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1. Director’s Report

Photovoltaics involves the direct production of electricity from light, especially sunlight, when it falls upon devices known as solar cells. Silicon is the most common material used to make these photovoltaic cells, similar to its key role in microelectronics, although a range of other photovoltaic materials is being actively investigated.

This is the second annual report of the Australia-US Institute for Advanced Photovoltaics (AUSIAPV), supported by the Australian Government through the Australian Renewable Energy Agency (ARENA) for an initial eight-year period. The Institute encompasses the activities of the locally based Australian Centre for Advanced Photovoltaics (ACAP) as well as synergistic international activities with US-based partner organisations.

AUSIAPV aims to significantly accelerate photovoltaic development beyond that achievable by Australia or the US individually. This goal is to be reached by leveraging the development of “over the horizon” photovoltaic technology, thereby providing a pipeline of improved technology for increased performance and reduced cost. A second aim is to provide high-quality training opportunities for the next generation of photovoltaic researchers, particularly through enhanced collaborations between Australian and US researchers, with one goal being to consolidate Australia’s position as the photovoltaic research and educational hub of the Asia-Pacific manufacturing region.

AUSIAPV/ACAP came into being on 1 February 2013 after the signing of a Head Agreement between University of New South Wales (UNSW) and ARENA. Subsequently, collaborations were established 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) (now Wuxi Suntech Power Co. Ltd.), Changzhou Trina Solar Energy Co. Ltd., Bluescope Steel and BT Imaging. Further, partnerships were established with the major international participants, the NSF-DOE Engineering Research Center for Quantum Energy and Sustainable Solar Technologies (QESST) and the US National Renewable Energy Laboratory (NREL), as well as from additional key US partners, Sandia National Laboratories, The Molecular Foundry, Berkeley, Stanford University, Georgia Institute of Technology and the University of California, Santa Barbara.

This report covers the period from 1 January to 31 December 2014. As well as setting up the broad framework for collaboration on an international scale, both AUSIAPV and ACAP have moved very quickly to establish a high profile within the international research community. Following on from the world-record 24.4% energy conversion efficiency cell developed at ANU during 2013 and confirmed early in 2014, a second world record was demonstrated later in 2014. A system based on splitting focused sunlight into four different colour bands, designed and fabricated at UNSW then tested at US partner NREL, became the first to convert sunlight to electricity with over 40% energy conversion efficiency. These and several of the other highlights over the year are summarised in the pages immediately following my report.
This report covers the period from 1 January to 31 December 2014. As well as setting up the broad framework for collaboration on an international scale, both AUSIAPV and ACAP have moved very quickly to establish a high profile within the international research community.

Other achievements outlined in the body of this 2014 Annual Report contributed to making 2014 an extremely successful year for the Institute. The photovoltaic industry fared better than most other industries through the recent global financial crisis and is now growing vigorously as costs continue to go down, driven by the ongoing uptake of improved technology that ACAP is uniquely positioned to supply. As an indicator of the growing appreciation of the large role photovoltaics will play in future energy supply, Bloomberg New Energy Finance brought forward to 2016 the company’s forecast date for when photovoltaics would surpass coal generators worldwide as the largest source of new electricity generation capacity.

I would like to thank ARENA for ongoing financial support and also for the very effective involvement of ARENA personnel in supporting the AUSIAPV/ACAP program, both informally and via the ACAP National Steering Committee and the AUSIAPV International Advisory Committee. I would additionally like to thank, in particular, all researchers affiliated with the Institute for their contributions to the broad range of progress reported in the following pages.

Finally, I am pleased to be able to report that AUSIAPV/ACAP has taken its second major step towards attaining its significant long-term objectives by achieving all second year milestones, on time and within budget. We look forward to a similar result in 2015 and in subsequent years.

Martin Green
Director
2. Highlights

40% Sunlight to Electricity Conversion

The program attained a landmark result internationally in 2014 with the first demonstration of sunlight conversion to electricity with efficiency above 40%. In an AUSIPV project supported by ARENA, UNSW, NREL and commercial partners, RayGen Resources Pty Ltd and Spectrolab Inc., 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.

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 with greater than 20% efficiency, using silicon wafers made with 100% ‘solar-grade’ silicon feedstock (see Section PP1.1). 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. Using a cell fabrication process that has been modified to maintain high electronic quality in the UMG wafers, a peak efficiency of 20.1% was achieved, as measured at ANU, almost identical to the value subsequently confirmed at the Fraunhofer Institute, Germany. Further innovations in the cell fabrication sequence are expected to allow efficiencies above 21% during the ACAP program.

