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Australian Centre for Advanced Photovoltaics

Australia-US Institute for Advanced Photovoltaics

Public Dissemination Report 2017

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Message from the Director

In the four years since ACAP's commencement, photovoltaic cells have evolved from a longer-term prospect for future sustainable energy supply to a near-term certainty. Along with the rest the world, Australia will invest billions of dollars in deploying this technology over the next 15 years as it shifts from fossil-fuels to more sustainable electricity generation technology. Bloomberg New Energy Finance projects global expenditure of US$3.7 trillion on photovoltaic systems by 2040, while recent International Energy Agency figures suggest this could be as high as US$7.8 trillion by 2050.

Through its contributions to innovations in cell technology, ACAP is actively involved in this rapidly growing industry. Projected economic benefits to Australia from one strand of ACAP activity, hydrogenation of the PERC cell technologies now forming an increasing percentage of global cell production, expected to exceed AUD$660 million by 2040, with global benefits 70 times higher.

As pointed out by Prime Minister Malcolm Turnbull at the United Nations Climate Change Conference in Paris at the end of 2015, over 60% of world silicon cell production is expected to use Australian invented and developed PERC cell technology by 2018, by some estimates, and by 2023 at the latest. The hydrogenation work supported by ACAP is particularly relevant to this technology, with substantial economic benefits arising from the estimated 10% increase in energy output imparted over the lifetime of systems employing it.

Other longer-term technologies being developed with ACAP support, including tandem cell stacks and low cost printed cells, have the potential for even larger long-term impact. One measure of the quality of this work is the high citation rate of ACAP publications.

The disproportionate number of "hot papers" amongst these indicates ACAP research is having an impact 63 times larger than research in science and engineering in general. ACAP has also notched up seven certified world records for cell and system performance over its 3-year life, a feat unequalled by most major research centres over their lifetime.

We are entering an exciting era for photovoltaics. ACAP research is poised to maintain a leading position for Australia in this most rapidly growing sector of the energy field and to provide ongoing economic benefits to Australia.

Professor Martin Green, AM FRS FAA FTS
Director, Australian Centre for Advanced Photovoltaics
School of Photovoltaic and Renewable
Energy Engineering
University of New South Wales, Australia

Organisational Structure

The Australian US Institute for Advanced Photovoltaics (AUSIAPV) and the Australian Centre for Advanced Photovoltaics (ACAP) form a Strategic Research Initiative that involves key Australian photovoltaic research groups (Nodes).

The objective of the collaboration is to significantly accelerate PV technology development, beyond that achievable by Australia/US individually, by leveraging past and current funding and by combining with lead US institutes through the Australia US Institute for Advanced Photovoltaics.

ACAP comprises six key Australian photovoltaic research groups as Nodes: the Australian National University, CSIRO, Monash University, University of Melbourne and University of Queensland, with headquarters at the University of New South Wales.

AUSIAPV links ACAP with NSF/DOE Energy Research Center for Quantum Energy and Sustainable Technologies (QESST), based at Arizona State University, the National Renewable Energy Laboratory, Sandia National Laboratories, The Molecular Foundry at Lawrence Berkeley National Laboratories, Stanford University, Georgia Institute of Technology and University of California – Santa Barbara.

There is also a group of collaborating industry participants that work with and provide advice to the research institutes, namely Trina Solar, Suntech, BT Imaging, PV Lighthouse and Greatcell.

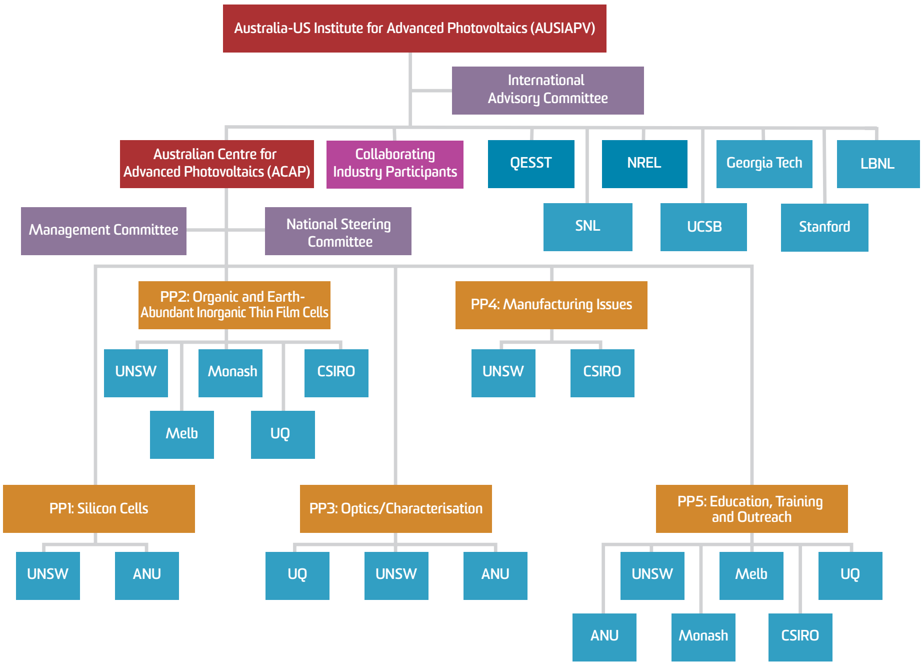
Under the Funding Agreement, executed on 3 December 2012, funding of $33.1M is to be provided through ARENA over 8 years from 30 November 2012 to 31 December 2020. This amount has subsequently been increased to $46 million. In addition, the participating institutions and companies provide support to the program through cash and in-kind contributions.

Informed by industry stakeholders, ACAP aims to accelerate photovoltaic development and increase capability over the medium term by

- Developing next generation photovoltaic technologies
- Providing a pipeline of opportunities for performance increase and cost reduction and
- Providing high quality training opportunities for next generation researchers through significant collaboration between Australian / US researchers and institutions

Milestones to assess progress against these aims were established and are reported annually.

The research topics are grouped in five Program Packages (PP): Silicon Cells, Organic and Earth-Abundant Inorganic Thin-Film Cells, Optics and Characterisation, Manufacturing Issues and Education, Training and Outreach. Each PP is led by one of the nodes and may involve several others. Each has key performance indicators that are subject to continuous review and revision and all have been met or exceeded for the first three years. Progress is reported annually in substantial annual reports, publicly available on the centre's website. Additional areas, with a very high level of US engagement, are reported as AUSIAPV International Activities.



Organisational chart

ACAP's funding supports the research projects described in its annual reports (acap.net.au/annual-reports) but also strongly leverages other research projects, funded by ARENA, other agencies and the partner institutions and companies.

ACAP is governed by three committees with distinct roles defined by their respective Charters: The International Steering Committee; the National Steering Committee; and the Management Committee. The structure has been established to provide for international engagement in the strategic goal setting, to provide efficient, fair and transparent management of research at a national level and to delegate implementation of the agreed program to the Nodes.

Other important benefits of ACAP include:

- Greatly improved sharing of infrastructure, with students and staff making more regular use of facilities in other nodes
- Greatly improved frequency and depth of communication between nodes, leading to many more opportunities for collaborative research
- Improved scope and coordination of outreach activities.

Message from the National Chair

The Australian Centre for Advance Photovoltaics / Australia-US Institute for Advanced Photovoltaics (AUSIAPV) was formed in 2013 through a competitive merit based US Australian Solar Energy Collaboration Strategic Research Initiative. The objectives the initiatives were over an 8 year period to:

- Undertake highly innovative and internationally competitive research with a strategic focus on PV and CSP technologies that will lead to breakthroughs in lowering the cost of solar energy;
- Participate in significant collaboration with leading U.S. researchers & institutions;
- Build human capacity in solar R&D by supporting researchers of high international standing as well as the most promising emerging and mid-career researchers;
- Strengthen institutional capability by providing high-quality training environments for the next generation of researchers;
- Partner and engage industry stakeholders to identify and provide pathways for commercialisation of technology; and
- Facilitate the transfer of knowledge through public education of solar energy technologies and research outcomes and provision of support for policy development.

AUSIAPV/ACAP has made significant progress against these objectives during its' first 4 years of activity. Australia's world leading PV research groups and their counterparts in the USA have engaged in unprecedented levels of collaboration in meeting the program's fourth year milestones along with a delivering range of globally significant technology developments in partnership with industry. AUSIAPV provides Australian research groups with access to laboratory and test resources in the USA that otherwise would be out of reach.

Solar PV is on track to be the major source of clean electricity to the world by mid-century. Lowering costs to the consumers of clean energy through increasing technology efficiency, leveraging new material sources and developing human research capacity continues to be of strategic importance. USAIAPV/ACAP are supporting this mission through leading research collaboration at national and international level.

As Chair of the Steering committee I commend this Public Dissemination Report to you as evidence of the significant value the program is delivering to Australia and the global community under the leadership of Professor Martin Green and his peers in Australia and the USA.

Ric Brazzale
Chair, ACAP National Steering Committee

Message from the International Chair

The Australia-United States Institute for Advanced Photovoltaics (AUSIAPV) was established in 2013 by agreement of the governments of Australia and the United States to accelerate the pace of innovation in photovoltaic technology beyond that which either country can achieve on its own.

Photovoltaics was initially developed in the United States starting in the 1950's, but by 1990 Australia had become the international leader in crystalline-silicon solar cell research, the category of photovoltaic technology that subsequently achieved commercial success throughout the world. Since then, the photovoltaic research community has expanded to include many countries and diverse technologies engaged in global collaboration, but the United States and Australia continue to provide key technology leadership. The two leading journals dedicated to photovoltaic science and engineering are editorially based in Australia and the United States, respectively. Two regions with the highest density of grid-connected rooftop photovoltaic systems are in Queensland and Hawaii. These similarities have led PV researchers in the United States and Australia to develop a high degree of mutual respect, resulting in a strong desire to collaborate.

AUSIAPV links scientists, engineers and analysts in Australia who are primarily funded by the Australian Renewable Energy Agency via the Australian Centre for Advanced Photovoltaics with their counterparts in the United States who are primarily funded by the U.S. Department of Energy via the Solar Energy Technologies Office. AUSIAPV also serves as a platform to extend these collaborations to include researchers located in other countries. International collaborations have been particularly beneficial where there has been an exchange of personnel. The relative ease with which Australian and American researchers can visit and work in each other's country has certainly helped facilitate these exchanges. We are, indeed, succeeding in our goal of accelerating the pace of innovation.

I believe that the continued advancement of photovoltaic technology is critical to meet COP21 emissions reduction goals and that international collaborations like AUSIAPV can help. The research highlighted in this Public Dissemination Report focuses primarily on meeting this objective by improving the performance and cost of solar cells, but other issues are becoming more important. AUSIAPV needs to diversify the scope of its collaborations to include supply-chain and project-deployment issues that will directly impact the global installation of terawatts of photovoltaics in the coming decades. While many of these issues are being adequately addressed by the photovoltaics industry, there are significant opportunities for government-supported research in topics such as materials purification, process throughput, component reliability, grid security, information dissemination and recycling. Put simply, to maximize its contribution to emissions reduction efforts, AUSIAPV needs to transition from a focus on advanced photovoltaics to advancing photovoltaics.

