greenhouse-gas-emissions-121571>

- PERC Conversation article reprinted in EcoGeneration, “How an Aussie invention could soon cut 5% of the world’s greenhouse gas emissions”
https://www.ecogeneration.com.au/how-an-aussie-invention-could-soon-cut-5-of-the-worlds-greenhouse-gas-emissions/?utm_source=Ecogeneration&utm_campaign=95ec8235ef-EMAIL_CAMPAIGN_2017_01_25_COPY_01&utm_medium=email&utm_term=0_cd04baabb5-95ec8235ef-137142021
- Prime Minister’s Science Prizes winners: ABC News
<https://www.abc.net.au/radionational/programs/scienceshow/more-prime-minister%E2%80%99s-science-prizes-winners/12855676>
- Principal speaker at a webinar in Nepal to discuss the prospect of pumped hydro storage
- Quoted in press release from the Minister for Energy and Emissions Reduction Angus Taylor
<https://www.minister.industry.gov.au/ministers/taylor/media-releases/record-new-renewable-capacity-2019>
- Renew Economy article, “Why Angus Taylor’s electorate would make an excellent renewable energy zone”
<https://reneweconomy.com.au/why-angus-taylors-electorate-would-make-an-excellent-renewable-energy-zone-79243/>
- Renew Economy summary of Australia, renewable energy pathfinder webinar, “Yes we can’: Energy experts plot path to fossil-free grid”
<https://reneweconomy.com.au/yes-we-can-energy-experts-plot-path-to-fossil-free-grid-68239/>
- “Researchers use ‘trick of the light’ to eliminate flaws in next-gen solar cells”, Renew Economy
<https://reneweconomy.com.au/researchers-use-trick-of-the-light-to-eliminate-flaws-in-next-gen-solar-cells-92392/>
- Rooftop solar tipped to hit 2.9GW in 2020, solar-wind outstrip gas: CER, ANU: EcoGeneration
https://www.ecogeneration.com.au/rooftop-solar-tipped-to-hit-2-9gw-in-2020-cer/?utm_source=Ecogeneration&utm_campaign=94a5b69a85-EMAIL_CAMPAIGN_2017_01_25_COPY_01&utm_medium=email&utm_term=0_cd04baabb5-94a5b69a85-137142021
- “Solar-flow battery to capture, store solar energy at record efficiency”, News.com.au
<https://www.news.com.au/technology/innovation/inventions/solarflow-battery-to-capture-store-solar-energy-at-record-efficiency/news-story/8184154bf684e252dcb70176756ce9a0>
- Speaker at a 30-minute Solar Citizens webinar (900 attendees) about the future of ARENA including three MPs Zali Steggall, Adam Bandt and Mark Butler
- Speaker at a webinar (230 people) organised by Renew Economy on the topic, Andrew Blakers (ANU) “How efficient can big solar be?”
<https://reneweconomy.com.au/webinar-how-efficient-can-big-solar-be-56984/>
- Substantial speaking roles (Professor Andrew Blakers & Professor Martin Green) in ABC TV documentary The Great Acceleration, Series 1 Episode 3 “Energy Revolutions” (54 minutes)
<https://iview.abc.net.au/show/great-acceleration>
- “Three UNSW researchers elected as Fellows of the Australian Academy of Technology and Engineering”, UNSW Newsroom
<https://newsroom.unsw.edu.au/news/science-tech/three-unsw-researchers-elected-fellows-australian-academy-technology-and>
- “Three women awarded Prime Minister’s Prize for their work in science”, Women’s Agenda
<https://womensagenda.com.au/latest/three-women-awarded-prime-ministers-prize-for-their-work-in-science/>
- “Top 20 influencers in renewable energy industry in Australia”, Rated Power
<https://blog.ratedpower.com/top-24-influencers-in-renewable-energy-industry-in-australia>
- “Understanding LeTID”, Alison Ciesla and Brett Hallam, PV Magazine
<https://www.pv-magazine-australia.com/2020/04/06/understanding-letid/>
- “Universities form global network to coordinate on climate change”, Times Higher Ed
<https://www.timeshighereducation.com/news/universities-form-global-network-coordinate-climate-change>
- “UNSW awarded more than \$7m for renewable energy research and development”, UNSW Newsroom
<https://newsroom.unsw.edu.au/news/science-tech/unsw-awarded-more-7m-renewable-energy-research-and-development>
- “UNSW students and solar PV in remote Vanuatuan communities”, PV Magazine
<https://www.pv-magazine-australia.com/2020/02/18/unsw-students-and-solar-pv-in-remote-vanuatuan-communities/>
- “UNSW Sydney solar researcher wins prestigious international award - Brett Hallam”, UNSW Newsroom
<https://www.unsw.edu.au/engineering/news/unsw-sydney-solar-researcher-wins-prestigious-international-award-0>
- “UNSW to divest from fossil fuels”, PV Magazine
<https://www.pv-magazine-australia.com/2020/03/06/unsw-to-divest-from-fossil-fuels/>
- “UNSW welcomes government MPs to campus for renewables showcase”, Inside UNSW
https://www.inside.unsw.edu.au/innovation-and-engagement/unsw-welcomes-government-mps-campus-renewables-showcase?utm_source=All+Staff+-+August+2020&utm_campaign=b4f7aba68e-EMAIL_CAMPAIGN_2020_08_24_11_59&utm_medium=email&utm_term=0_4af8cefd63-b4f7aba68e-84227087
- Zoom seminar – Professor Andrew Blakers: 100% renewables and storage - with “Beneath the Wisteria”, a Shepparton-based group
<https://www.youtube.com/watch?v=BlcwaXRN1Hs>

COLLABORATIVE ACTIVITIES

OVERVIEW

The Australian Centre for Advanced Photovoltaics' international collaborations are directed at the highest level through an International Advisory Committee, with representatives from the key partners in Australia and from the world's most active PV R&D nations, with engagement fostered through the development of collaborative research programs, the annual ACAP conference and the major global research conferences.

Specific project activities that leverage the benefits of the international relationships include the following key projects.

- Section 6.1 describes the simplification of the overall design for the one-sun high efficiency spectrum splitting modules by inclusion of the band-pass filter into the cell fabrication sequence.
- Section 6.2 outlines the development of dye-sensitised solar cells.
- The project for Section 6.3, Carrier Selective Contacts, finished in 2016 and is not reported here.
- The collaboration described in Section 6.4 is a long-standing one that records the status of a whole range of photovoltaic technologies in the maintenance and publication of Solar Cell Efficiency Tables.
- The work on PV Manufacturing Education, reported in Section 6.5, a project with collaborating organisation, PV Lighthouse, has grown into a leading tool for teaching photovoltaics manufacturing globally.

In addition to the specific activities captured in this section, many of the reports already presented as detailed research reports also involve collaborations with international partners. Since late 2015 and through 2019 the organisation has had five rounds of small collaboration grants to researchers based at ACAP nodes. Many of the hot topics of the advancing silicon cell technology are being addressed by the collaboration grants. The progress reports for those still active in 2020 are presented online <https://www.acap.org.au/post/acap-s-annual-reports-2013-present> and their titles and participants are listed here. A sixth round of eight projects was selected in Q4 of 2020 and will begin in 2021.

Many of the 52 ACAP Fellowships awarded in three rounds involved collaborations and there is a report for each one that had 2020 activity included in <https://www.acap.org.au/post/acap-s-annual-reports-2013-present> and their titles and participants are listed here.

Finally, the education, training and outreach activities reported in PP5 include a wide range of international interactions, the ACAP Conference, regular and special public lectures, and partnership arrangements in teaching and on-line learning, such as the development and delivery of courses between institutes in Australia and around the world.

6.1 IMPROVED SUNLIGHT TO ELECTRICITY CONVERSION EFFICIENCY: ABOVE 40% FOR DIRECT SUNLIGHT AND ABOVE 30% FOR GLOBAL

Lead Partner

UNSW

UNSW Team

Dr Mark Keevers, Prof. Martin Green, A/Prof. Ned Ekins-Daukes, Dr Jessica Yajie Jiang, Dr Anastasia Soeriyadi

NREL Team

Dr Keith Emery, Dr Larry Ottoson, Dr Tom Moriarty, Dr Gregory Wilson, Dr Dean Levi, Dr Mowafak Al-Jassim

Industry Partners

RayGen Resources Pty Ltd: Ian Thomas, Danny Modra, Dr John Lasich
Spectrolab: Prof. Richard King (now ASU)
Trina Solar: Dr Pierre Verlinden, Yang Yang, Xueling Zhang

Funding Support

ASI/ARENA, AUSIAPV, NREL, Spectrolab, RayGen Resources Pty Ltd, Trina Solar, UNSW

Aim

The original aim of the project was to design, fabricate and test a proof-of-concept, prototype spectrum splitting concentrating photovoltaic (CPV) module demonstrating an independently confirmed efficiency above 40%. The combination of such a spectrum splitting or 'Power Cube' receiver and a CPV power tower system (Figure 6.1.1) has the potential to reduce the cost of utility-scale photovoltaics. With the targeted record performance level achieved in 2014, the project was extended in 2015 to target 42% CPV module efficiency and over 30% efficiency for a non-concentrating, flat-plate implementation of the spectrum splitting approach.

Progress

CPV prototype

The CPV prototype is based on a 287 cm² aperture area parabolic enhanced (that is, dielectric-coated) silver mirror, a custom band-pass (spectrum splitting) dielectric filter, and two 1 cm² high efficiency commercial CPV cells – one a triple-junction (3J) III-V cell and the other an Si cell – each mounted on a concentrator cell assembly and a water-cooled heatsink (Figure 6.1.2). The mechanical design uses optomechanical components to give a relatively lightweight, robust and fully adjustable structure, enabling optimisation about all critical linear and rotation axes. The high performance band-pass filter was supplied by Omega Optical Inc. The 3J III-V cell was a commercial Spectrolab concentrator cell ("C3MJ+" cell, nominally 39.2% efficient at 500-suns concentration, mounted on a ceramic substrate), while the Si cell was a SunPower back contact cell of circa 1998 vintage (nominally 26% efficient at 200 suns), mounted on a ceramic substrate and encapsulated under glass by ENEA, Italy, followed by MgF₂ AR coating at UNSW. This 3J + Si combination, or 3 + 1 = 4J receiver,

gave a record 40.4% efficiency in testing at NREL in late 2014, the first demonstrated conversion of sunlight to electricity with efficiency over 40% (Green et al. 2015).