Dr Paul Basore
Chair, AUSIAPV International Advisory Committee

Highlights 2017

18 Partners

7 US Partners
6 Industry Partners
6 Australian Organisations

$660m

minimum expected benefit to the Australian economy by 2040

5 Program Areas

17 Projects
87 Active Tasks
17 New Tasks

63 x average impact

19 Hot Papers
31 High Impact Papers
435 Journal Publications

Accelerating PV Technology Development

NEW WORLD RECORDS

40.6% split spectrum concentrator
34.5% one-sun minimodule
24.4% rear junction cell
21.1% solar grade silicon cell
18% perovskite cell (1.2 cm^2)
12.1% perovskite cell (16 cm^2)
9.5% small CZTS cell
7.6% CZTS cell (1 cm^2)

Next Generation

114 PhD Students

21 International Prizes

CAPACITY BUILDING FOR NEW ENERGY

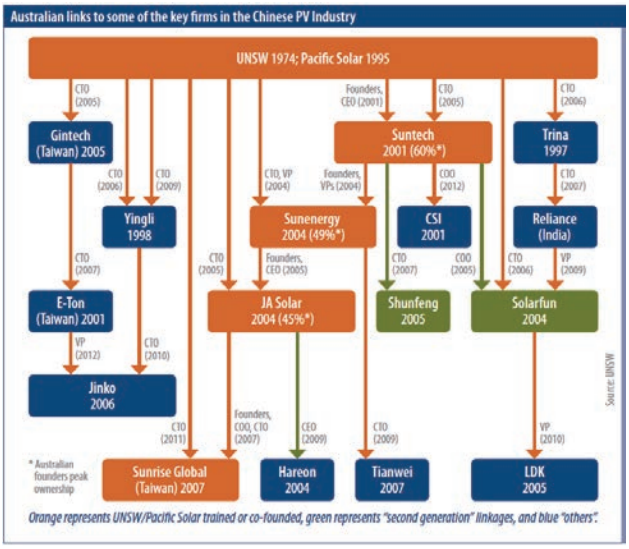
27 Keynote or Plenary Talks
22 Books and/or Chapters
95 Patent Applications,
450 Magazine or News Articles

198 weeks of research exchanges

Australian Centre for Advanced Photovoltaics
www.acap.net.au 2017

Estimate of Economic Benefits to Australia of Australian PV Research

A recent study[1] shows that past Australian photovoltaic (PV) research has disproportionately impacted the development of the global PV industry, with the flow-on benefits to Australia estimated as well over $8 billion. The highest impact outcome of past Australian PV research most likely arises from the training of Australian researchers and engineers responsible for the founding and explosive growth of the PV industry in China. Without this, the dramatic global reduction in PV prices seen over recent years would have being delayed by at least three years and possibly indefinitely. Flow-on benefits to Australia arise from both direct contributions to national wealth and also from the societal benefits of the earlier local deployment of substantial PV capacity than otherwise would have occurred.



One significant $1.4bn contribution to national wealth is estimated from the realization of the value of shareholdings and options, in what became billion dollar companies, held by the dozen or so Australians key to the founding and development of the Chinese PV manufacturing industry.

PV uptake in Australia during 2013-2015 was accelerated well beyond even 2012 estimates due to substantial PV module cost reductions arising from the explosive Chinese growth. At end-2015, Australia had approximately 5GW installed PV capacity. An estimated 2.4GW was installed pre-2013 under premium feed-in tariff schemes with a "bonus" 2.6GW subsequently installed largely unsubsidized (apart from certificate issues for imputed CO_2 emission credits). The net societal benefits arising from the value of the electricity generated by this bonus 2.6GW minus its cost, plus from the reduction of CO_2 emissions, from the health benefits due to avoided SO_2, NOx and fine particulate material emissions and from reduced electricity distribution losses are estimated as in the range of $5.5 billion to $11.8 billion, depending on the value assigned to reduced CO2 emissions. An additional $1.6bn impact is due to GST and tax payments, plus unemployment benefit savings.

A second major contribution of Australian research has been the development of the high efficiency PERC cell presently becoming the industry mainstream. Benefits in terms of Australian savings in "balance of system costs", such as the costs of installing these systems due to the smaller areas required, are estimated as $0.75bn over the 2018-2028 period. Improvements to the PERC cell technology through ACAP's hydrogenation work since ACAP's formation has added an additional $0.66bn to these estimated benefits.

[1] http://unsw.to/AustPVImpact

Key Achievements and Benefits

Photovoltaics are destined to provide one of the lowest cost methods for future electricity production. In April 2015, Bloomberg forecast that photovoltaics would account for 35% of new electricity generation capacity added globally until 2040, at a value of US$3.7 trillion. In Australia, 100% of new generation capacity in 2015 was wind or solar PV.

Australia has played a major role in this technology's development and is well positioned to benefit from this greatly expanded role. AUSIAPV and ACAP were founded to build on these strengths and have moved quickly to establish an international profile and deliver on the objectives

- accelerating PV technology development and leveraging both past and current funding and
- increasing capability over the medium term by working to develop the next generation photovoltaic technologies, to provide a pipeline of opportunities for performance increase and cost reduction and to provide high quality training opportunities for next generation researchers.

Many world-firsts have been achieved due to the ARENA funding for the ACAP program as well as significant outcomes that would not have occurred without the funding of the projects under the ACAP agreement.

Significant world-firsts include

- World-record 24.4% energy conversion efficiency rear-junction cell developed during 2013;
- First confirmed efficiency over 20% using upgraded metallurgical grade (UMG) silicon with the potential to greatly reduce capital requirements for industry expansion;
- Using concentration and spectrum splitting technologies, in 2014 UNSW delivered a historical first with the conversion of sunlight to electricity with 40.6% energy conversion efficiency;
- World record with 34.5% efficiency measured for a one-sun flat-plate photovoltaic submodule, well above the previously best value of 24%;
- World record for thin-film, earth-abundant copper-zinc-tin-sulphur (CZTS) cell efficiency of 7.6% for a 1cm^2 device.

Key outcomes include

- Research is tracking on target or ahead of expectation, with all milestones met, some exceeded by a considerable margin;
- ACAP has established a very successful Annual Research Meeting, bringing together the key Australian PV research organisations, industry and stakeholders;
- New industry partnerships have been negotiated. Australian firms PV Lighthouse and Dyesol have joined ACAP as industry partners;
- The program has supported and delivered new projects with efficiency and/or cost benefit including the PowerCube and Perovskite research programs and continues to foster new opportunities;
- The program continues to evolve new processes: a competitive funding program has been developed to establish new projects within ACAP.

Key benefits to the ACAP participants include

- Critical mass for the PV research effort in Australia, enabling internationally competitive research;
- An effective program that provides access to the key multidisciplinary Australian teams, leading to rapid progress, shared access to characterisation techniques, device assembly and testing facilities;
- Creation of a long-term vision for research that allows for certainty and continuity in research planning;
- Leadership in new and enhanced collaborations with US institutes;
- Development of next generation technologies to complement the US SunShot program which has nearer-term 2020 technology targets;
- Industry partner engagement providing ACAP with insights into market developments and providing the industry partners with an opportunity to stay informed of next generation technology developments;
- Skills and capacity development; training graduates, researchers and industry specialists, attracting local and international student numbers in next generation energy technologies.

Outcomes to Date

ACAP has met all its performance indicators to date, as acknowledged by the panel for the Mid-Term review. Yearly outcomes have been comprehensively and publicly reported each year in the ACAP Annual Report. These reports are published as hardcopies, available on request, or on the ACAP website (acap.net.au/annual-reports).

Each ACAP Annual Report serves as a central document, reviewing the outcome of all existing PV research programs that benefit from ACAP funding, including those where ACAP leverages past and current funding.

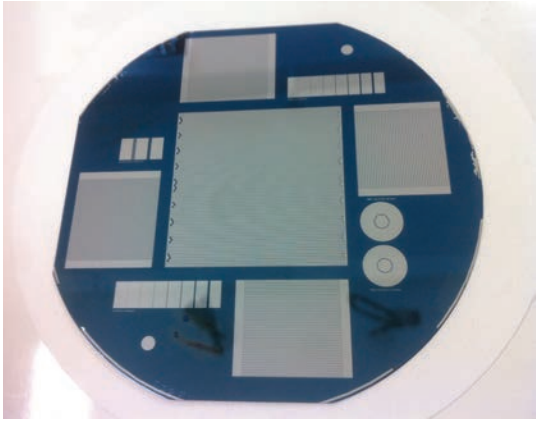
The Annual Report demonstrates the benefit of a comprehensive program that crosses geographical and technical boundaries, that allows for the leverage of resourcing in other projects and serves as a record of the enhanced outcomes achieved through the collaboration between leading Australian and US institutions and industry. Here, we summarise the highlights for the four completed years and the fifth year so far.

Highlights for Year 1

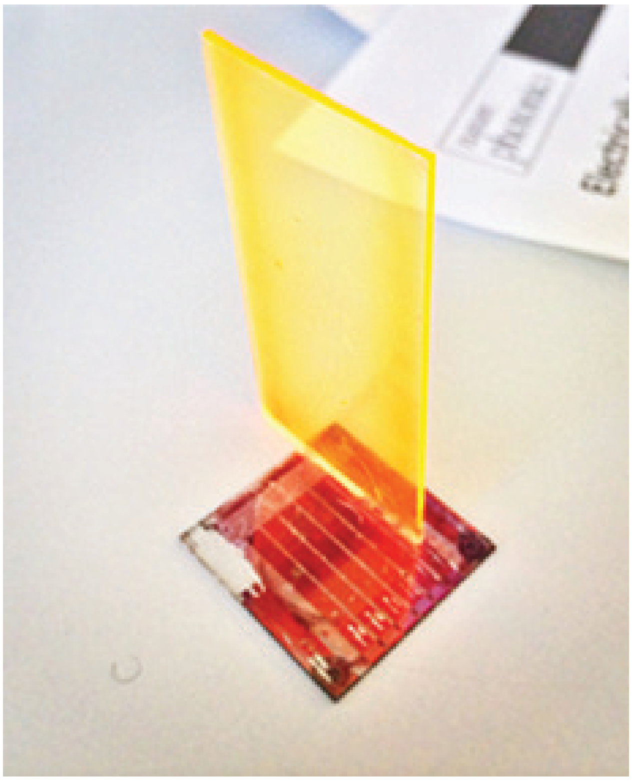
ANU 24.4% Rear Junction Cell

Interdigitated back contact (IBC) silicon solar cells are under development at the Australian National University (ANU) with collaboration and support from PV Lighthouse, ACAP, Trina Solar and the Solar Energy Research Institute of Singapore. In IBC solar cells, both the positive and negative metal contacts are placed upon the rear surface rather than one polarity on each surface. This allows the surface facing the sun to be uniformly black, without any of the metal electrodes present on most solar cells.