In 2015, the enhanced-silver parabolic mirror was replaced by an all-dielectric mirror custom-designed and fabricated by Omega Optical Inc., with shorter focal length (800 mm versus 1000 mm). Independent measurements of the dielectric mirror by the US National Institute of Standards and Technology (NIST) confirmed $R = 99.7\% \pm 0.2\%$ over the 400–1800 nm range (Figure 6.1.3), likely setting a record for high reflectance over solar wavelengths (Fredel et al. 2017). An improved version of the prototype using this new parabolic mirror was independently tested at NREL's outdoor test facility in Colorado in 2016, again in a four-terminal configuration, with efficiency of 40.6% at AM1.5 certified, a new world record for a system of this size. Presently, we are reoptimising the CPV receiver targeting 42%.

In March 2019, NREL launched its "Champion Module Efficiencies" chart, to complement its "Best Research-Cell Efficiency" chart. Our 40.6% efficiency result tops the Champion Module Efficiencies chart (Figure 6.1.4).

One-sun module

The project was extended in 2015 to investigate how the spectrum splitting approach could be applied to standard non-concentrating terrestrial solar modules that have to respond to sunlight from a wide range of incident angles. The approach adopted was based on an earlier UNSW discovery (Mills and Guitronich 1978) of the near-ideal angular response properties of triangular glass prisms. In our application of this "prismatic encapsulation" concept, light reflected from the first cell along the prism hypotenuse is channelled to the second cell (Figure 6.1.5). We envisage that a PV module could be comprised of an array of these cell-sized prisms, without increasing module thickness.

For our mini-module, we used a 4 x 8 cm 3J III-V cell designed for one-sun applications (Bett et al. 2009) acquired from AZUR SPACE and a 4 x 4 cm high performance interdigitated back contact Si cell specially fabricated by Trina Solar for the project with anti-reflection coating optimised for the narrow-band (900–1050 nm) illumination involved. The spectrum splitting band-reflect filter (inverse of the band-pass filter used for the CPV prototype) was deposited on the hypotenuse face of the triangular prism prior to encapsulation of the 3J III-V cell on that face.

An efficiency of 34.5% in a four-terminal configuration was independently confirmed in April 2016 by NREL for the 28 cm² mini-module, the highest ever one-sun measurement for a solar module of this size, far above the previous record of 24.1% (albeit for an appreciably larger area module). This result received considerable media attention and there are now mini-modules on display at the Sydney Powerhouse Museum and at the London Science Museum in "The Sun" exhibition. Presently, the approach is being used to fabricate a much larger 800 cm² device, using 30 such mini-modules, with similar high efficiency targeted.

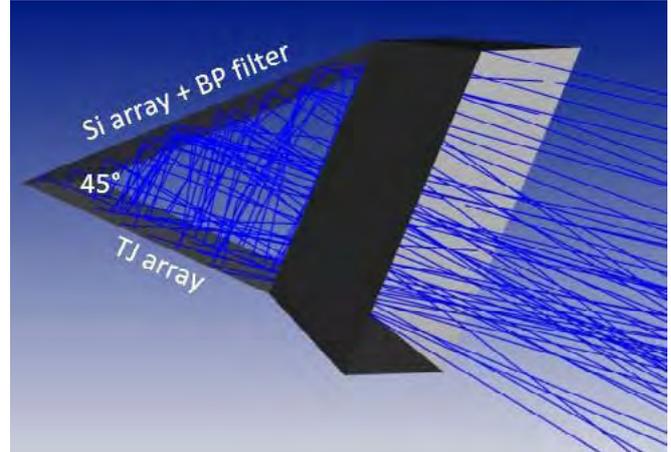


Figure 6.1.1: CPV power tower: (left) RayGen's PV ultra technology uses a field of heliostats to concentrate sunlight onto a 1 m² high efficiency PV receiver (inset shows a close-up of the receiver); and (right) possible design of an advanced spectrum splitting receiver implementing the demonstrated improvements at scale (in this example, the band-pass "BP" filter cover glass on the Si array transmits 900–1050 nm sunlight to the Si array and reflects the remainder of the solar spectrum to the triple-junction "TJ" array).

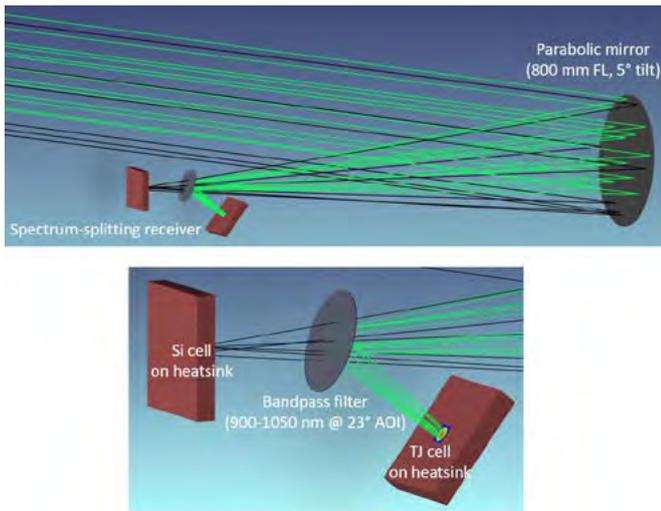


Figure 6.1.2: CPV prototype: (top) ray trace diagram, including enlarged view of the filter and cell layout; and (bottom) during outdoor testing at NREL with Mark Keevers 5 April 2016 where a four-terminal efficiency of 40.6% at AM1.5 was measured on that day.

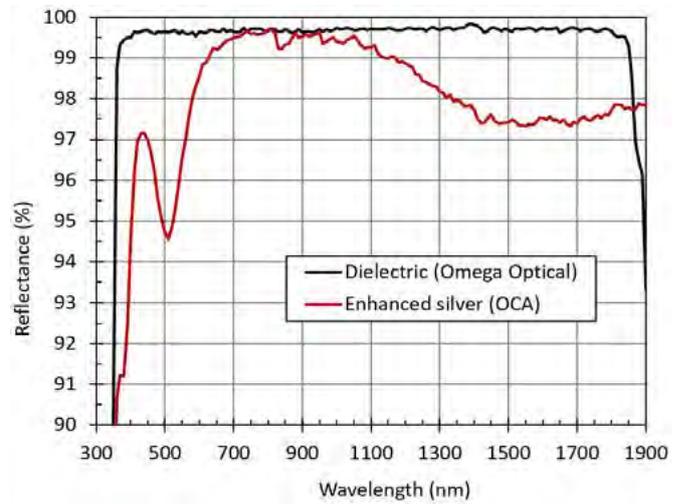


Figure 6.1.3: Measured reflectance of the concentrating mirrors, showing the remarkable performance of the dielectric mirror (measured by NIST).

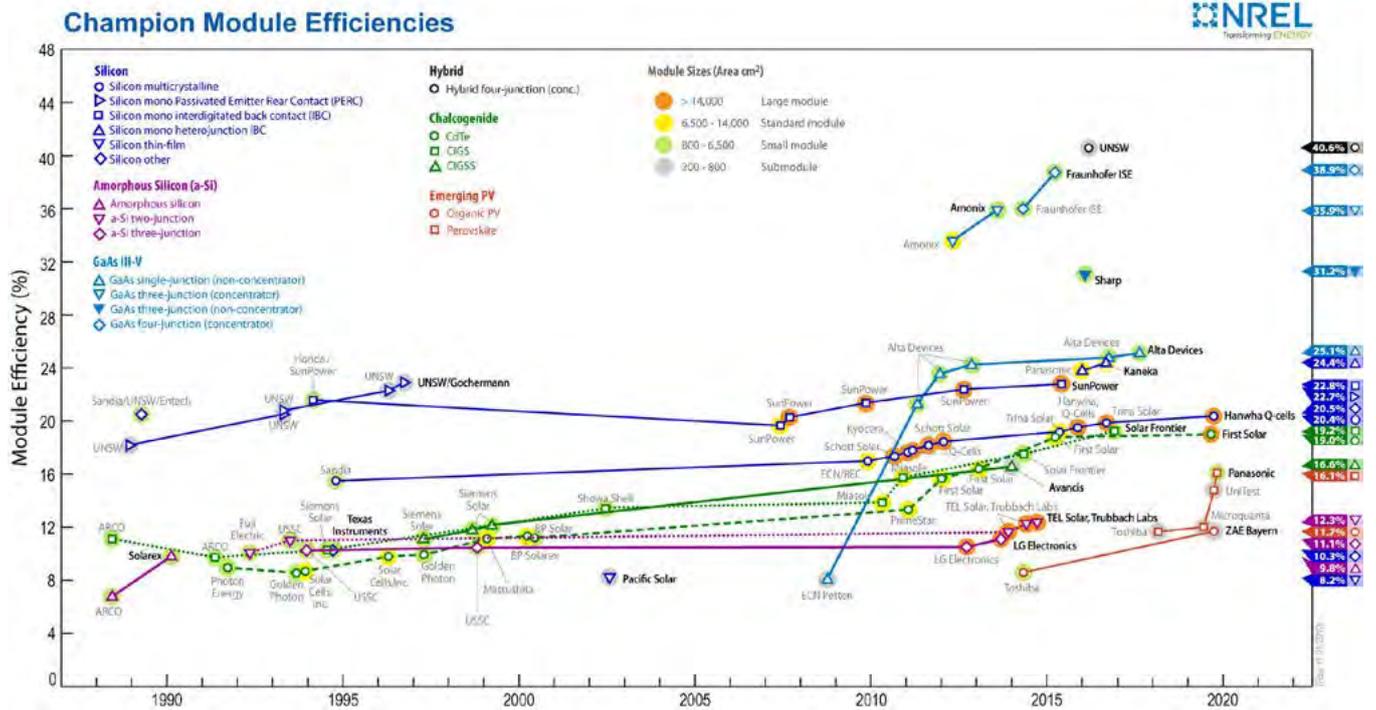


Figure 6.1.4: UNSW holds the top entry on NREL's international Champion Module Efficiencies chart (<https://www.nrel.gov/pv/module-efficiency.html>).

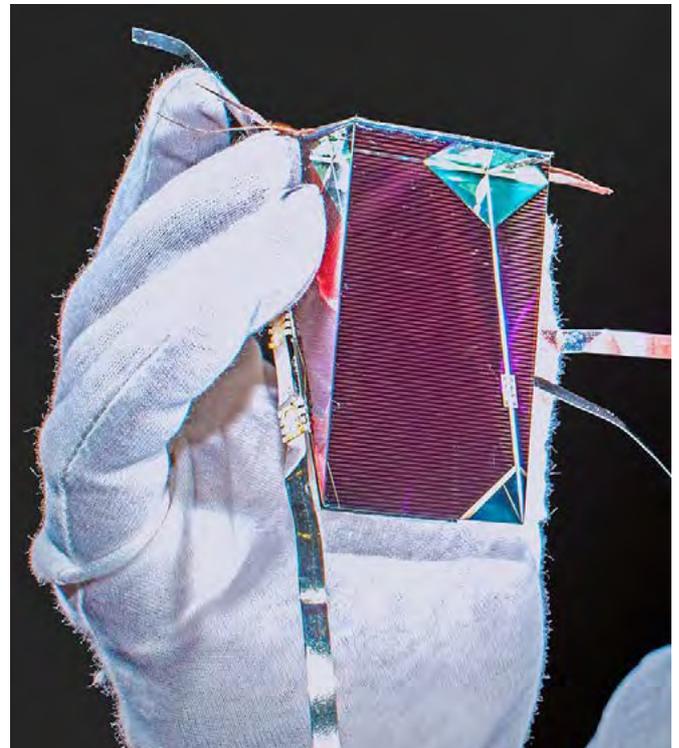


Figure 6.1.5: One-sun spectrum splitting mini-module: (left) concept (courtesy Channel 7 News); and (right) a fabricated minimodule. A four-terminal efficiency of 34.5% was certified at NREL in April 2016.

Bragg reflectors for spectrum splitting

During this project we realised that (band-reflect) spectrum splitting could be achieved using a Bragg reflector incorporated into the 3J III-V cell during fabrication, instead of using a separate dielectric filter. A Bragg reflector is already used in some commercial 3J III-V space cells, and a modified Bragg design to broaden its reflectance range could be used for spectrum splitting applications, giving lower cost and reduced angle-of-incidence dependence compared to dielectric filters (Jiang et al. 2019). This approach is now the subject of a more detailed study (see sections 6.43 and F7).

Practical path to landmark 50% efficiency

During this project we identified a practical path to achieving a landmark 50% PV efficiency, utilising spectrum splitting between two triple-junction (3J) solar cells grown on separate GaAs and InP substrates, to form a 3 + 3 = 6J receiver. Benefits include simpler solar cell structures (three instead of six monolithic sub-cells), better optimised AR coatings (smaller wavelength ranges) and avoidance of costly solar cell bonding (used by other groups). Future projects are planned to pursue this path to 50% efficiency, including to optimise/fabricate the required 3J solar cells, longpass filter and overall receiver, and develop a commercialisation roadmap for application to RayGen's CPV technology. Seed funding has enabled us to begin this work (see section 6.44).

Highlights

- Highest efficiency (40.6%) entry on NREL's newly introduced "Champion Module Efficiencies" chart.
- The Power Cube project was officially closed on 1 June 2019.
- Progress continues towards a higher efficiency CPV prototype and a one-sun module comprised of 30 mini-modules.
- Realisation that a Bragg reflector incorporated into the 3J III-V cell, rather than use of a dielectric filter, has advantages for spectrum splitting → spin-off project.
- Identification of a practical path to a landmark 50% efficiency, using a 3 + 3 = 6J spectrum splitting receiver → spin-off project.

Project Completion and Future Work

The Power Cube project (1 January 2012–1 June 2019) is now officially closed

Due to unanticipated delays with a number of critical supplies and services, the final milestones are now being pursued after the official project closure: (1) Further refinement of the concentrator prototype design is expected to allow an efficiency of 42% to be demonstrated, increasing the margin over the alternative CPV and solar thermal approaches. (2) Applying a similar spectrum splitting approach to a standard non-concentrating, flat-plate module is expected to result in confirmation of a record efficiency well over 30% for an 800 cm² module.

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6.2 DYE-SENSITISED SOLAR CELLS

Lead Partner

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Academic Partner

CSIRO

Funding Support

ACAP, ARENA, ARC, Monash

Aim

Lewis bases are typically added to copper-based electrolytes for dye-sensitised solar cells (DSSCs) to improve the device efficiency. To this date, the working mechanism for this improvement is poorly understood. The aim of this project is to gain insights into the performance determining the role of Lewis bases in dye-sensitised solar cells employing copper phenanthroline electrolytes.

Progress

The team at Monash, led by Dr Sebastian Furer and Dr Rebecca Milhuisen, has thoroughly studied the coordination of three Lewis bases, TFMP (4-(trifluoromethyl)pyridine), tBP (4-tert-butylpyridine) and NMBI (1-methyl-benzimidazole) to two redox couples, [Cu(dmp)₂]^{+/2+} and [Cu(dpp)₂]^{+/2+} (with dmp = 2,9-dimethyl-1,10-phenanthroline and dpp = 2,9-diphenyl-1,10-phenanthroline). Through single-crystal X-ray diffraction analysis, absorption and ¹H-NMR spectroscopies the coordination of Lewis bases to the Cu(II) centres was studied.

The team found, that strong Lewis bases such as tBP and NMBI coordinate to Cu(II) phenanthroline complexes, while in weaker Lewis bases, such as TFMP, no coordination occurs.

For $[\text{Cu}(\text{dmp})_2]^{2+}$ the oxidised redox species in the presence of strong Lewis bases was found to be the pentacoordinated complex $[\text{Cu}(\text{dmp})_2\text{LB}]^{2+}$. In the case of $[\text{Cu}(\text{dpp})_2]^{2+}$, a ligand exchange with strong Lewis bases to form $[\text{Cu}(\text{LB})_4]^{2+}$ was observed. The formation of these species was found to be crucial for the redox behaviour of these redox couples and their performance as electrolytes in DSSCs. The coordination of the Lewis bases to the Cu(II) centre efficiently slows down recombination. If $[\text{Cu}(\text{LB})_4]^{2+}$ is formed we generally observed a lower performance in DSCs due to limitations at the counter electrode. With NMBI, we successfully introduced a new Lewis base as an additive for Cu-phenanthroline-based electrolytes that outperforms the commonly used additive tBP.

In this study we could not only establish the nature of Lewis base interaction with Cu-phenanthroline mediators, but also how the presence of Lewis bases is a requirement for high performing solar cells. We outlined the importance of fine-tuning the Cu(II) complex – Lewis interaction in order to suppress recombination through coordination but simultaneously avoid ligand dissociation to enable an efficient electrolyte regeneration for high performing devices.

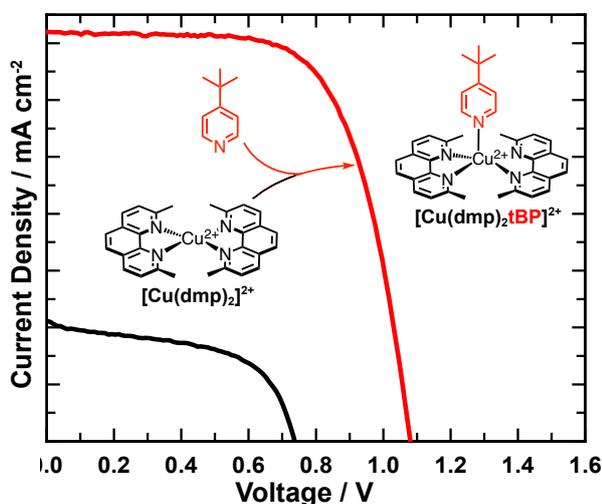


Figure 6.2.1: JV-curves of champion devices employing a $[\text{Cu}(\text{dmp})_2]^{2+}$ electrolyte in the absence (black) and presence (red) of 4-tert-butylpyridine.

Highlights

- This work was published in *Advanced Energy Materials*: <https://doi.org/10.1002/aenm.202002067>.
- Coordination of strong Lewis bases with Cu(II) phenanthroline complexes is crucial for their performance as electrolytes in DSCs. The coordination of the Lewis bases to the Cu(II) centre efficiently slows down recombination.
- Ligand dissociation, rather than coordination, reduces the device performance due to limitations at the counter electrode.

Future Work

The Cu(II) complex – Lewis base coordination and their reduction at the counter electrode will be further optimised to allow for open circuit voltages well above 1.1 V and further improvement of the device efficiency. In addition, the gained insights will be highly relevant to design and incorporate new hole transport materials based on copper complexes for perovskite solar cells.

6.4 SOLAR CELL PERFORMANCE DOCUMENTATION

Lead Partner

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NREL Team

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Academic Partners

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NPVM China

Fraunhofer Institute for Solar Energy Systems, Germany

ISFH Germany

JRC Ispra, Italy

AIST Japan

JET Japan

Funding Support

ACAP, UNSW, NREL

Aim

To improve accuracy and quality of photovoltaic device measurement and reporting.

Progress

A long-standing research collaboration between UNSW and NREL, now being conducted as an ACAP international collaborative project, involves the reliable documentation of the status of the whole range of photovoltaic technologies worldwide. This is achieved by the biannual publication of the "Solar Cell Efficiency Tables" in the Wiley journal, *Progress in Photovoltaics*.

By enforcing guidelines for the inclusion of solar cell efficiency results into these tables, they not only provide an authoritative summary of the current state of the art but also ensure measurements are reported on a consistent basis. One criterion that has been important to enforce has been that results be independently certified at one of a limited but increasing number of "designated test centres", generally of a national facility status, with a certified measurement capability and additionally involved in international "round robin" testing. CSIRO (Newcastle) is the first test centre in the southern hemisphere accepted as a designated test centre.