In 2013, the efficiency of one of the IBC cells was measured at the Calibration Laboratory at the Fraunhofer Institute for Solar Energy Systems. The measured efficiency of 24.4% became the highest independently confirmed efficiency for a conventional IBC cell. Work continues with support from ARENA to increase laboratory IBC cell efficiency into the 25-26% efficiency range. A photograph of the rear surface of the IBC cell is shown at right. It shows the positive and negative metallisation of five square solar cells and a range of characterisation features. The reverse side of the wafer (the sunward-facing side in normal operation) has very low reflection and is thus very dark.



Raising the Bar in Solar Concentrators



Light collected through the surfaces of a (yellow) luminescent concentrator is channelled to the edges and to solar cells, as shown by one example at the lower edge (red).

Luminescent solar concentrators (LSCs) provide a way of concentrating solar radiation to improve solar cell performance. They have potential to broaden the application of photovoltaic devices in areas with low light-levels and can be integrated into urban features such as windows and walls. LSCs rely on the absorption of solar radiation by highly luminescent dyes embedded in large areas of glass or plastic substrates. The luminescence from the dyes is trapped within the substrate medium by total internal reflection, resulting in a concentration of the light at the thin edges of the planar substrate (see photo above).

A limitation of the current materials used for LSCs is that their luminescence declines at the high concentrations necessary for efficient light absorption, due to aggregation of the dyes. Luminescence reabsorption restricts the light concentration factor that can be achieved. In a project at the University of Melbourne ACAP node by PhD student, James Banal, a number of luminescent dyes, that do not exhibit the aggregation and reabsorption deficiencies of existing materials, have been synthesised and investigated.

Researchers Honoured

In July 2013, ACAP Director, Professor Martin Green, was one of 44 new fellows, from a pool of 700 applicants, elected to the Royal Society, the United Kingdom's venerable National Academy of Science. The Royal Society Fellowship is comprised of some 1,450 of the world's most distinguished scientists and engineers, including more than 80 Nobel Laureates. "It's really quite an honour," said Professor Green. In an academic career spanning several decades at UNSW, Green has supervised more than 60 PhD students and set numerous world-records for silicon solar cell efficiency, including the current record of 25% conversion efficiency for a conventional silicon cell. He is renowned for developing and commercialising silicon solar cell technologies, and has often been referred to as the 'father of modern photovoltaics'. The photograph below shows him signing the Charter Book, signed in earlier days by scientific giants such as Isaac Newton, Charles Darwin and James Maxwell.

In December 2013, Professor Leone Spiccia from the Monash ACAP node was honoured to receive the 2013 Royal Australian Chemistry Institute's (RACI) prestigious Burrows Award. Professor Spiccia is respected internationally for his contributions to research in the fields of inorganic and materials chemistry. He was also recently made Fellow of the Royal Society of Chemistry in the UK in recognition of his contributions to chemistry over the past 25 years. The Burrows Award is presented by the Inorganic Division of the RACI and is based on consideration of the candidate's scientific work published in the past 10 years, together with other evidence of his or her standing in the international community. Sadly, Professor Spiccia passed away in 2016.

Professor Andrew Holmes, Director of the University of Melbourne ACAP node, was elected as the next President of the Australian Academy of Science. He assumed the role after the Academy's Annual General Meeting in May 2014. Professor Holmes is a Laureate Professor of Chemistry at the University of Melbourne's Bio21 Institute, a CSIRO Fellow and Distinguished Research Fellow in the Department of Chemistry at the Imperial College London. The current President of the Australian Academy of Science, Professor Suzanne Cory, noted that the Academy would benefit greatly from Professor Holmes' international reputation and experience. "Professor Holmes will lead our Academy with great distinction, energy and integrity," she said. "As Foreign Secretary, he has worked tirelessly on behalf of the Academy and its programs, with the deep conviction that Australia's future prosperity depends on strong research and education in science and mathematics and in further developing international science linkages."

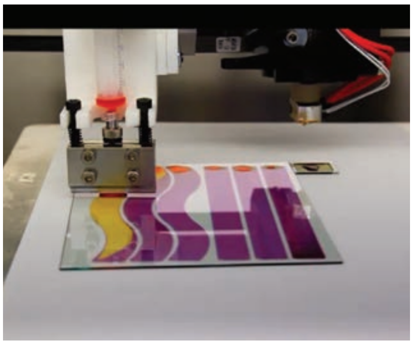
Thin Organic Solar Cells: Hot Excitons or Optical Cavity Effects?

Researchers Ardalan Armin, Paul Burn and Paul Meredith from the University of Queensland ACAP node have deciphered a previously puzzling feature of thin-film organic solar cell operation. Since these cells are so thin, the internal optical field distribution is significantly affected by cavity effects such as interference and parasitic absorption of light in the non-active layers of the cell. The optical field distribution as a function of wavelength defines the free carrier photo-generation profile, which in turn affects the shape of the external quantum efficiency (EQE). To optimise an organic solar cell structure, for example when testing a new material, it is necessary to fully understand and model the physics to arrive at an appropriate cell structure. Furthermore, the internal quantum efficiency (IQE) of any solar cell provides important information as to the basic charge generation processes and their efficiencies.

To accurately calculate the IQE from the measured EQE one must determine the number of photons absorbed by the junction as a function of wavelength. This in turn requires measurements and simulations of the junction and the whole device as a low finesse multi-layer structure. In this work these optical effects have been studied in a model polymer: fullerene solar cell and developed a robust and accurate methodology for measuring the IQE. This enabled the rapid optimization of new junction materials prior to laboratory fabrication. It was also observed that the aforementioned energy dependence of the IQE in the Grancini report was due to a failure to account for such effects, rather than being due to hot excitons. This work was recently published in the ACS Photonics journal.

From Benchtop to Rooftop: Scaling Up

The primary aim of a project at the CSIRO, Melbourne ACAP node is to develop the tools and processes required to translate small, laboratory-based devices to large area, mass-produced modules. Small scale, laboratory devices are currently produced using a robust and reproducible method for depositing very thin, uniform layers. While this is an excellent way to optimize the device architecture, it is, unfortunately, not scalable. The aim of the present project is to develop techniques that closely emulate manufacturing processes (spray, print) on a small, but scalable, format. In the course of this project, a member of the research staff, Dr Doojin Vak, has designed and built a mini-slot die coater. The modular construction can incorporate a heating stage and air drier and requires microlitres of ink only. Different heads can be fitted to produce different coating widths. With this set-up a wide range of different printing configurations can be tested. Preliminary solar cell power conversion efficiencies of >10% have been achieved with a variety of materials. The team has also further optimised the dual-feed spray deposition equipment to enable rapid assay of blend ratio and thickness in evaluating materials for solution processed solar cells.



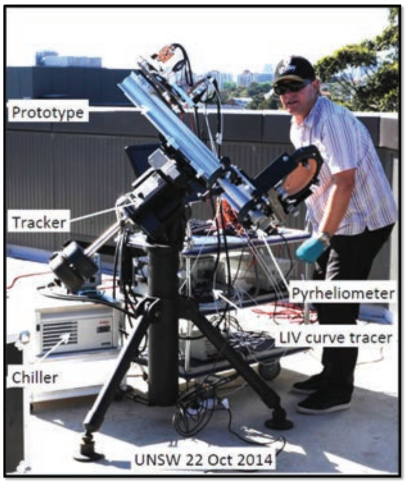
The a mini-slot die coater at work, printing solar cells

Highlights for Year 2

40.6% Sunlight to Electricity Conversion

The program attained a landmark result internationally in 2014 with the first demonstration of sunlight conversion to electricity with efficiency 40.6%. In an AUSIAPV project supported by ARENA, UNSW, US National Renewable Energy Laboratory (NREL, an AUSIAPV partner) and commercial partners, RayGen Resources and Spectrolab, a 287 cm^2 aperture area prototype was constructed by combining a commercial triple-junction III-V concentration solar cell with a commercial silicon cell in a 4-junction system. Innovative bandpass filtering was used to achieve the required partitioning of the solar spectrum so that currents in the III-V cell were balanced.

The 40% landmark efficiency was first measured in outdoor testing in Sydney in October 2014, after which the system was shipped to the outdoor test facility at NREL, Colorado, where slightly higher efficiency was independently confirmed in November. The result attracted considerable local and international media attention. An ABC Catalyst program has since been aired based on this achievement.

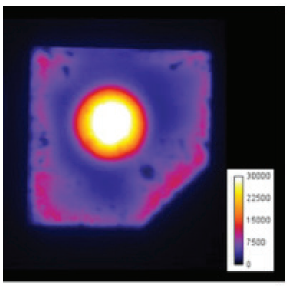


Dr Mark Keevers, project manager of the 40% module project, with the system under test at UNSW.

First 20% Efficient Cells Using Low-Cost Solar-Grade Silicon

Researchers at the Australian National University ACAP node have demonstrated the world's first silicon solar cell made with 100% 'solar-grade' silicon feedstock to achieve greater than 20% efficiency. The n-type silicon wafers were supplied by industry partner Apollon Solar, and were grown using Upgraded Metallurgical-Grade silicon material (UMG Si), a low-cost and low-energy refining process that promises to reduce both the cost and energy-intensity of silicon solar cells.

Photoluminescence count for an Apollon Solar wafer made from solar-grade silicon. The circular region represents the implementation of localised hydrogen charge-state control, greatly improving quality via the passivation of contaminants and defects.



Photoluminescence count for an Apollon Solar wafer made from solar-grade silicon. The circular region represents the implementation of localised hydrogen charge-state control, greatly improving quality via the passivation of contaminants and defects.

Professor Stuart Wenham (centre) at Harvey Prize award ceremony

Stuart Wenham Receives Harvey Research Prize

In May 2014, Professor Stuart Wenham was awarded the prestigious Institution of Engineering and Technology's (IET) AF Harvey Engineering Research Prize in London and delivered the Prize Lecture. The award recognises the discovery by Professor Wenham and his team of a mechanism to control the charge state of hydrogen atoms to correct deficiencies in silicon, the most costly part of a solar cell . "Our patented advanced hydrogenation technology will allow lower-quality silicon to outperform solar cells made from better quality materials, producing higher efficiencies at significantly lower cost," said Professor Wenham.

High Performance OPVS Using Nematic Liquid Crystals

Researchers at the University of Melbourne ACAP node have pushed the efficiency of organic photovoltaic (OPV) devices using molecular hole transport materials (BTR) to over 9%. The research recently published in Nature Communications demonstrated a maximum efficiency of 9.3%, an improvement thought to be due to the nematic liquid crystalline nature of the new material. This has recently been improved to 9.6% in collaborative research with Professor Paul Meredith and Professor Paul Burn at the University of Queensland under the ACAP program.

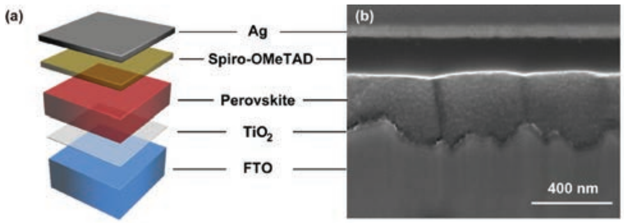
The nematic liquid crystalline form appears to greatly improve hole mobilities in the organic material, allowing thicker films to be used in devices. As thicker films are easier to print, the use of the nematic liquid crystalline BTR may facilitate printing of OPV without loss of performance.