This rigour has been important particularly as new device technologies come to the fore and groups relatively inexperienced with cell testing suddenly are thrust into the limelight. The other important role has been in developing measurement standards when international standards are not available. Figure 6.4.1 shows standards in this category developed for defining the area used for efficiency determination for experimental laboratory cells.

Several results from the ACAP program have set new world standards and are featured in these tables. In 2020, these included the retention of two UNSW record efficiencies for CZTS cell performance, with 10.0% confirmed for a 1 cm² device and 11.0% for a smaller device, an ANU 21.6% record for a perovskite solar cell, a 20.1% record for a GaAsP/Si monolithic tandem solar cell (UNSW with Ohio State University and SolAero), a 32.9% efficiency for a GaInP/GaAs multi-junction solar cell involving multiple quantum wells (UNSW with NREL), a 34.5% UNSW record for a GaInP/GaInAs/Ge plus Si spectral split mini-module, a UNSW 40.6% result for a concentrator submodule using a similar cell combination and 21.7% for a large-area UNSW Si concentrator cell.

The tables are widely used and referenced by the photovoltaic research community. According to the ISI Web of Knowledge, the fourteen versions prepared since 2013 under the ACAP banner have all been among the most cited papers published since then in the engineering discipline worldwide.

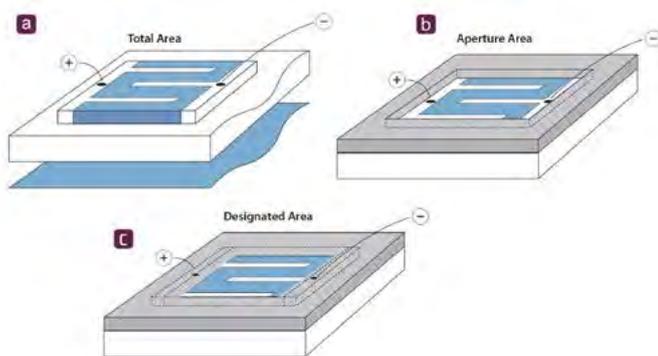


Figure 6.4.1: Cell area definitions: (a) total area; (b) aperture area; and (c) designated illumination area.

Highlight

- Value and widespread use of tables validated by exceptionally high citation rates.

Future Work

- Publish two updated versions of the tables during 2021.

6.5 PV MANUFACTURING EDUCATION

Lead Partner

UNSW

UNSW Team

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UNSW Students

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Tong Li

PV Lighthouse Team

Ben Sudbury, Malcolm Abbott, Keith McIntosh

QESST Team

Prof. Stuart Bowden, Dr André Augusto

Funding Support

ACAP, UNSW

Aims

UNSW has a strong track record in the development of (online) educational resources in PV manufacturing. In 2014, PV Factory [a cloud-based simulation platform (UNSW and PV Lighthouse, 2015)] was developed through an ACAP-supported collaboration involving PV Lighthouse, UNSW and Arizona State University as a teaching application that engages PV and Solar Energy Engineering students as they learned about how solar cells are made.

PV Factory was released to the public in January 2015 and can be accessed at <https://factory.pvlighthouse.com.au>. It has attracted over 3,500 unique users since its inception and is currently used by at least five universities in their teaching programs (including UNSW and ASU). The users have completed over 402,000 solar cell batches with a compounded output power of 131 MW to date. More recently, the PV-Manufacturing.org platform was released in January 2018 (Hoex 2018). This platform was developed in an ACAP-funded project in a collaboration between UNSW and Arizona State University and combines text with videos and tailored animations to teach students and engineers about solar cell manufacturing. The site has received close to 17,000 unique visitors in 2020 from all over the world (see Figure 6.5.1) and is complemented by a playlist on YouTube (Hoex 2017).

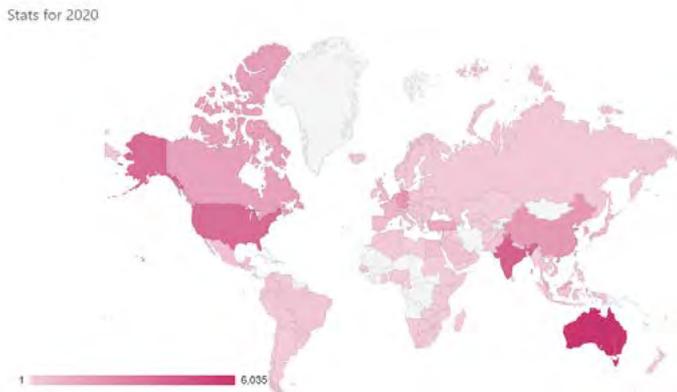


Figure 6.5.1: Screenshot of the usage statistics of PV-manufacturing.org website showing that visitors from all over the world have been using the website to find information about PV manufacturing.

In 2019 we extended our online education offering using SunSolve from PV Lighthouse, which is a commercial ray tracer coupled with an electrical solar cell and circuit solver used by many of the leading PV companies to simulate wafers, solar cells, modules and systems. The standard version is “out of the box” and not suitable for use in tertiary education or for the training of engineers. We implemented significant changes in administrative management, user management, cloud capacity allocation, undergraduate-level self-run tutorials on how to use the software and expanded the availability of features. The updated version of SunSolve went live in April 2019 (PV Lighthouse 2019).

Progress

The following work package was completed during the reporting period.

WP1: Development of the online educational modules (Lead: UNSW)

We developed online education modules targeting key manufacturing steps and trends in PV manufacturing. Each module consists of a tailored exercise in the SunSolve server complemented with a section on PV-Manufacturing.org which contains the training material. The topics which were released to date on PV-Manufacturing.org are (Abdullah-Vetter and Hoex 2019b):

1. Optimisation of surface texturing
2. Optimisation of anti-reflection coatings
3. Optimisation of metallisation
4. Optimisation of metallisation – more busbars
5. Optimisation of bill of materials
6. Bifacial vs monofacial solar cells
7. Incident angle modifier
8. Cell mismatch
9. Heterojunction and passivating contacts



Figure 6.5.2: Screenshot of the SunSolve tutorial on Incident Angle Modifier PV-Manufacturing.org/incident-angle-modifier.

Highlights

- PV Factory and PV-Manufacturing.org are widely used for PV education.
- A set of nine SunSolve tutorials was developed and published on PV-Manufacturing.org.
- SunSolve was used for the second year in the SOLA3020 course at UNSW.

Future Work

We will continue to work on developing more tutorials using SunSolve and articles about recent development and publishing them on PV-Manufacturing.org.

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COLLABORATION GRANTS

ACAP's competitively selected Collaboration Grants, whose titles are shown below, are reported online at <http://www.acap.net.au/annual-reports>.

6.35 A CASE STUDY OF THE DEGRADATION OF FLEXIBLE PHOTOVOLTAIC MODULES

Lead Partner

CSIRO

CSIRO Team

Dr Hasitha Weerasinghe, Mrs Régine Chantler, Dr Doojin Vak, Ms Jyothei Ramamurthy, Mr Andrew Faulks, Mr Karl Weber, Ms Fiona Glenn, Dr Andrew Scully
Interns: Mr Rahul Banakar, Mr Oscar Elsasser

Academic Partner

Australian Academy of Technology and Engineering (ATSE): Mr Peter Pentland, Executive Manager ATSE Schools Program
Stanford University: Prof. Reinhold Dauskardt, Dept. of Materials Science and Engineering

Funding Support

ACAP, CSIRO

6.36 LIFE CYCLE ASSESSMENT OF RECYCLING PROCESSES OF SILICON SOLAR MODULES

Lead Partner

UNSW

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Dr Marina Monteiro Lunardi, Dr Jose Bilbao, Dr Richard Corkish

Academic Partner

Federal University of Rio Grande do Sul (UFRGS) – Brazil: Dr Hugo Marcelo Veit, Dr Pablo Ribeiro Dias

6.37 IMPROVING UV STABILITY AND EFFICIENCY OF FOUR-TERMINAL PEROVSKITE-SILICON TANDEM SYSTEM WITH LUMINESCENT DOWNSHIFTING INCORPORATED ENCAPSULANT

Lead Partner

ANU

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Academic Partners

Karlsruhe Institute of Technology (KIT): Prof. Bryce Richard, Dr Ulrich Paetzold
CSIRO Newcastle: Dr Benjamin Duck

Funding Support

ACAP

6.38 NANOSCALE LOCALISATION OF DEFECTS IN SILICON AND CZTS VIA CATHODOLUMINESCENCE AND PHOTOLUMINESCENCE SPECTROSCOPY

Lead Partner

UNSW

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A/Prof. Xiaojing Hao
Dr Michael Pollard
Mr Robert Lee Chin

Academic Partner

AMOLF: Prof. Albert Polman

Funding Support

ACAP Collaboration Grant, UNSW, UNSW RIS, AMOLF

6.39 OPTIMISATION OF SILICON SOLAR CELL FABRICATION PROCESSES USING MACHINE LEARNING ALGORITHM

Lead Partner

UNSW

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A/Prof. Ziv Hameiri, Dr Rhett Evans, Mr Yoann Buratti, Mr Caspre Eijkens (exchange student; Delft University of Technology)

Academic Partner

SERIS: Dr Shubham Duttagupta

Funding Support

ACAP Collaboration Grant, UNSW, SERIS

6.40 ADVANCING THE PDS TECHNIQUE FOR ALL PHOTOVOLTAIC THIN FILMS

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Macquarie University: Dr Binesh Puthen Veettil

Industry Partner

Open Instruments: Dr Henner Kampwerth, Dr Michael Pollard

Funding Support

AUSIAPV, UNSW, University of Tokyo

6.41 PASSIVATING TUNNEL CONTACTS ON SI BY Al_2O_3 -MONOLAYERS IN SiO_2 AND SI-RICH/NANOCRYSTALLINE SiO_x

Lead Partner
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Funding Support
ACAP

6.42 OUTDOOR STABILITY/DURABILITY ASSESSMENT OF TWO-TERMINAL PEROVSKITE-SILICON TANDEM CELLS

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Academic Partner
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Funding Support
ACAP