The material is being developed by Dr David Jones at the University of Melbourne and with Professor Seth Marder at the Georgia Institute of Technology in a collaborative effort as part of the AUSIAPV program.

Compact $CH_3NH_3PBI_3$ for High Efficiency Perovskite Cells

A remarkable power conversion efficiency of 17% was achieved in 2014 at the Monash ACAP node by controlling the morphology of $CH_3NH_3PbI_3$ film. The quality of the perovskite film is extremely important for perovskite solar cells, especially for planar structured devices. Monash developed two facile one-step solution methods to fabricate uniform compact perovskite films for high efficiency devices. In addition, the reproducibility of the devices has been much improved, giving a small deviation around ±1% in the conversion efficiency.

By controlling the nucleation and crystal growth rates, Monash successfully prepared pin-hole free perovskite films of ~300nm in thickness. The monolayer film consisting of single-crystals was the first of this type to be reported. This structure is expected to facilitate charge transport due to lack of grain boundaries. Two high impact papers were published in Angewandte Chemie International Edition and Nano Energy, respectively.



Uniform compact $CH_3NH_3PbI_3$ film for a planar perovskite solar cell

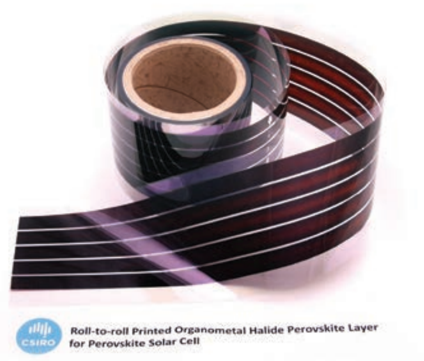
High Efficiency Perovskite Solar Cell

A team at the University of Queensland ACAP node recently reported a breakthrough in perovskite solar cell technology in the journal Nature Photonics in 2014. They measured a cell efficiency of 16.5% in the simplest possible architecture – an organohalide perovskite homojunction sandwiched between a metallic cathode and transparent conducting anode. This is the highest efficiency reported to date in such a geometry. The efficiency achievement was only one element of the work – probably of equal if not greater import were the findings associated with the basic operating principles of perovskite solar cells. The team provided compelling evidence for a non-excitonic charge generation mechanism and reported accurate values for perovskite dielectric constant from static to optical frequencies. These optical constants were used to model the cell cavity electro-optics, optimise the structure, and predict the maximum possible photogenerated current density as a function of junction thickness. Hence, the 16.5% result was not an empirical result so characteristic of the young perovskite solar cell field, but was arrived at by systematic analysis of the device electro-optics. Other important elements of the work included: the elimination of current-voltage hysteresis (a plague of these types of cells); demonstrated cell stability over many months; and a flat 100% internal quantum efficiency (IQE) for the highest performing cells.

This work, published on-line in Nature Photonics in November 2014 (Armin Li, first author) had immediate impact, receiving instant published citations and > 9000 downloads in its first 2 months.

3D Printing of Perovskite Solar Cells

Perovskite solar cells are an emerging technology with rapidly increasing record efficiency (from 3.8% to 20% in the 2010-2014 period), which can potentially be produced using low-cost industrial printing processes. However, the rapid progress described has been made exclusively by spin-coating, which is neither scalable nor transferable to large scale production. CSIRO has developed a solar coater based on a 3D printing platform as a research tool for solution processed thin-film solar cells. The solar coater has an industry-compatible slot-die coating head with 3-dimensional positional control via a standard text-file protocol. Full 3-dimensional freedom provides the ability to simulate production processes and enables rapid process optimization. Once a process is optimized using this small printer, the process can be easily translated to larger scale industrial printers. This 'lab-to-fab' tool has been used to optimize lab scale organic solar cells with a high performance polymer, and it was demonstrated that the optimized conditions can be effortlessly translated to larger printed modules. The solar coater was also used to develop a process for the fabrication of printed perovskite solar cells.



Roll-to-roll printed organometal halide perovskite Solar Cell

Highlights for Year 3

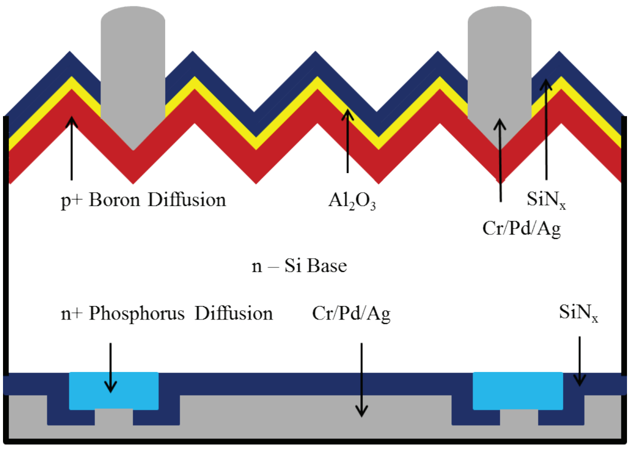
Andres Cuevas Receives 2015 Becquerel Prize

In September 2015, Professor Andres Cuevas, from the ANU node of ACAP, was awarded the prestigious Becquerel Prize in Hamburg, one of the highest honours for researchers in the photovoltaic field, and delivered the prize lecture, "The Great Adventure of Photovoltaics" at the European Photovoltaics Solar Energy Conference. The award honours his scientific achievements in the development and characterization of silicon solar cells. "The decision of the Becquerel Prize Committee is based on the outstanding work of Professor Cuevas covering the design and processing of solar cells, their fundamental material characterization and the modelling of photovoltaic energy conversion. His superior understanding of the physics of solar cells has made him to one of the key authorities in the field. With his engagement and his outstanding presentations Professor Cuevas has inspired generations of students and young scientists."

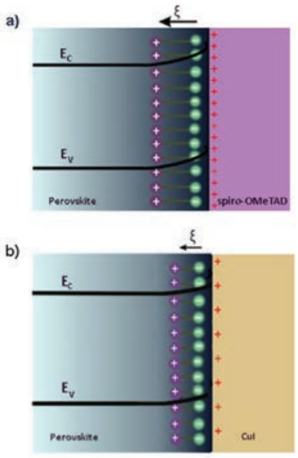
Prof Andres Cuevas (right) after receiving the 2015 Becquerel Prize, together with Prof Joachim Luther, Chairman of the Becquerel Prize Committee.

Cells Using Low-Cost Solar-Grade Silicon Wafers Nudge 21% Efficiency

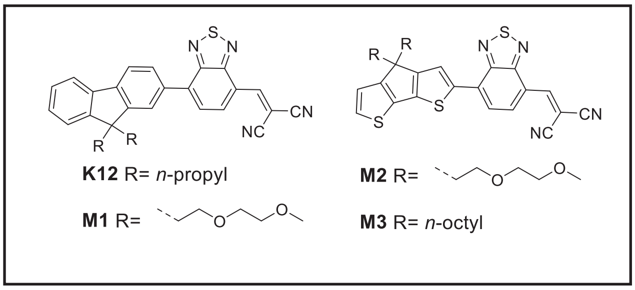
Researchers at the Australian National University node improved on the efficiency for cells using silicon wafers made with 100% "solar-grade" silicon feedstock in 2015. The n-type silicon wafers were supplied by industry partners Apollon Solar and FerroPem, and were grown using upgraded metallurgical-grade silicon material (UMG Si), a silicon refining process that promises to reduce both the cost and energy intensity of silicon solar cells. Using a cell fabrication process that has been specially developed to maintain high electronic quality in the UMG wafers, an independently confirmed efficiency of 20.9% was achieved (measured at Fraunhofer ISE CalLab, Germany). In particular, a localized rear phosphorus diffusion achieved by a novel etch-back process allows for the effective removal of unwanted impurities in the UMG wafers.



Schematic diagram of the n-type UMG solargrade silicon cell with full front boron diffusion and rear localised phosphorus diffusion, achieved via an etch-back process.



The relative amount of charges and strength of polarisation at the interface upon the use of Spiro-OMeTAD (a) and CuI (b) as the hole-conducting material.



Chemical structures of the glycolated and non-glycolated non-fullerene electron acceptors. The glycol chain is routinely used to improve organic semiconductor solubility but the presence of electron-rich oxygen atoms in the chain increases the low-frequency dielectric constant.

Probing J-V Hysteresis in Planar Perovskite Solar Cells

Research into photovoltaics based on organo-ammonium lead halides is developing rapidly. However, the relatively poor long-term stability and high material costs of certain cell components are limiting the potential commercialisation of these devices. Organic hole-conducting materials (HTMs) and additives used to improve charge transport within the HTM layer are the primary sources of high cell cost and operational instability. Further, as observed in previous studies, the current-voltage (J-V) performance of the conventional (Spiro-OMeTAD) organic HTM-based devices differed, depending on the scanning direction of the J-V curve, often denoted as the "J-V hysteresis".

In Monash University's work, published in Advanced Functional Materials in 2015 by Gaveshana Sepalage and colleagues, a power conversion efficiency of 7.5% was achieved for perovskite-based devices employing a relatively stable and inexpensive inorganic HTM, copper iodide (CuI) and CuI-based devices did not show a pronounced J-V hysteresis. In accordance with observations obtained using small-perturbation and transient characterisation techniques, the team hypothesised that CuI, in comparison to Spiro-OMeTAD, facilitates a faster charge extraction and consequently a faster relaxation of the polarized perovskite material at the perovskite/HTM interface. The concept of employing CuI as an HTM in planar perovskite architectures and the analysis of the interfacial polarization were developed under the ACAP program for organic and organohalide perovskite solar cells. These findings strengthen the understanding of charge generation and charge transfer across different perovskite/HTM interfaces, and promote the use of inorganic HTMs in perovskite solar cell assemblies.

Highest Low-Frequency Dielectric Constant for Organic Semiconductors

The ACAP Node at the University of Queensland team has modified non-fullerene electron acceptors to increase the low-frequency dielectric constant to 9.8, believed to be the highest yet reported for a non-metal containing organic semiconductor. The low dielectric constants of conventional organic semiconductors leads to poor charge carrier photo-generation in homojunction organic solar cells due to large exciton binding energies, requiring the use of high and low electron affinity organic semiconductor (acceptor and donor) blends in a heterojunction architecture instead. The team has suggested in the journal, Chemical Communications, in 2015 that increasing the organic semiconductor dielectric constant in both the low-frequency and optical-frequency regimes could lower the exciton binding energy and facilitate more efficient free carrier generation and, possibly, also decrease geminate recombination from the charge transfer state. To test this hypothesis they designed, synthesized and characterised a series of model non-fullerene electron acceptors with and without short glycol chains to predominantly increase the low-frequency dielectric constant. Glycolation increased the low-frequency dielectric constant and, critically, the glycolated and non-glycolated compounds had similar electronic (energy levels) and transport properties, lending weight to the proposition that increasing the dielectric constant can be achieved without detrimentally affecting other key solar cell material properties.