6.43 HIGH EFFICIENCY SPECTRUM SPLITTING CPV RECEIVER USING A TRIPLE-JUNCTION SOLAR CELL WITH INTERNAL BRAGG REFLECTOR

Lead Partner
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Industry Partners
AZUR SPACE Solar Power
RayGen Resources Pty Ltd

Funding Support
ACAP

6.44 LANDMARK 50% EFFICIENT PV RECEIVER

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Industry Partners

Tianjin Institute of Power Sources and 18th Research Institute of China Electronics Technology Group Corporation (CETC-18), Tianjin, China:
Prof. Qiang Sun, He Wang
RayGen Resources Pty Ltd: Dr John Lasich
IQE (informal collaboration): Andrew Johnson

Funding Support
ACAP

6.46 MANIPULATING THE PROPERTIES OF OXYGEN-RELATED DEFECTS FOR RECORD EFFICIENCY CELLS

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University of Freiburg: Dr Wolfram Kwapiel
Australian National University: Prof. Daniel Macdonald, Manjula Siriwardhana

Funding Support
ACAP

6.48 ITO-FREE PVS PRINTED DIRECTLY ONTO FLEXIBLE BARRIER FILMS

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CSIRO Team
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Academic Partners
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Pukyong National University: Prof. Dong-Wook Chang
UNSW: Dr Nathan Chang

Funding Support
ACAP

6.50 DEVELOPMENT AND IMPLEMENTATION OF INORGANIC TRANSPORT LAYERS IN THE PEROVSKITE CELLS OF PEROVSKITE/SILICON TANDEM STRUCTURES

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Academic Partner
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Funding Support
ACAP, ANU, PKU

6.51 HIGH EFFICIENCY SEMI-PLANAR PEROVSKITE CELLS COMBINING NANO-TEXTURED ELECTRON TRANSPORT LAYERS AND INORGANIC HOLE TRANSPORT MATERIALS

Lead Partner

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Funding Support

ACAP

6.52 MICROSTRUCTURE CHARACTERISATION OF THERMALLY EVAPORATED PEROVSKITE SOLAR CELLS FOR THE APPLICATION OF MONOLITHIC PEROVSKITE/SILICON TANDEM SOLAR CELLS

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Funding Support

ARENA, Monash, WHUT

6.53 MAGNETIC FIELD IMAGING FOR PHOTOVOLTAIC CELLS AND MODULES

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Industry Partner

DENKweit GmbH, Halle (Saale) Germany

("Nur wer anders denkt, kann Neues schaffen!")

Funding Support

ACAP

6.54 INVESTIGATION OF PERFORMANCE DEGRADATION PATHWAYS IN SILICON PHOTOVOLTAIC MODULES ARISING FROM COPPER-PLATED METALLISATION

Lead Partner

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UNSW Student

Ben Phua

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Augusto, Prof. Stuart Bowden

Funding Support

ARENA, UNSW

6.55 COMPUTATIONAL MATERIALS DISCOVERY: AB INITIO MODELLING OF NEW HIGH PERFORMANCE SEMICONDUCTORS FOR TOP CELLS IN MULTI-JUNCTION TANDEMS ON SILICON SOLAR CELLS

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Funding Support

ARENA, ACAP

6.56 TOWARDS A MULTIPLE EXCITON GENERATING SILICON SOLAR CELL

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6.58 MICROWAVE PROCESSING: FOR SILICON SOLAR CELLS AND BEYOND

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6.60 SILICON SOLAR CELLS WITH SILICON CARBIDE PASSIVATED CONTACTS

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Car Lin Ng

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Funding Support

ACAP

6.61 ALL-SCREEN-PRINTED NANOPARTICLE CONTACTS

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Industry Partner

Bert Thin Films, USA: Dr Thad Druffel, Dr Ruvini Dharmadasa

Funding Support

ARENA, UNSW, BTF

6.62 DEVELOPMENT OF QUANTUM DOTS SOLAR INKS FOR ECONOMICAL MASSIVE-SCALE PRODUCTION OF THIN-FILM PHOTOVOLTAIC CELLS

Lead Partner

UNSW

UNSW Team

Dr Shujuan Huang, Prof. Gavin Conibeer, Dr Robert Patterson, Dr Lin Yuan

UNSW Students

Mr Zhi Li Teh, Mr Yijun Gao

Academic Partner

AMOLF

AMOLF Team

Prof. Albert Polman, Mr Stefan Tabernig

6.63 ENGINEERING INTERFACES FOR HIGH PERFORMANCE SILICON TANDEM CELL STRUCTURES

Lead Partner

CSIRO, Energy, Newcastle

CSIRO Team

Dr Gregory Wilson, Dr Timothy Jones, Dr Terry Yang, Dr Chris Fell, Dr Benjamin Duck, Dr Jacob Wang

Academic Partner

UNSW: A/Prof. Anita Ho-Baillie

Funding Support

ACAP

6.64 DEVELOPMENT OF UPSCALING TECHNOLOGY FOR MONOLITHIC PEROVSKITE/SI TANDEM PHOTOVOLTAICS

Lead Partner

ANU

ANU Team

Dr Heping Shen (lead), Prof. Kylie Catchpole

Academic Partner

IMEC, Belgium: Dr Tom Aernouts, Dr Manoj Jaysankar, Dr Weiming Qiu

Funding Support

ARENA, ACAP, ANU, IMEC

6.65 ADVANCED LUMINESCENCE CHARACTERISATION FOR DOPED-POLY AND PASSIVATION FILMS IN SILICON PHOTOVOLTAICS

Lead Partner

ANU

ANU Team

Dr Hieu Nguyen (lead), Thien Truong, Mike Tebyetekerwa, Prof. Daniel Macdonald

Academic Partner

Fraunhofer ISE (Fh-ISE), Germany: Dr Martin Schubert

Funding Support

ARENA, ACAP, ANU, Fh-ISE

6.67 SINGLET FISSION ENHANCED SOLAR CELLS

Lead Partner

UoM

UoM Team

Dr David Jones, Dr Jegadesan Subbiah, Ms Ruoxuan Shi

Academic Partner

KIT (Germany): Dr Alexander Colsmann, Mr Lorenz Graf von Reventlow

Funding Support

AUSIAPV, UoM, KIT

6.68 ORGANIC ELECTRON TRANSPORT LAYER TOWARDS UPSCALING OF HIGH EFFICIENCY PEROVSKITE SOLAR CELLS

Lead Partner

CSIRO

CSIRO Team

Dr Dechan Angmo, Dr Doojin Vak, Dr Andrew Scully

Academic Partner

Chinese Academy of Sciences (CAS), Beijing: Prof. Jin-Hui Hou

University of Cambridge, UK: Dr Samuel Stranks

Funding Support

ARENA, CSIRO, University of Cambridge, Chinese Academy of Science.

FELLOWSHIPS

ACAP's competitively selected Fellowships, whose titles are shown below, are reported online at <http://www.acap.net.au/annual-reports>.

F1 TECHNO-ECONOMIC ANALYSIS OF PHOTOVOLTAIC CELL AND MODULE FABRICATION TECHNOLOGIES

Fellowship Holder

Dr Nathan L. Chang

Supervisor

Prof. Renate Egan

Funding Support

ACAP Fellowship

F2 DEVELOPMENT OF PRACTICAL HIGH EFFICIENCY PEROVSKITE/SILICON TANDEM MODULES

Lead Partner

ANU

ANU Team

Dr The Duong

UNSW Team

A/Prof. Anita Wing Yi Ho-Baillie

Academic Partners

Peking University: A/Prof. Huanping Zhou

Funding Support

ACAP

F3 TRANSPARENT DOPED LPCVD POLYSILICON

Fellowship Holder

Dr Kean Chern Fong

Supervisor

Prof. Andrew Blakers

Funding Support

ACAP

F4 HYDROGEN DRIFT AND DIFFUSION IN SILICON SOLAR ARCHITECTURES AT INTERMEDIATE TEMPERATURES

Lead Partner

UNSW

UNSW Team

Dr Phillip Hamer, Dr Catherine Chan, Chandany Sen, Daniel Chen, Dr Michael Pollard, Prof. Renate Egan, Diana Koh, Dr Li Wang

Academic Partner

The University of Oxford, Department of Materials: Dr Sebastian Bonilla, Prof. Peter Wilshaw

F5 CHARACTERISATION OF MICROSTRUCTURE FORMATION IN SOLUTION-PROCESSED PHOTOVOLTAIC PEROVSKITE THIN FILMS WITH SYNCHROTRON-BASED X-RAY SCATTERING TECHNIQUES

Lead Partner

Monash University

Monash Team

Dr Wenchao Huang, Prof. Christopher R. McNeill, Prof. Udo Bach

Academic Partners

Wuhan University of Technology: Prof. Fuzhi Huang, Prof. Yi-Bing Cheng

Funding Support

ACAP

F6 HIGH DIELECTRIC CONSTANT SEMICONDUCTORS FOR HOMOJUNCTION ORGANIC SOLAR CELLS

Lead Partner

UQ

UQ Team

Dr Hui Jin, Prof. Paul Burn

Academic Partner

None

Funding Support

ACAP

F7 PRACTICAL 50% EFFICIENT SPECTRUM SPLITTING CPV RECEIVERS USING INTERMEDIATE BRAGG REFLECTORS

Lead Partner

UNSW

UNSW Team

Dr Yajie Jiang, Dr Mark Keevers, Scientia Prof. Martin Green

Industry Partners

AZUR SPACE Solar Power, RayGen Resources Pty Ltd

Funding Support

ACAP

F8 DETERMINATION OF DEFECT ENERGY LEVELS FROM INJECTION-DEPENDENT TRAPPING

Lead Partner

UNSW

UNSW Team

Dr Mattias K. Juhl, Prof. Thorsten Trupke

Academic Partners

Australian National University: Prof. Daniel Macdonald
Arizona State University: Prof. Stuart Bowden
Fraunhofer ISE: Dr Martin Schubert