James Cook Medal and Ian Wark Medal and Lecture For Martin Green

James Cook medal awarded to Professor Martin Green

ACAP Director Professor Martin Green was awarded the prestigious James Cook Medal by the Royal Society of New South Wales in May 2015, joining a list of luminaries including Sir Frank M. Burnet, Sir Ian Clunies Ross, Albert Schweitzer, Sir Marcus L. Oliphant and Sir Gustav Nossal. The James Cook Medal was established in 1947 and is awarded periodically by the Royal Society of New South Wales for outstanding contributions to science and human welfare in and for the Southern Hemisphere.

Further, in November 2015, the Australian Academy of Science announced that Professor Green had been awarded the 2016 Ian Wark Medal and Lecture. The award recognizes research which contributes to the prosperity of Australia. Professor Green is an acknowledged world-leader in the field of photovoltaics. He has published extensively and influentially, made many highly significant contributions to the knowledge base of the field, and successfully established a world-class research hub that is responsive to Australian needs in the photovoltaics industry. Several generations of his group's technology have been successfully commercialized including, most recently, the Passivated Emitter and Rear Cell (PERC) that produced the first 25% efficient silicon cell in 2008 and accounted for the largest share of new manufacturing capacity added worldwide in 2014. His fundamental and applied research has led to, and will continue to lead to, significant economic benefits both in Australia and worldwide."

Julius Award for Early Career Development at CSIRO

Dr Doojin Vak is a research scientist with CSIRO's Manufacturing business unit. After completing his PhD on developing optoelectronic materials in GIST (Korea), he joined the University of Melbourne as a Korea Research Fellowship Program fellow and expanded his research on scalable fabrication processes for organic solar cells as a key participant in the Victorian Organic Solar Cell Consortium (VICOSC) project. Since joining CSIRO as a research scientist in 2010, he has been working on developing industrial printing processes for the manufacturing of next generation solar cells.

Dr Doojin Vak, recipient of the 2015 Julius Award

Dr Vak's recent research focuses on translating lab-scale advances in printed solar cells to manufacturing-scale processes (lab-to-fab translation). With recent groundbreaking developments in a new class of "solar ink" based on organic-inorganic perovskites, efficiency of lab-based solar cells has been rapidly increasing and record efficiencies of over 21%, comparable with that of commercialised silicon solar cells, have been reported internationally. With market competitive efficiencies for lab-based solar cells, "lab-to-fab" translation will be a key challenge in the field. Dr Vak developed a new printing platform based on 3D printers as a tool for "lab-to-fab" translation and has been making rapid technical progress on an industry-friendly fabrication process for the new class solar technology. The process has already been adopted by ACAP Collaborating Industry Participant, Dyesol. Dr Vak has filed two patent applications on this emerging technology as a first inventor. While working on industry-focused research, he has also developed a strong publication record with over 40 publications and over 1,300 citations.

Highlights for Year 4

World Record for CZTS Cell

ACAP, through its UNSW node, is at the forefront of development of cells made from earth-abundant and non-toxic materials, other than the currently dominant silicon. The most promising current candidate in this category is a compound of copper, zinc, tin and sulfide, commonly called CZTS. In April 2016 the US National Renewable Energy Laboratory confirmed a world efficiency record for CZTS cells made at UNSW by the team led by Dr Xiaojing Hao. The record, 7.6% efficiency in a cell 1cm^2 area, is an important milestone in the march towards finding a low-cost, stable and efficient partner for silicon in tandem structures.

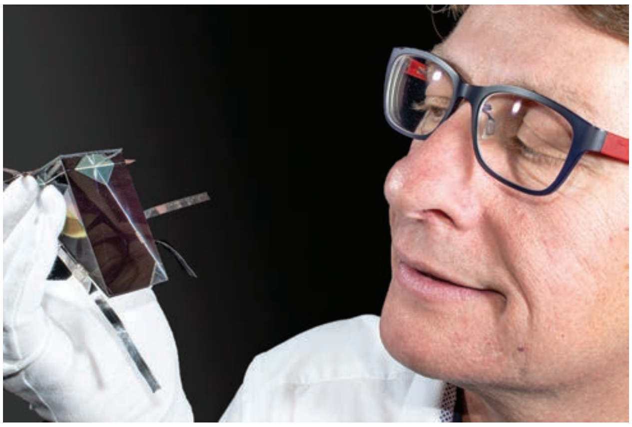
PhD student, Chang Yan and Dr Xiaojing Hao, deposit thin film CZTS layers.

34.5% Efficient One-Sun Minimodule

The ACAP program achieved yet another significant efficiency milestone with a large increase in the highest efficiency ever reported for a standard, flat-plate, one-sun solar module, the type dominating the commercial market and universally used in residential photovoltaic systems. Also in April 2016, the US National Renewable Energy Laboratory confirmed a world efficiency record set by Dr Mark Keevers and Professor Martin Green, Senior Research Fellow and Director, respectively, of the UNSW Node of ACAP. Improving such efficiency is important to ongoing photovoltaic cost reductions.

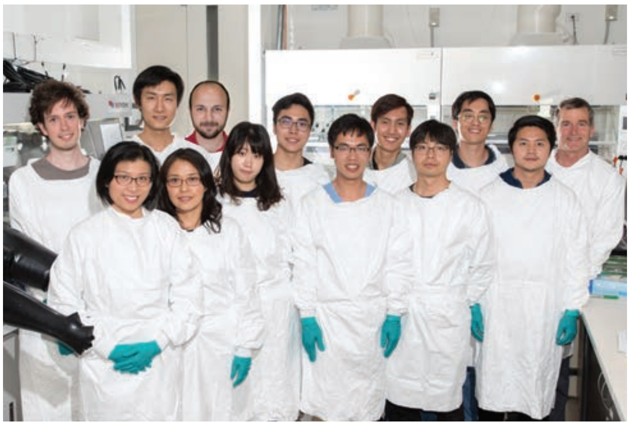
An efficiency of 34% was measured for a 30 cm^2 minimodule in September 2015, with this subsequently improved to 37%, by far the highest efficiency demonstrated for unconcentrated sunlight for a device this size.

This large improvement in experimental performance was obtained by converting four different colour bands in sunlight by dedicated solar cells to combine a commercial triple-junction cell with a high performance, custom-designed silicon cell supplied by ACAP partner, Trina Solar. This cell design benefitted from earlier results from the ACAP program, incorporating the rear junction design that set another world-record in year 1 of the program, in a joint project between ANU and Trina Solar. The near-ideal light collecting properties of the prisms used to optically couple the cells were a UNSW discovery of the late-1970s.



34.5% efficient, 30cm^2 one-sun minimodule;

Record Perovskite Cells



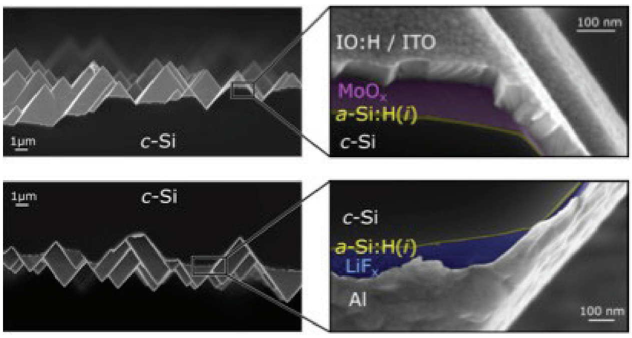
The team that developed the record perovskite cells.

As announced at the Asia-Pacific Solar Research Conference in Canberra in December 2016, the UNSW node team, led by Dr Anita Ho-Baillie, has achieved the highest efficiency rating with the largest perovskite solar cells to date. A 12.1% efficiency rating for a 16 cm^2 perovskite solar cell, the largest single perovskite photovoltaic cell certified with the highest energy conversion efficiency, was independently confirmed by an international testing centre, Newport Corporation, in Bozeman, Montana. The new cell is more than 10 times larger than the current certified high efficiency perovskite solar cells on record. The same team also achieved an 18% efficiency rating on a 1.2 cm^2 single perovskite cell, and 11.5% for a 16 cm^2 four-cell perovskite mini-module, both independently certified by Newport.

Perovskite is a structured compound, where a hybrid organic-inorganic lead or tin halide-based material acts as the light-harvesting active layer. They are the fastest-advancing solar technology to date, and are attractive because the compound is potentially cheap to produce, at low temperatures, and simple to manufacture, and can even be sprayed onto surfaces. Although perovskites hold much promise for cost-effective solar energy, they are currently sensitive to temperature and moisture, allowing them to last only a few months without protection. As part of its current research program, ACAP is trying to extend perovskite cell durability. The project's goal is to lift perovskite solar cell efficiency to 26%.

Novel Silicon Solar Cells with Passivating Contacts

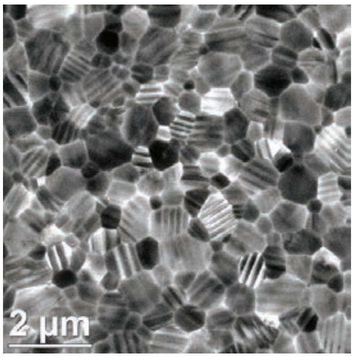
Most photovoltaic systems are based on crystalline silicon solar cells, which keep getting cheaper and better. Further progress hinges upon the use of "passivating contacts" to selectively transport electrons and holes towards the cell's terminals. As an example, ANU PhD student Di Yan has developed 21.1% efficient cells with a rear passivating contact based on a tunnelling oxide coated with polysilicon. In an alternative pathway, ACAP is investigating a wide range of materials, many of them transparent, that can be deposited at low temperatures, thus simplifying the fabrication of high efficiency silicon solar cells. Recently, ANU's James Bullock and collaborators from the University of California at Berkeley and École Polytechnique Fédérale de Lausanne in Switzerland have demonstrated a dopant-free silicon cell, referred to as a DASH (dopant free asymmetric heterocontact) cell, with an efficiency of 19.4%. PhD students Thomas Allen and James Bullock, with co-workers, have applied materials like lithium fluoride, calcium and titanium oxide to make first-of-a-kind n-type silicon solar cells with partial-area rear contacts, achieving efficiencies in the range of 20.6% to 21.8%. See Section 6.7 for more information.