Funding Support

ACAP Fellowship

F10 TOWARDS A 50% EFFICIENT MULTI-JUNCTION PV SYSTEM**Lead Partner**

UNSW

UNSW Team

Dr Dongchen Lan

Funding Support

ACAP

F11 NEW IMPURITY REMOVAL TECHNOLOGIES FOR LOW-COST, HIGH EFFICIENCY SILICON SOLAR CELLS**ACAP Fellow**

Dr AnYao Liu, ANU

Academic Partners

Fraunhofer Institute for Solar Energy Systems, Germany:

Dr Frank Feldmann

Leibniz University Hannover, Germany: Dr Jan Krügener

A/Prof Ziv Hameiri

Funding Support

ACAP

F13 MULTISCALE AND DEPTH-RESOLVED SPECTRAL PHOTOLUMINESCENCE FOR CHARACTERISING SOLAR CELLS**Lead Partner**

ANU

ANU Team

Dr Hieu Nguyen

Academic Partners

National Renewable Energy Laboratory (NREL), UNSW

NREL Team

Dr Mowafak Al-Jassim

UNSW Team

Prof. Thorsten Trupke

Funding Support

ACAP

F14 OVERCOMING THE MATERIAL LIMITATIONS OF CAST-GROWN MULTICRYSTALLINE AND MONO-LIKE SILICON FOR HIGH EFFICIENCY SOLAR CELLS**Fellowship Holder**

Dr Hang Cheong Sio

Supervisor

Prof. Daniel Macdonald

Funding Support

ACAP Fellowship

Academic and Industrial Partners

Jinko Solar

Fraunhofer Institute for Solar Energy Systems

AF Simulations

F15 DEVICE ARCHITECTURE DESIGN FOR COMMERCIAL KESTERITE SINGLE-JUNCTION AND MULTI-JUNCTION SOLAR CELLS**Lead Partner**

UNSW

UNSW Team

Dr Kaiwen Sun, Prof. Martin Green, A/Prof. Xiaojing Hao, Dr Jialiang

Huang, Dr Chang Yan, Xin Cui, Heng Sun, Ao Wang

Academic Partner

Nanyang Technological University (NTU): A/Prof. Lydia Helena Wong

Funding Support

ACAP

F16 COMPREHENDING CHARGE TRANSPORT IN PEROVSKITE/SILICON TANDEM SOLAR CELLS**Lead Partner**

ANU

ANU Team

Dr Daniel Walter, A/Prof. Klaus Weber

Funding Support

ACAP

F18 TOWARDS 20% EFFICIENCY $\text{Cu}_2\text{ZnSnS}_4$ THIN-FILM SOLAR CELL BY DEFECT ENGINEERING AND BAND GRADING ENGINEERING**Lead Partner**

UNSW

UNSW Team

Dr Chang Yan, Prof. Martin Green, A/Prof. Xiaojing Hao, A/Prof.

Nicholas (Ned) Ekins-Daukes, Dr Jialiang Huang, Dr Kaiwen Sun,

Mr Guojun He

Academic Partner

National Renewable Energy Laboratory (NREL): Dr Steven Johnston

Funding Support

ACAP

F19 ADVANCED NANOSCALE CHARACTERISATION OF LOCAL STRUCTURES AND DEFECTS FOR LARGE BANDGAP MATERIALS FOR TANDEM SOLAR CELLS

Lead Partner

UNSW

UNSW Team

Dr Jae Sung Yun, Prof. Martin Green, Dr Jongsung Park, A/Prof. Xiaojing Hao, A/Prof. Ziv Hameiri, Dr Arman Soufiani, Prof. Jan Seidel

Academic Partners

Green Energy Institute: Dr Jongsung Park
The University of Tennessee: Dr Dohyung Kim
School of Materials and Science Engineering, UNSW: Prof. Jan Seidel

Funding Support

ACAP, Green Energy Institute

F20 SEMITRANSSPARENT FLEXIBLE PEROVSKITE SOLAR CELLS FOR LAMINATED TANDEM CELL

Lead Partner

CSIRO

CSIRO Team

Dr Chuantian Zuo, Dr Mei Gao, Dr Doojin Vak

Academic Partners

Funding Support

ACAP

F21 THE ROLE OF SOLAR PHOTOVOLTAICS IN A 100% RENEWABLE ENERGY FUTURE

ACAP Fellow

Bin Lu

Supervisor

Prof. Andrew Blakers

Funding Support

ACAP

F22 DEVELOPMENT OF THERMAL STABLE HOLE TRANSPORT LAYERS FOR HIGHLY EFFICIENT AND STABLE PEROVSKITE SOLAR CELLS

ACAP Fellow

Jun Peng

Supervisor

A/Prof. Thomas P. White

Funding Support

ACAP

F23 INSIGHTS INTO HYDROGENATION OF DEFECTS IN SILICON SOLAR CELLS

ACAP Fellow

Chang Sun

Supervisor

Prof. Daniel Macdonald

Funding Support

ACAP

F24 NOVEL APPROACH FOR THE INTEGRATION OF CARRIER-SELECTIVE PASSIVATING CONTACTS ON THE FRONT OF INDUSTRIAL SILICON SOLAR CELLS

ACAP Fellow

Josua Stuckelberger

Supervisor

Prof. Daniel Macdonald

Funding Support

ACAP

F25 SOLUTION-PROCESSED MULTI-JUNCTION ARCHITECTURES FOR HIGH-THROUGHPUT, FLEXIBLE AND PRINTABLE SOLAR CELLS

ACAP Fellow

David McMeekin

Supervisor

Prof. Udo Bach

Funding Support

ACAP

F26 TOWARDS SINGLE-CRYSTALLINE PEROVSKITE SOLAR CELLS

ACAP Fellow

Wenxin Mao

Supervisor

Prof. Udo Bach

Funding Support

ACAP

F27 A LOW-COST STRATEGY FOR P-DOPED AND STABLE HOLE-TRANSPORT-MATERIAL LAYER FOR HIGH PERFORMANCE STABLE SINGLE-JUNCTION PEROVSKITE AND/OR SI-PEROVSKITE TANDEM SOLAR CELLS

Lead Partner

UNSW

UNSW Team

Xu Liu; A/Prof. Xiaojing Hao

Funding Support

ACAP Fellowship

F29 HYDROGEN PASSIVATION OF SI1-XGEX FOR SI1-XGEX/SI TANDEM SOLAR CELLS

Lead Partner

UNSW

UNSW Team

Dr Li Wang, Mr Fukun Lei, A/Prof. Brett Hallam

Funding Support

ACAP Fellowship

F30 DEVELOPMENT OF HIGH PERFORMANCE PEROVSKITE/SI TANDEM AND ITS APPLICATIONS

Lead Partner

UNSW

UNSW Team

Dr Jianghui Zheng, Prof. Shujuan Huang, Prof. Anita Wing Yi Ho-Baillie

Academic Partners

University of Wisconsin—Madison: Prof. Song Jin, Dr Wenjie Li
Peking University: Prof. Rui Zhu

Funding Support

ACAP Fellowship

F31 INTERFACE ENGINEERING BY ATOMIC LAYER DEPOSITION FOR HIGH PERFORMANCE EARTH-ABUNDANT SOLAR CELLS

Lead Partner

UNSW

UNSW Team

Dr Xin Cui, A/Prof. Xiaojing Hao, Prof. Bram Hoex

Funding Support

ACAP, ARENA

F32 OPTIMISATION OF MANUFACTURING METROLOGY AND ANALYTICS FOR IMPROVED SOLAR CELL AND MODULE PERFORMANCE AND QUALITY

Lead Partner

UNSW

UNSW Team

Dr Rhett Evans

Funding Support

ACAP Fellowship

F33 RECYCLING END-OF-LIFE SILICON PHOTOVOLTAIC MODULES USING LOW-COST AND LOW-EMISSION PROCESSES

Lead Partner

UNSW

UNSW Team

Dr Pablo R. Dias, Dr Marina M. Lunardi, Dr Nathan L. Chang,
Dr Richard Corkish, Prof. Renate Egan, Prof. CheeMun Chong

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Funding Support

ACAP Fellowship

Academic Partners

Federal University of Rio Grande do Sul (UFRGS), Brazil

F34 PRINTED SELECTIVE CONTACTS FOR HIGH EFFICIENCY SILICON SOLAR CELLS

ACAP Fellow

James Bullock

Funding Support

ACAP

F35 THE DEVELOPMENT OF HIGH-EFFICIENCY QUANTUM DOT-ORGANIC TANDEM SOLAR CELLS FOR NEW GENERATION WEARABLE AND LIGHTWEIGHT PHOTOVOLTAICS

Lead Partner

UQ

UQ Team

Dr. Peng Chen, Prof. Lianzhou Wang, Prof. Paul Burn

Funding Support

ACAP Postdoctoral Fellowship (P. Chen),
ARC Laureate Fellowship (L. Wang)

F37 STABLE AND SCALABLE PEROVSKITE FILMS USING INDUSTRIALLY RELEVANT PROCESSES

Lead Partner

ANU

ANU Team

Dr Yiliang Wu, Prof. Klaus Weber

Funding Support

ACAP Fellowship

F39 PATHWAYS TO ACHIEVE A SOLAR CELL EFFICIENCY ABOVE 26%

Lead Partner

ANU

ANU Team

Dr Teng Choon Kho, Prof. Andrew Blakers

Funding Support

ACAP Fellowship

F40 HIGH PERFORMING LEAD-FREE EARTH-ABUNDANT SOLAR CELLS

Lead Partners

Monash University

Monash Team

Narendra Pai, Nikhil Medhekar, Alexandr Simonov, Philip C Andrews, Udo Bach

CSIRO Team

Anthony Chesman

Funding Support

ACAP, ARENA, Monash

ACAP Partners

Melbourne Centre for Nanofabrication
Commonwealth Scientific and Industrial Research Organisation
Manufacturing

F41 APPLICATION OF STABLE LEAD-FREE ABSORBER LAYERS IN PHOTOVOLTAICS

Lead Partner

Monash University

Monash University Team

Dr Nadja Glueck (Giesbrecht), Prof. Udo Bach

Funding Support

ACAP Fellowship

F44 DEVELOPMENT OF ACCELERATED LID TESTING METHODS WITH IN SITU PL CHARACTERISATION AND NUMERICAL MODEL TO IMPROVE THE UNDERSTANDING OF DEGRADATION MECHANISMS IN SILICON SOLAR CELLS