ANU's dopant-free heterocontact silicon solar cells with efficiencies of ~20%

Direct Observation of Intrinsic Twin Domains in Tetragonal $CH_3NH_3PbI_3$

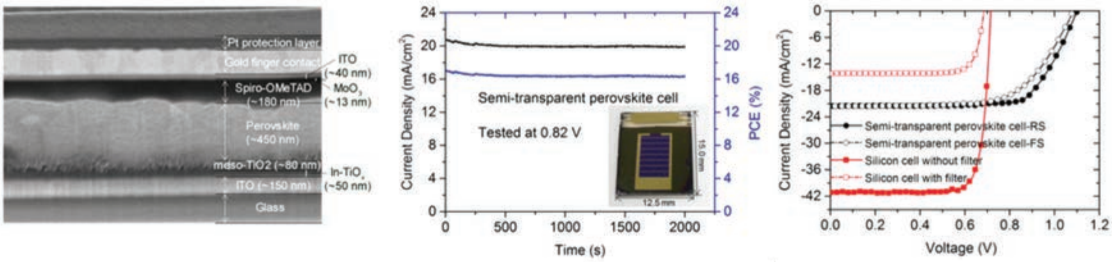
Organic-inorganic hybrid perovskites are exciting candidates for next generation solar cells, with $CH_3NH_3PbI_3$ being one of the most widely studied. While there have been intense efforts to fabricate and optimise photovoltaic devices using $CH_3NH_3PbI_3$, critical questions remain regarding the crystal structure that governs the unique properties of the hybrid perovskite material. A team with membership from CSIRO, the Melbourne Centre for Nano Fabrication, Monash University and Wuhan University of Technology has provided direct and unequivocal evidence, by using transmission electron microscopy, for the existence and crystallography of twin domains in tetragonal methylammonium lead tri-iodide ($CH_3NH_3PbI_3$) thin films used for solar cell applications. These twins have eluded observation so far, possibly due to their very fragile nature under the electron beam, as well as the inherent instability of the material itself. Given the scale of these domains is comparable to the thickness of typical methylammonium lead iodide perovskite layers used in solar cells, and given that the twinning transition temperature lies within the operational temperature range of solar cells, these twin domains are likely to play an important role in the functional performance of perovskite solar cells. A report of this work has now been published in *Nature Communications*.



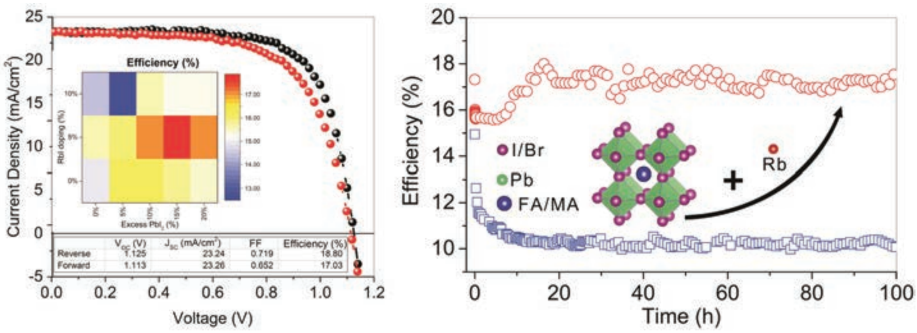
Crystallographic twin in hybrid perovskite materials. Bright field TEM image of a $CH_3NH_3PbI_3$ thin film at room temperature shows clearly twinning bands in perovskite grains.

In-doped TiO_x Electron Transport Layers for Efficient Perovskite Cells and Perovskite-Silicon Tandems

Achieving high efficiency perovskite cells requires careful optimisation of both the perovskite active layer and the carrier-selective transport layers on either side. In an effort to improve both the fill-factor and voltage of perovskite cells, ANU PhD student Jun Peng developed a simple, one-step solution-based method for producing high quality In-doped TiO_x films as the electron transport layer. The process requires only a minor modification to the standard method used for depositing compact TiO_2 electron transport layers, so can be readily adopted by other groups. The electronic properties of the TiO_x films produced in this way (specifically conductivity



In-doped TiO_x electron transport layers for thin-film perovskite cells and perovskite-silicon tandems.



ANU reported in-house performance of a RbI-doped perovskite cells with highest efficiency of 18.8%.

and energy level alignment) can be tuned by varying the indium doping concentration in the precursors, providing significant efficiency gains compared to perovskite solar cells made with commonly used pure-TiO_2 transport layers.

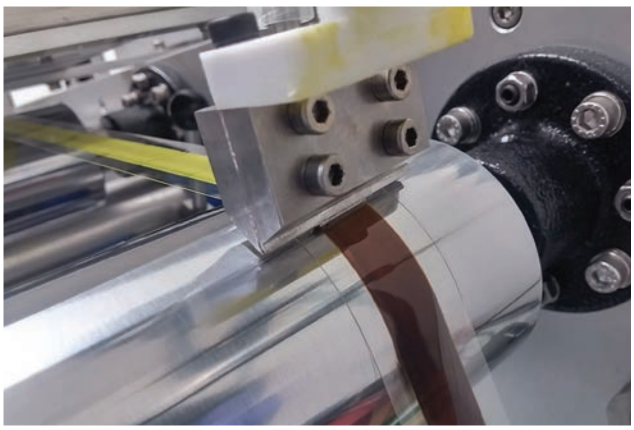
Using the optimised transport layers, steady-state efficiencies of 17.9% for $CH_3NH_3PbI_3$–based cells and 19.3% for mixed-cation/mixed-halide cells were measured at ANU, corresponding to absolute efficiency gains of 4.4% and 1.2% respectively compared to TiO_2-based control cells. In addition, a steady-state efficiency of 16.6% was achieved for a semi-transparent perovskite cell and used to demonstrate a four-terminal perovskite-silicon tandem cell with a steady-state efficiency of 24.5% measured at ANU.

Compositional and Structural Engineering of Perovskites for Efficient and Stable Solar Cells

A critical hurdle to the commercial fabrication of perovskite solar cells is their limited stability. The popular methylammonium lead iodide (MAPI) perovskite is known to degrade following exposure to humidity, heat, oxygen and UV radiation; processes that have been linked partly to the presence of the organic (MA) cation. Compositional engineering of perovskites by partial substitution of the organic cation and other components provides a wide parameter space to optimise their physical and chemical properties. In this work, ANU PhD student The Duong reported the impact of substitutional doping with rubidium iodide (RbI) to control the phase formation and crystallisation of mixed-cation, mixed-halide perovskites. High quality, single-phase films were obtained through systematic optimisation of RbI and PbI_2 ratios in the precursor solutions, supported by a combination of cathodoluminescence and X-ray diffraction studies. The RbI-doped perovskite cell gave efficiency of up to 18.8%, based on ANU measurements. Notably, these cells exhibited significantly improved thermal/photo stability compared to un-doped cells, ascribed mainly to the effect of RbI on the structure and compositional change of perovskite. The study demonstrated the potential of rubidium as an alternative cation for use in high efficiency perovskite cells.

'Lab-to-Fab' Translation of Perovskites

CSIRO has continued to work on 'lab-to-fab' translation of perovskites using its bespoke mini-slot die coating suite and range of pilot printing lines. For two-step (sequential) perovskite deposition on glass, spiro-MeOTAD was substituted with an in-house developed hole transport material (HTM), resulting in excellent results compared with printing of spiro-MeOTAD. Efficiencies up to 14.7% (glass, 0.1 cm^2) and up to 9% for larger area devices (glass, 1 cm^2) have been demonstrated. Notably, these results have also been translated to roll-to-roll printed devices on flexible substrate (ITO/PET) yielding a power conversion efficiency of 11% (0.1 cm^2). This is an excellent outcome for ambient deposition via a potentially industry-relevant process on a flexible substrate, providing a promising grounding for further scale-up.



Roll-to-roll printing of photovoltaic devices on flexible substrate at CSIRO.

Opposition Leader Bill Shorten Visits ACAP Nodes

The Monash, ANU and UNSW nodes of ACAP all hosted visits by the Leader of the Opposition in the lead-up to the 2016 Federal Election.

Dr Mark Keevers, UNSW, explains the record-performance spectrum-splitting prismatic mini-module to Leader of the Opposition, Hon Bill Shorten MP, and Member for Kingsford Smith, Hon Matt Thistlethwaite MP on the roof of the Tyree Energy Technologies Building at UNSW on 2 July 2016.

IEEE PVSC Young Professional Award to Bram Hoex

Dr Bram Hoex, based at the UNSW node, was presented with the sought-after PVSC Young Professional Award at the 2016 IEEE Photovoltaics Specialists Conference (PVSC), in Portland, Oregon, in June 2016. The award recognises people who have made significant contributions to the science and technology of photovoltaic energy conversion, including work on PV materials, devices, modules and/or systems. Additionally, the award recipient has demonstrated significant promise as a leader in the field. Bram is an example of the next generation of Australian-based solar researchers whose careers are benefiting from the support and international linkages provided by ACAP.

Bram Hoex receives the IEEE PVSC Young Professional Award in Portland, Oregon.

Pierre Verlinden Lauded with William Cherry Award

Dr Pierre Verlinden, the Principal Investigator for ACAP's Collaborating Industry Participant, Trina Solar and an active and valued representative at ACAP's committee meetings, has been awarded the 2016 IEEE William R. Cherry Award, the most prestigious research award within the international photovoltaics community. The award was presented in June 2016 at the opening ceremony of the 43rd IEEE Photovoltaic Specialists Conference in Portland, Oregon.

This brings to four the number of ACAP-affiliated researchers who have received this award, with Professors Martin Green, Allen Barnett and Stuart Wenham as previous awardees. The only other organisation that can boast a similar number of awardees is ACAP partner, the US NREL.

Dr Pierre Verlinden, Principal Investigator for ACAP's Collaborating Industry Participant, Trina Solar and an active and valued representative at ACAP's committee meetings.

ACAP Researcher Named a Rising Star

Dr Xiaojing Hao of the UNSW node was named as one of twenty "Rising Stars" at the university. Dr Hao is developing a promising, low-cost solar cell using copper, zinc, tin and sulfide (CZTS). One of the benefits is that the cells could find deployment in countries where chemical regulations have traditionally posed barriers. She expects her group to exceed 10% efficiency by early 2016, and has a target of achieving a new world record for CZTS solar cells of 15% within three years – a milestone she says will prompt a lot of interest from industry. "We think we have developed the lift-off technology needed to take this new solar cell to the next level," she says. "I believe we can make this solar cell much better. It could have a big future in the rooftop PV market and in building integrated PV, and it could make a huge difference to people's lives around the world."

Dr Xiaojing Hao, a UNSW "Rising Star".

Education and Training

A primary aim of the AUSIAPV initiative is to provide high-quality training opportunities for next generation researchers, through significant collaboration between Australian / US researchers and institutions.

Expected outcomes include new IP, training of significant numbers of world-leading science and engineering researchers in photovoltaics, the most rapidly expanding of all energy technologies, and public education in the potential of solar technologies.

In addition, and in line with its objectives, ACAP is pro-active in broader knowledge sharing. ACAP activities have featured in over 400 magazine and newspaper articles since 2013, with nearly 300 publications in technical and scientific journals. Of these publications, over 6% have been independently rated as 'hot papers' which normally applies to 0.1% of publications in any given field. This suggests that ACAP publications are having an impact that is 62.5 times greater than the average for their field.

Hot and High Impact Papers

2013

Two 2013 AUSIAPV journal papers were identified by the ISI Web of Knowledge as "hot papers", within the top 0/1% in their field, based on their impact, as calculated from rates of citation by other researchers. These papers "Solar Cell Efficiency Tables", published by the Wiley Journal in Progress in Photovoltaics by Martin Green at the UNSW ACAP node and Keith Emery at AUSIAPV partner NREL, document progress in independently confirmed solar cell conversion efficiencies, measured at a group of designated international test centres. Not only are key features of enhanced performance cells described but guidelines are also established for standardised measurement procedures, such as for defining cell area. Of the 80 papers published worldwide in 2013 and designated as "hot papers" in the engineering discipline, both AUSIAPV papers were ranked near the top, with one earning the distinction of being the most cited in this discipline.