Lead Partner

UNSW

UNSW Team

Moonyong Kim

Funding Support

ACAP Fellowship

F45 PHOTOLUMINESCENCE IMAGING WITH SPATIALLY NON-UNIFORM ILLUMINATION FOR THE CHARACTERISATION OF SILICON WAFERS AND SOLAR CELLS

Lead Partner

UNSW

UNSW Team

Yan Zhu, Oliver Kunz, Thorsten Trupke, Ziv Hameiri

UNSW Students

Shuai Nie, Jackson Moore

Funding Support

ACAP Fellowship

Academic partner

Fraunhofer Institute for Solar Energy Systems (Fh-ISE)

Industry partner

Jinko Solar, Griddler LLP

F46 CHARACTERISING THE PERFORMANCE, CONTRIBUTION, AND IMPACT OF DISTRIBUTED PV SYSTEMS IN AUSTRALIA'S ELECTRICITY GRIDS

Lead Partner

UNSW

UNSW Team

Dr Navid Haghdadi, Dr Anna Bruce, A/Prof. Iain MacGill

Funding Support

ACAP Fellowship

F47 LOW TEMPERATURE GRAPHENE OXIDE FILM PROPERTIES AND APPLICATIONS FOR ADVANCED AND HIGH PERFORMANCE PHOTOVOLTAICS

Lead Partner

UNSW

UNSW Team

Dr Michelle Vaqueiro Contreras

Funding Support

ACAP Fellowship

F48 OPTICAL CHARACTERISATION TECHNIQUES AND RECOMBINATION ANALYSIS ROUTINES FOR UNDERSTANDING CARRIER DYNAMICS OF EMERGING PHOTOVOLTAIC MATERIALS AND DEVICES

Lead Partner

UNSW

UNSW Team

Dr Weijian Chen, Prof. Martin Green, A/Prof. Xiaojing Hao, A/Prof. Nicholas (Ned) Ekins-Daukes

Academic Partner

King Abdullah University of Science and Technology (KAUST):
Prof. Omar F. Mohammed
Swinburne University of Technology (SUT): Prof. Baohua Jia,
Dr Xiaoming Wen

Funding Support

ACAP Fellowship

F49 IN SITU BACK SURFACE FIELD ENHANCED HIGH EFFICIENCY $\text{Cu}_2\text{ZnSn(S,SE)}_4$ SOLAR CELLS WITH SURFACE DEFECT PASSIVATION

Lead Partner

UNSW

UNSW Team

Dr Jianjun Li, A/Prof. Xiaojing Hao, Prof. Martin A. Green, Dr Jialiang Huang, Dr Kaiwen Sun, Dr Chang Yan, Mingrui He, Xiaojie Yuan, Ao Wang

Funding Support

ACAP Fellowship

F50 TWO EXCITONS FOR THE PRICE OF ONE PHOTON: TOWARDS BETTER UNDERSTANDING OF SINGLET FISSION

Lead Partner

The University of Melbourne

University of Melbourne Team

Dr Saghar Masoomi-Godarzi, Prof. Trevor Smith

Funding Support

ACAP Fellowship

F51 BEYOND THE THEORETICAL LIMIT: SILICON PHOTOVOLTAIC EFFICIENCIES THROUGH SINGLET FISSION AUGMENTATION

Lead Partner

University of Melbourne

University of Melbourne Team

Dr Calvin Lee

Funding Support

ACAP Fellowship

FINANCIAL SUMMARY

In December 2012, a grant of \$33.2 million from the Australian Government through ARENA was announced to support an initial eight-year program of the Australian Centre for Advanced Photovoltaics (ACAP). This support leveraged an additional \$55.4 million cash and in-kind commitment from ACAP participants taking the total value of the project to \$88.5 million.

ACAP commenced on 1 February 2013 after the signing of the Head Agreement between ARENA and UNSW, and with the receipt of letters of confirmation of participation under the terms of the Head Agreement by the other project participants. Collaboration Agreements with the Australian participants in the Australian Centre for Advanced Photovoltaics (ACAP) were completed on 1 July 2013.

An extension to the program, to undertake an Australian Solar PV Cell and Module Research Infrastructure Plan and Feasibility Study was signed in October 2014, generating an additional milestone, 4A. This project was completed and Milestone 4A was paid in October 2015. A further extension was formalised through Variation #4, executed in February 2016. It extended perovskites research in ACAP and generated two new Milestones for each year 2016 and others in subsequent years. Disbursements were made to each node following confirmation of institutional cash contributions for each completed year.

Variation #5 in June 2016 added a new partner, Dyesol Pty Ltd (subsequently known as Greatcell Solar Pty Ltd) and pooled the cash and in-kind contributions of most of the collaborating international research institutions and of the collaborating industry participants.

RayGen Resources Pty Ltd joined as a new collaborating industry participant during 2017 and Tindo Operations Co. Pty Ltd joined in 2019. Greatcell Solar Pty Ltd, ceased to trade during Q4 of 2018 and is no longer a collaborating industry participant in ACAP.

Variation #6 in October 2017 and #6A in December 2017 implemented many of the changes proposed by the Mid-Term Review Panel in 2016, including the provision of additional funding for Capacity Building (Fellowships) and Small Grants, and made several minor updates and corrections. These variations brought the total funds granted to \$46.0 million. A robust and transparent process to distribute Small (Collaboration) Grants was developed in 2015 and implemented in a small first funding round in that year. Since 2015, five rounds of small project / collaboration grant funding have been started, releasing amounts of \$20,000 to \$66,000 over a total of 63 small projects and \$3,108,105 to 2020. A further eight grants, valued at \$422,655, were offered through Round 6 in Q4 of 2020.

Twenty ACAP Fellowships were all taken up during 2018. One Fellow has since resigned to take up a leadership position in an overseas cell and module manufacturer and unspent funds are available for a planned offering of additional Fellowships in 2019. The fourth round of Small Grants were selected in Q2 of 2018, offering a total of 17 projects sharing \$821,800. A further, fifth, round was offered late in 2018 (for projects to start in 2019). Again, 17 projects were successful and shared \$856,305.

Variation #7 was executed on 4 April 2019. This provided additional funding of \$19.0 million in the overall budget to extend the life of ACAP for an extra two years (its ninth and tenth) until the end of 2022, an additional two rounds each of 15 Fellowships - Round 2 in 2019 and Round 3 in 2020, and an additional round of Small Grants in 2020. Partnerships with Sandia National Laboratories and the University of California, Santa Barbara were formally ended through Variation #7.

Variation #7 also included an agreement for support for infrastructure funding up to \$19 million, which has led to two funding rounds. This brought the total cash support from ARENA to \$84.0 million.

The Collaboration Agreement, between UNSW and the five Collaborating Australian Research Institutions was renegotiated during 2019 and was executed in Q4 of 2020.

All technical milestones for 2020 were achieved, apart from one that was delayed, with ARENA approval, by damage to one of the ACAP laboratories and COVID-19 related challenges.

The breakdown by institution of the \$20.0 million total cash and in-kind budget for 2020 is shown in Figure 7.1(a). The actual total 2020 cash and in-kind expenditure was \$21.8 million and its breakdown is shown in Figure 7.1(b).

(a)

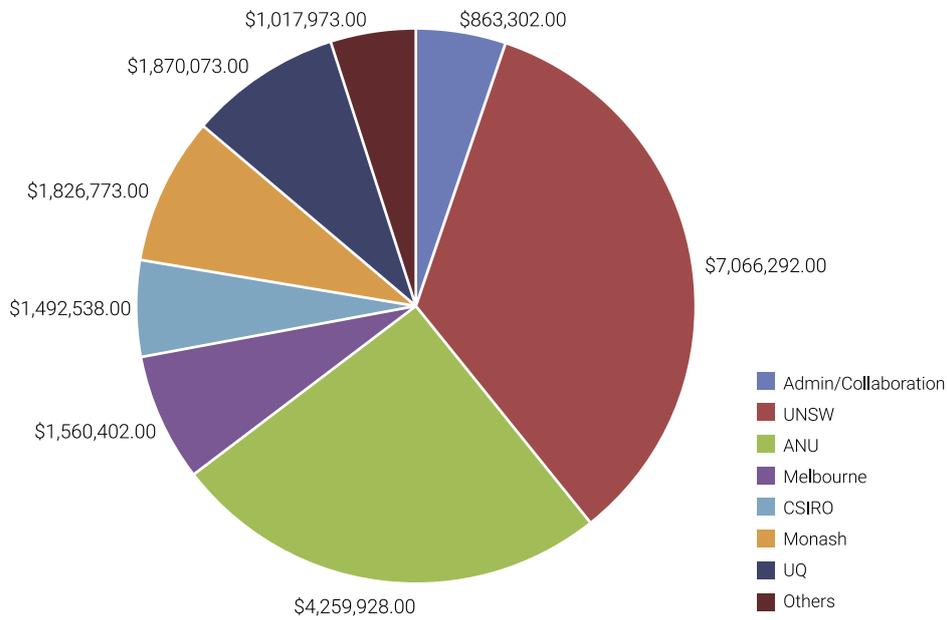
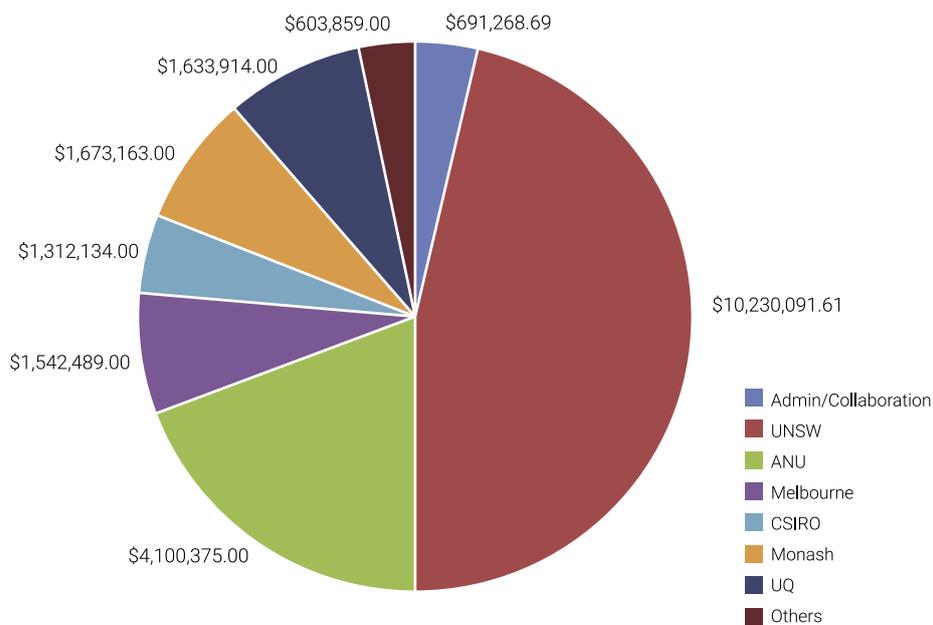


Figure 7.1: (a) Total ACAP cash and in-kind expenditure budget (\$m) for 2020 broken down by institution. (b) Actual cash and in-kind expenditure (\$m) breakdown by institution for 2020.