A third paper resulting from collaboration between the group of Professors Udo Bach and Leone Spiccia at the ACAP Monash node and Jeff Long and Chris Chang at the University of California, Berkeley, on dye-sensitised cells based on cobalt mediators, was also selected as the editor's choice for hot paper designation (M. K. Kashif, M. Nippe, C. M. Forsyth, C. J. Chang, J. R. Long, L. Spiccia and U. Bach, Angew Chem. Int. Ed., 52, 5527, 2013).

A fourth paper from a combined UNSW and Suntech Research and Development, Australia team of Jonathon Dore, Rhett Evans, Ute Schubert, Bonne Eggleston, Daniel Ong, Kyung Kim, Jialiang Huang, Oliver Kunz, Mark Keevers, Renate Egan, Sergey Varlamov and Martin Green titled "Thin-film polycrystalline silicon solar cells formed by diode laser crystallisation" became one of the 10 most accessed papers published in the journal Progress in Photovoltaics during 2013.

2014

Ten publications published under the ACAP program in 2014 have been identified as “Highly Cited” papers.

The first of these highly cited papers, with lead author Thomas White from ANU, investigates top cell requirements for tandem cells stacked on silicon . The next seven arise from the ACAP program Organic and Earth-Abundant Thin Film Cells. The first two with lead author Ardalan Armin of the University of Queensland, identifies new requirements on carrier mobility and optical cavities for the fabrication of high-efficiency, thin-film organic solar cells. The third, involving authors from Monash and HUST in China, reports improved photocurrents in dye-sensitised solar cells. The fourth with Jonathon Dore as the lead author, discusses recent UNSW progress on laser-crystallised polycrystalline silicon thin-film solar cells. The fifth, a joint UNSW paper with Central South University, Hunan, discusses the fabrication of relatively high performance 5.1% efficient solar cells using the earth-abundant Cu2ZnSnS4 compound prepared by a non-toxic, sol-gel route.

Two papers receiving this distinction described progress in the rapidly emerging field of perovskite solar cells and were both additionally identified as “Hot Papers”. One, published in Nature Photonics with Martin Green from UNSW as lead author, discusses developments across the field and the challenges facing the technology. The other, published in Angewandte Chemie with lead author Manda Xiao from Monash, discusses a new crystallisation approach for these cells leading to higher performance. The other two “Hot Papers” were joint papers involving AUSIAPV partners UNSW and NREL reporting recent progress with solar cell efficiency improvements across the whole photovoltaic field.

An eleventh paper with Ms. Ning Song of UNSW as lead author, also on work directed at Cu_2ZnSnS_4 solar cells, received the distinction of featuring on the cover of the May 2014 issue of Physica Status Solidi Rapid Research Letters.

2015

A further ten “Highly Cited Papers” and an additional seven “Hot Papers” were published in 2015.

Eight of the 2015 “Highly Cited Papers” were based on results generated in ACAP program strand on “Organic and Earth-Abundant Thin Film Cells”. The first of these, with lead author

Kuan Sun, affiliated with the University of Melbourne node, reported a new class of nematic liquid crystal material capable of providing improved organic solar cell performance, while also enabling easier roll-to-roll printing of environmentally friendly, mechanically flexible and potentially cost-effective photovoltaic devices. The materials reported have formed the basis of new collaborations with the University of Queensland node, as well as with US partners National Institute of Standards and Technology and Georgia Institute of Technology. It was one of the papers earning the additional distinction of being identified as a “Hot Paper”, within the top 0.1% in its field. A second paper, also on organic photovoltaics and also earned the “Hot Paper” label. Lead author was Jegadesan Subbiah, also of the University of Melbourne node, with coauthors from this node as well as the CSIRO node. The paper reported the synthesis of a high molecular weight donor-acceptor conjugated polymer and its use in fabricating a 9.4% efficient solar cell. A third, another “Hot Paper”, with lead author Kyeongil Hwang of CSIRO also involving co-authors from the University of Melbourne node and Gwangju Institute of Science and Technology, South Korea reported progress in the scale-up and printing of perovskite solar cells on flexible substrates. This paper was ranked amongst the top most accessed papers of the Advanced Energy Materials journal over the year, with an illustration of the process appearing on the rear cover of the February 2015 issue.

The fourth “Highly Cited Paper”, with lead author Qianqian Lin from the University of Queensland node, addressed the electro-optics of perovskite solar cell. It also earned the additional distinction of being identified as a “Hot Paper”. The fifth of these, with lead author Yu Han of the Monash University node, but also involving co-authors from both the University of Melbourne and CSIRO nodes, reported on the degradation properties of encapsulated perovskite solar cells, one of the most important issues determining the future prospects of this technology. The sixth with lead author Yasmina Dkhissi of the University of Melbourne and involving co-authors from Monash University and CSIRO nodes, reported on the low temperature deposition of perovskites onto flexible polymer substrates, something that is difficult to achieve with other cell technologies. The seventh, with lead author Rui Sheng of the University of New South Wales (UNSW) node, involved vapour-assisted deposition of lead bromide perovskite, of interest as a high bandgap cell in a double junction bromide/iodide/silicon device. The eighth “Highly Cited Paper” in this strand, with lead author Jae Sun Yun from UNSW and involving co-authors from the Monash University node, describes the experimental role of grain boundaries in improving perovskite cell performance.

Two further “Highly Cited Papers” arose from collaboration between AUSIAPV partners, UNSW and Colorado-based NREL, documenting recent efficiency improvements in photovoltaics across a range of technologies, including the recent UNSW 40% sunlight to electricity conversion milestone and the record 20.8% result for multicrystalline silicon obtained by ACAP industrial partner, Trina Solar, using Australian-developed PERC cell technology (Passivated Emitter and Rear Cell). Both papers also received the additional “Hot Paper” distinction.

2016

An additional nine papers published under the ACAP program in 2016 have already been identified as making a large impact at the international level. These have been classified as “Highly Cited Papers”, earning a ranking within the top 1% in their field. Six of these have earned the additional distinction of being identified as “Hot Papers”. This is a disproportionately high number relative to the ACAP total and brings the total to 32 papers earning the “Highly Cited” distinction over the first four years of ACAP operation.

Five of the 2016 “Highly Cited Papers” were based on results generated in ACAP program strand PP2: “Organic and Earth-Abundant Thin-Film Cells”. The first of these, with lead author Naveen Kumar Elumalai affiliated with the UNSW Sydney node, elaborates the governing mechanisms affecting the VOC of organic solar cells and analyses the interdependencies between the factors influencing this parameter, highlighting potential research strategies to improve it. Another with lead author Dian Wang, also affiliated with the UNSW Sydney node, addresses the key topic of stability issues relevant to perovskite solar cells. This paper has the additional distinction of being identified as a “Hot Paper”. Another with lead author Xiaoming Wen, also with UNSW Sydney node affiliation, studies defect trapping states and carrier recombination dynamics in organic-inorganic halide perovskites using steady state and time-resolved photoluminescence. A fourth, another “Hot Paper”, with lead author Young Chan Kim from the Korean Research Institute for Chemical Technology, but with co-authors Jae Sun Yun, Anita Ho-Baillie, Shujuan Huang and Martin Green from the UNSW Sydney node, addresses the beneficial effects of incorporating PbI2 into organo-lead halide perovskite solar cells. The final highly cited paper in the PP2 strand, with lead author Xiaolei Liu, also with the UNSW Sydney node affiliation, but additionally involving Duke University, North Carolina, addresses CZTS cell technology, focusing on the following three key aspects of the device and providing suggestions for their improvement and for future research: the interface between the CZTS absorber and the Mo back contact; bulk defects and grain boundaries; and the interface between the CZTS absorber and the buffer layer.

Two “Highly Cited Papers” were based on results generated in ACAP program strand PP1: “Silicon Cells”. The first, a “Hot Paper”, with lead author Evan Franklin, affiliated with the ANU node, but also involving ACAP partners PV Lighthouse and Trina Solar, documents the 24.4% interdigitated back contact (IBC) result obtained earlier in the ACAP program. A second “Hot Paper” with Andres Cuevas, affiliated with the ANU node as one co-author, reviews high efficiency silicon photovoltaics from a device-engineering perspective, discusses key factors responsible for the success of the classic dopant-diffused silicon cell, analyses two high efficiency device architectures, the IBC and the silicon heterojunction cell, and, finally, summarises pathways for further efficiency improvements and cost reduction.

The final two “Highly Cited Papers” arose from collaboration between AUSIAPV partners, UNSW and Colorado-based NREL, documenting recent efficiency improvements in photovoltaics across a range of technologies, including the recent UNSW 40.6% sunlight to electricity concentrator submodule, the 34.5% one-sun minimodule, record 7.6% and 9.5% CZTS cell results, 11.5% for a perovskite minimodule and the record 21.3% result for multicrystalline silicon obtained by ACAP industrial partner, Trina Solar, using UNSW-developed PERC (Passivated Emitter and Rear Cell) technology. Both papers also received the additional “Hot Paper” distinction, being within the top 0.1% in their field.

The article, “High efficiency rubidium incorporated perovskite solar cells by gas quenching” by a UNSW team of Meng Zhang, Jae Sung Yun, Qingshan Ma, Jianghui Zheng, Cho-Fai Jonathan Lau, Xiaofan Deng, Jincheol Kim, Dohyung Kim, Jan Seidel, Martin Green, Shujuan Huang and Anita Ho-Baillie, was among the most read articles in American Chemical Society’s ACS Energy Letters for February 2017. The team applied gas quenching to fabricate perovskite films incorporating rubidium for high efficiency perovskite solar cells achieving 20% power conversion efficiency on a 65 mm2 device.

From a slightly different perspective, Australia published 3.7% of all papers between 2013-2016 with “Perovskite Solar Cell” included in the title, but 9.5% in the highest impact category of “Hot Papers”, according to the Web of Science. Similarly, Australia published 7.4% of all papers with “Silicon Solar Cell” in the title over the same period, but a massive 13.3% in the top category of “Highly Cited Papers”, if perovskite and graphene papers are excluded. All the papers in the most highly cited category had ACAP authorship in both cases.

Student Awards

2013

39th IEEE Photovoltaics Specialists Conference, Florida

Two ACAP students, Brett Hallam and Jonathan Dore, supported by the UNSW node, were awarded “Best Student Presentation” for Topic Areas 4 (“Silicon Feedstock”) and 5 (“Thin Film Silicon Based Solar Cells and Panels”) respectively, at the 39th IEEE Photovoltaics Specialists Conference in Tampa, Florida in June 2013. Later in 2013, at the 28th European PVSEC, Professor Green’s opening plenary presentation was commended by the scientific committee as one of the most outstanding papers of the conference. This was a joint paper with NREL and Ohio State University, one of the first to be presented under

Brett Hallam (4th from the left) and Jonathon Dore (5th from the left) awarded “Best Student Presentation” for Topic Areas 4 and 5, respectively at the 39th IEEE Photovoltaic Specialists Conference in Florida in June 2013.

the AUSIAPV logo. In November, Jonathon Dore followed up on his earlier success by also becoming the winner of the Australian Institute of Physics Postgraduate Presentation for 2013, for his talk on Laser Crystallised Silicon Films for Second Generation Solar Cells, also ACAP supported research.