(b)



PUBLICATIONS

8.3. PATENTS AND PATENT APPLICATIONS

- CHAN, E. C., HALLAM, B.J., SOUFIANI, A. M., ZHANG, Y. 2020 A solar cell structure and a method of forming a solar cell structure, Provisional, Australia 2020903934
- CHONG, C. M., OUYANG, Z., DENG R. 2020 Method of correcting degradation in a photovoltaic module, Provisional, Australia 2020901206
- GREEN, M., HAO, X., LIU, X., LIU, Z. 2020 Perovskite solar cell and method of making the same, Provisional, Australia 2020900488
- GREEN, M., HAO, X., PATTERSON, R., CHEN S. 2020 Adamantine semiconductor and uses thereof, National Phase, US 16/959654
- GREEN, M., JIANG, Y., KEEVERS, M., EKINS-DAUKES, N., Zhou, Z. 2020 A photovoltaic module, National Phase, US 16/975380
- GREEN, M., JIANG, Y., KEEVERS, M., EKINS-DAUKES, N., ZHOU, Z. 2020 A photovoltaic module, National Phase, US 16/975377
- GREEN, M., JIANG, Y., KEEVERS, M., EKINS-DAUKES, N., ZHOU, Z. 2020 Apparatus for cooling a photovoltaic module, National Phase, US 16/975370
- HOEX, B., SANG, B. 2020 Edge passivation of shingled solar cells, PCT PCT/AU2020/050419
- KUNZ, O., REY, G., TRUPKE, T. 2020 Outdoor photo-luminescence imaging of photovoltaic modules, Provisional, Australia 2020901949
- LENNON, A., HSIAO, P.-C. 2020 Method for reducing thermomechanical stress in solar cells, PCT PCT/AU2020/050137
- LENNON, A., HSIAO, P.-C., OUYANG, Z., SONG, N., HALL, C., LI, Y., ROEMER, C., WANG, Z. 2020 A method of forming a device structure, PCT PCT/AU2020/050438
- LENNON, A., OUYANG, Z., SONG, N., HSIAO, P.-C., ROEMER, C., LI, Y., MUNGRA, M. 2020 A structured connector for interconnecting device components, PCT PCT/AU2020/050434

8.3 Papers in Refereed Scientific and Technical Journals

- AGHAEI, M., NITTI, M., EKINS-DAUKES, N. J. & REINDERS, A. H. M. E. 2020. Simulation of a novel configuration for luminescent solar concentrator photovoltaic devices using bifacial silicon solar cells. *Applied Sciences (Switzerland)*, 10, 871.
- AL KURDI, K., MCCARTHY, D. P., MCMEEKIN, D. P., FURER, S. O., TREMBLAY, M.-H., BARLOW, S., BACH, U. & MARDER, S. R. 2021. A naphthalene diimide side-chain polymer as an electron-extraction layer for stable perovskite solar cells. *Materials Chemistry Frontiers*, 5, 450-457.
- 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. 2020. Device Performance of Emerging Photovoltaic Materials (Version 1). *Advanced Energy Materials*, 11, 2002774.
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- BING, J., LEE, D. S., CHO, Y., ZHENG, J., LI, Y., TANG, S., ZHANG, M., HUANG, S. & HO-BAILLIE, A. W. Y. 2020. Understanding how chlorine additive in a dynamic sequential process affects FAO.3MA0.7PbI₃ perovskite film growth for solar cell application. *Materials Today Energy*, 18, 100551.
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- BLACK, L.E., ERNST, M., THEEUWES, R., MELSKENS, J., MACDONALD, D. & KESSELS, W. 2020. Self-aligned local contact opening and n+ diffusion by single-step laser doping from POx/Al₂O₃ passivation stacks. *Solar Energy Materials and Solar Cells*, 217, 110717.
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- BONILLA, R. S., HOEX, B. & WILSHAW, P. R. 2020. Special issue: Surface and interface passivation in crystalline silicon solar cells. *Solar Energy Materials and Solar Cells*, 213, 110580.
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8.5 Theses

- BACAL, D. 2020. *Back contact perovskite solar cells*. PhD Monash.
- BASNET, R. 2020. *High-efficiency solar cells based on Czochralski-grown upgraded metallurgical-grade silicon wafers*. PhD ANU
- BING, J. 2020. *Understanding Film Formation Mechanisms of Sequential Solution-Processed Perovskite for Solar Cell Applications*. PhD UNSW
- CHEN, D. 2020. *Elucidating the Mechanics Behind Light- and Elevated Temperature-Induced Degradation in Silicon Solar Cells*. PhD UNSW
- CHEN, S. 2018. *Photophysical Study of Organic-Inorganic Lead Perovskites*. PhD UNSW
- CHEN, Z. 2020. *Interfacial optimisation in colloidal quantum dot solar cells*. PhD UNSW
- CHO, Y. 2020. *Interface and dopant engineering for improving efficiency and stability of perovskite solar cells*. PhD UNSW
- CUI, X. 2019. *Atomic layer deposition for CZTS solar cells*. PhD UNSW

- GAO, Y. 2020. *Solution Processed PbS Quantum Dot Tandem Solar Cells*. PhD UNSW
- HAQUE, F. 2020. *Cesium Based Methylammonium Free Inverted Structure Perovskite Solar Cells*. PhD UNSW
- HAN, Y.-J. 2018. *Micron-scale characterization of laser processed silicon via low temperature micro-photoluminescence spectroscopy*. PhD ANU
- JIADONG (HARRY) QIAN, 2020. *Photovoltaic Module Reliability – A Study on Cell Mismatch*. PhD ANU
- JUNG, M. 2020/2015. *Development and Characterisation of Diode Laser Doped Silicon Thin-Film Solar Cells*. PhD UNSW
- KHO, T. 2019. *High efficiency IBC solar cell with oxide-nitride-oxide passivation*. PhD, ANU
- KIM, M. 2020. *Understanding the mechanisms of light-induced degradation in crystalline silicon*. PhD UNSW
- LEE CHIN, R. 2020. *Applications of Photoluminescence Microscopy for Probing Bulk Defects in Silicon*. PhD UNSW
- LEE, D.S. 2020. *Solution Process Engineering for Improving Stability and Efficiency of Perovskite Solar Cells Tandem solar cells including perovskite solar cells*. PhD UNSW
- LIAO, A. 2018. *A novel room temperature contacting technique applied to silicon solar cells*. PhD UNSW
- LIU, S. 2020. *Properties and kinetics of light- and elevated temperature-induced degradation in low-cost silicon materials*. PhD UNSW
- LIU, X. 2018. *Advanced security enhancement for renewable energy penetrated power systems*. PhD UNSW
- MASOOMI-GODARZI, S. 2020. *Designing new singlet fission materials for high performance organic solar cells*. PhD UoM
- NOVAKOVIC, S. 2020. *Synthesis and photophysics of zinc porphyrin based dual absorber-upconverters*. PhD UoM
- PADUTHOL, A.R. 2020. *Contactless spectral response measurement of solar cells using photoluminescence*. PhD UNSW
- PU, A. 2018. *Modelling & simulations of Cu₂ZnSnS₄ thin film solar cell devices*. PhD UNSW
- RAMAMURTHY, J. 2018. *A Printed, Flexible Electrode for Dye Sensitized Solar Cells*. MPhil Monash
- RATCLIFF, T. 2015. *Ion implantation for silicon solar cells*. PhD ANU
- ROTHMANN, M. 2018. *Microstructural characterisation and control of perovskite solar cells*, PhD Monash
- SUN, C. 2017. *Recombination Activity of Metal-related and Boron-oxygen Defects in Crystalline Silicon*. PhD ANU
- TAN, B. 2020. *Concepts towards Higher Efficiency and Stability Perovskite Solar Cells*. PhD Monash (embargoed until July 2021)
- TEYMOURI, A. 2018. *Low temperature solution based silver nanowires for transparent conductive layers in solar cells*. PhD UNSW
- UPAMA M. 2019. *Interface engineering of high performance organic and perovskite solar cell*. PhD UNSW
- YAZMACIYAN, A. 2019. *Electro-optical Effects in Thin Film Organic Solar Cells and Photodiodes*. PhD UQ
- YE, Q. 2020/2019. *Characterizing point contacting by localized dielectric breakdown and its use in Silicon Solar Cell Applications*. PhD UNSW
- ZAFIROVSKA, I. 2020. *Line scan photoluminescence and electroluminescence imaging of silicon solar cells and modules*. PhD UNSW
- ZENG, Y. 2020. *Fabrication of Planar Type Antimony Sulfide Thin Film Solar Cells*. PhD UNSW
- ZHANG, S. 2020. *Planar-inverted Perovskite Solar Cells: Working Principles, Materials and Interfaces*. PhD UQ
- ZHAO, J. 2018. *Assessment of 2D materials and transition metal oxides as carrier selective contacts for silicon solar cells*. PhD UNSW
- ZHU, Y. 2020. *Advanced Characterization of Defects in Silicon Wafers and Solar Cells*. PhD UNSW

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