2014

40th IEEE Photovoltaics Specialists Conference, Colorado

James Bullock and Thomas Allen, both PhD students at the ANU ACAP node, received awards at the 40th IEEE Photovoltaic Specialists Conference in 2014. James received the Best Student Paper Award for his development of a novel approach that increases the output power of solar cells whilst at the same time simplifying their fabrication procedure. Thomas received a best poster award, outlining results from his research in the application of black silicon to solar cells, which has shown the potential to increase the amount of light that solar cells can absorb, thereby increasing their efficiency. James Bullock is also the recipient of The American Australian Association’s Education Fund award for emerging Australian innovators and professionals, which provides up to US$40,000 for students to undertake research and study on sustainability, engineering and medicine at prestigious American institutions. From November 2014 James spent eight months at the University of California at Berkeley.

Materials Research Society Spring Meeting, San Francisco

James Banal, a PhD student at the University of Melbourne ACAP node, was the winner of the Best Poster Prize in the “Emerging Nanophotonics and Materials Symposium” at the international Materials Research Society Spring Meeting held in San Francisco in April 2014. James’ PhD project is supervised by Dr Wallace Wong and Professor Ken Ghiggino.

2016

31st European Photovoltaic Solar Energy Conference, Amsterdam

Mr Thomas Allen of the Australian National University won a Best Paper Award at the 31st European Photovoltaic Solar Energy Conference, Amsterdam as lead author of, “Calcium Contacts to n-Type Crystalline Silicon Solar Cells”. The entries were reviewed and scored by the conference’s international Scientific Committee, made up of more than 200 leading research and industry experts from the global PV community. The winning paper was about direct metallisation of lightly doped n-type crystalline silicon, which is known to routinely produce non-Ohmic (rectifying) contact behaviour. This

ANU's Tom Allen accepting his Student Award at the 32nd European Photovoltaic Solar Energy Conference in Munich in June 2016.

Mohsen Goodarzi of ANU, at the presentation of his Student Award at the 32nd European Photovoltaic Solar Energy Conference in Munich in June 2016.

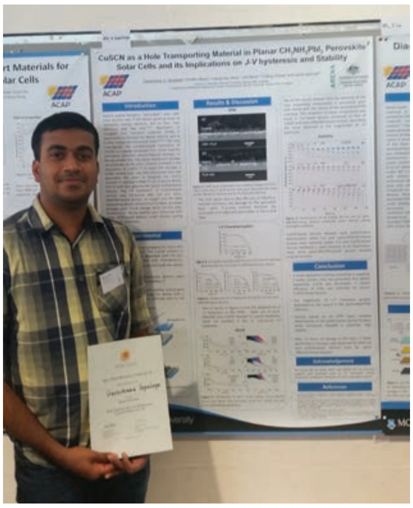
contribution demonstrated that low resistance Ohmic contact to n-type c-Si wafers can be achieved by incorporating a thin layer of the low work function metal calcium between the silicon surface and an overlying aluminium capping layer.

Mr Mohsen Goodarzi, also from ANU, won another Best Paper Award at the same conference as primary author of, "Modelling and Characterization of Multicrystalline Silicon Blocks by Quasi-Steady-State Photoconductance". Mohsen's research focuses on silicon material characterisation at the ingot level. This provides invaluable information about contamination, as well as providing immediate feedback on silicon crystalline growth quality.

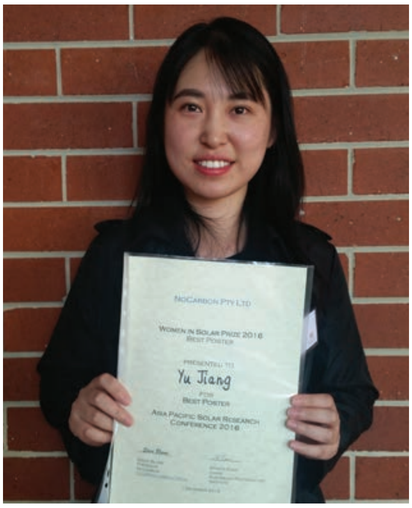
Third Asia-Pacific Solar Research Conference, Canberra

Monash University's Mr Gaveshana Anuradha Sepalage won the 2016 Wal Read Memorial Prize for Best Poster at the Third Asia-Pacific Solar Research Conference, Canberra, as lead author for "CuSCN as a Hole Transporting Material in Planar CH3NH3PbI3 Perovskite Solar Cells and its Implications on J-V hysteresis and Stability".

The 2016 Women in Solar Prize at that conference went to UNSW's Ms Yu Jiang for Best Poster for "Nanostructured Metal Oxide Electrochemical Capacitors for Rapid Response Module-Level Buffering of Silicon Photovoltaic Power". Photovoltaic modules can exhibit high variances in their power output due to the intermittence of illumination.



Gaveshana Sepalage with his winning poster.



Yu Jiang after the Asia-Pacific Solar Research Conference presentation ceremony.

6th International Conference on Silicon Photovoltaics

The annual Silicon PV Conference is a very important meeting of silicon photovoltaics researchers, held in the Colorado Rocky Mountains. This paper, "Titanium oxide: a re-emerging optical and passivating material for silicon solar cells", by Jason Cui et al., was judged to be among the ten best presented. It demonstrated effective passivation of a variety of crystalline silicon surfaces by a thin layer of thermal atomic layer deposited (ALD) titanium oxide (TiO2).

Jason Cui (third from left) at the Silicon PV Conference prize ceremony in Colorado.

Student Exchange: UQ to NREL

Mr Martin Stolterfoht, from the University of Queensland (UQ) Node, visited NREL in 2015.

The objective of our partners at NREL was to set up a charge transport measurement technique that had been developed at UQ.

The technique allows the quantification of charge carrier mobilities in operational organic solar cells under relevant conditions. Martin was to be able to advance his investigations on the dissociation of the so-called charge-transfer (CT) states, an important but poorly understood participant in organic cell operation.

Student Exchange: Monash to NREL

In 2014 a Monash University PhD student, Alex Pascoe, spent two and a half months at the National Renewable Energy Laboratory in Colorado, USA. The work program addressed the characterisation of both planar and mesoscopic architectures in perovskite-based solar cells.

Throughout the two months, Alex worked closely with

- Mengjin Yang and Kai Zhu on device fabrication and characterisation,
- Nikos Kopidakis on time-resolved microwave conductivity measurements and
- Matthew Reese on time-resolved and steady-state photoluminescence measurements.

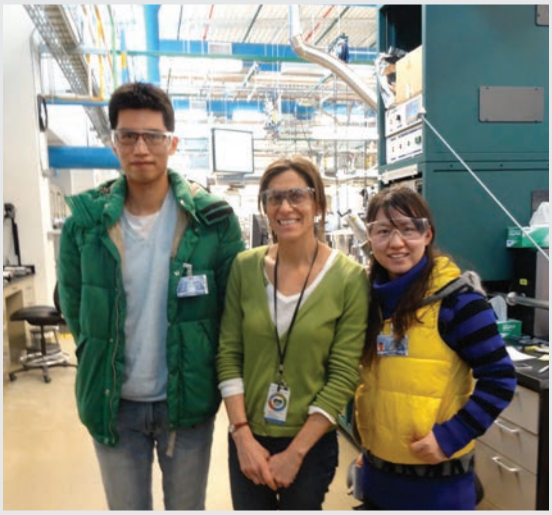
These measurements, in association with subsequent studies performed at Monash University and the University of Melbourne, revealed clear links between the perovskite microstructure and the charge transport/recombination dynamics.

Student Exchange: UNSW to Arizona State University

Ning Song spent 4 weeks at Arizona State University in November 2014 during which she was able to access the ASU Saguaro high performance computing cluster, to run photovoltaic device simulations using Synopsys' Sentaurus TCAD . In addition, Ms Song made use of her time at ASU to connect with former mentors and colleagues, meet new students and professors, exchange research results and plans, and discuss ideas for new projects and experiments.

Discussions with Dr. Laura Ding on the issue of lifetime degradation in silicon following epitaxial gallium phosphide (GaP) growth led to the planning of two experiments.

Ms Song also met with John Mitchell, Director of Corporate Engagement at the ASU QESST Engineering Research Center to discuss avenues for research commercialization and intellectual property protection.



Mid-term Review

ACAP underwent a Mid-Term Review in 2016 and the report of the external review panel was provided to ACAP in August. The Panel concluded that ACAP has met or exceeded its key performance indicators through outstanding research and is succeeding in its aim of improving the competitiveness of photovoltaics. Although it noted that ACAP's research has often led and informed the PV industry's development, the committee believed that paths should be explored to allow the capture of additional benefits from industry interactions. Refreshment of ACAP's performance indicators was also suggested, in light of ongoing developments in the industry as well as changes to streamline ACAP's administrative burden.

Future Direction

ACAP brings together the lead PV research institutions in Australia. The leadership team has an international reputation across all areas of solar cell research and technology development and is uniquely placed internationally to identify and assess new opportunities.

Key areas already identified for potential expansion include

- Capacity building, through establishment of a competitive program to recruit and retain expertise;
- Infrastructure investment, in particular to develop commercialization pathways;
- Moduling technology and environmental testing capabilities for demonstrating commercial viability of the technologies developed within ACAP;
- Life cycle environmental analysis, markets and least-cost-of-energy (LCOE) analysis to develop market and technology roadmaps in Australia and to inform investment decision makers;
- Deployment, addressing issues of technology, policy, risk and finance;
- Storage and integration technologies, which are now integral to increasing deployment of solar technologies.

Notably, ACAP has been significant in building a strong national collaboration and supporting excellence in research in photovoltaics in Australia. Without the ARENA funding of ACAP, advanced photovoltaics research in Australia would have been substantially diminished.

Continuous improvement

ACAP is young and, while delivering on its objectives on time and on budget, recognizes that it can continue to improve. Examples of improvements to the program already in place include;

- New processes have been established around competitive funding allocations;
- New industry partnerships are being forged, with a continuing focus on Australian industry needs; and
- Existing work is continuously re-evaluated, with resources adjusted and new programs initiated.

Summary

AUSIAPV and ACAP were established to promote collaboration between the lead research organisations in Australia, to deliver a greater impact from the collective than would otherwise be possible individually and to accelerate PV technology development, beyond what is achievable by Australia/US individually.

Over the three years since inception, ACAP has delivered on technical milestones, developed new programs, established new collaborations and strengthened the national and international network, but there is more to do.

Solar and wind generation combined now represent the largest investment in new energy generation capability. It is fully expected that solar photovoltaics will become increasingly competitive and alone will dominate energy investment in the very near future. For example, Bloomberg New Energy Finance expects photovoltaics to account for 35% of energy investments until 2040, valued at 3.5 trillion USD (Bloomberg 2015). This figure may well prove conservative since growth rates assumed in this analysis are much smaller per annum than the historical rate of 44% compound growth over the 20110-2015 period.

ACAP aims to build on its collective expertise by delivering on the significant value in the existing collaborations and stands ready to build on its capability with an increase in scope to reflect the increasing significance of photovoltaics as the leading source of energy for future generations.

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