Figure 2.1: Dr Mark Keevers, project manager of the 40% module project, with the system under test at UNSW.

Figure 2.2: 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.
Stuart Wenham receives Harvey Research Prize

In May 2014 Prof Stuart Wenham, from the UNSW node of ACAP, was awarded the prestigious IET AF Harvey Engineering Research Prize in London and delivered the Prize Lecture, “Trends in Photovoltaic Technology and Applications”. 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 wafers, the most costly part of a solar cell (see Section PP1.1). This allows solar cells made with lower quality silicon to outperform those made from better quality materials, producing higher efficiencies at lower cost. This technology has captured the imagination of some of the world’s leading silicon solar cell technology companies, who have partnered with ARENA and Prof Wenham’s team to develop the technology in the Solar Industrial Research Facility on the UNSW campus in a series of major collaborations.

In May 2014 Prof Stuart Wenham, from the UNSW node of ACAP, was awarded the prestigious IET AF Harvey Engineering Research Prize in London and delivered the Prize Lecture, “Trends in Photovoltaic Technology and Applications”. 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 wafers, the most costly part of a solar cell (see Section PP1.1). This allows solar cells made with lower quality silicon to outperform those made from better quality materials, producing higher efficiencies at lower cost. This technology has captured the imagination of some of the world’s leading silicon solar cell technology companies, who have partnered with ARENA and Prof Wenham’s team to develop the technology in the Solar Industrial Research Facility on the UNSW campus in a series of major collaborations.

Student Awards 2014

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. The award recognises outstanding work by students in each technical area. 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 will spend eight months at the University of California at Berkeley.

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. His poster entitled “Concentrating aggregation-induced emission from twisted aromatics in planar waveguides” described his progress in developing solar concentrators with improved performance based on luminescence from new types of twisted aromatic molecules. James’ PhD project is supervised by Dr Wallace Wong and Prof. Ken Ghiggino (see Section PP2.1).

High Impact Papers

Ten publications published under the ACAP program in 2014 have been identified as already making a large impact at the international level, earning the distinction of being classified as “Highly Cited Papers”, within the top 1% in their field. This is a disproportionately high number relative to the ACAP total. Four of these 10 earned the additional distinction of identification as “Hot Papers”, within the top 0.1% in their field, even further skewing the distribution.

The first of these highly cited papers, with lead author Thomas White from ANU, investigates tandem cell requirements for tandem cells stacked on silicon (see Section PP1.3). The next seven of these papers arise from the ACAP program strand PP2 on “Organic and Earth-Abundant Thin Film Cells” but involve four different thin film approaches, reflecting the breadth of good quality ACAP work across this strand. The first two of these, 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 Huazhong University of Science and Technology (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 Cu$_2$ZnSnS$_4$ compound prepared by a non-toxic, sol-gel route.

The final two PP2 thin-film strand papers receiving this distinction described progress in the rapidly emerging field of perovskite solar cells (PeSCs) 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$_2$ZnSnS$_4$ solar cells, received the distinction of featuring on the cover of the May 2014 issue of Physica Status Solidi Rapid Research Letters, with this cover reproduced in the accompanying figure.

The final two PP2 thin-film strand papers receiving this distinction described progress in the rapidly emerging field of perovskite solar cells (PeSCs) 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.

Figure 2.4: Cover of the May 2014 issue of Physica Status Solidi Rapid Research Letters featuring ARENA-supported UNSW research on Cu$_2$ZnSnS$_4$ for solar cells.

Figure 2.3: Prof Stuart Wenham (centre) at Harvey Prize award ceremony.
**High Performance Organic Photovoltaics 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 (DOI: 10.1038/ncomms7013) 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 Prof. Paul Meredith and Prof. 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 with Prof. Seth Marder at the Georgia Institute of Technology in Atlanta in a collaborative effort as part of the AUSIAPV program.

**Compact CH$_3$NH$_3$PbI$_3$ for High Efficiency Perovskite Cells**

A remarkable power conversion efficiency of 17% has been achieved at the Monash ACAP node by controlling the morphology of CH$_3$NH$_3$PbI$_3$ film. The quality of the perovskite film is extremely important for PeSCs, 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. Our study has attracted a significant amount of interest around the world. The Nano Energy paper has been downloaded more than 2,600 times since it appeared online in September 2014, while the Angew. Chem. paper has been designated as a “Hot paper” (top 0.1% of papers in its field).

Crystal packing in liquid crystal mesophases influences charge transport properties with, a) Discotic liquid crystals giving 1D transport, b) Smectic liquid crystals giving 2D transport, and c) Nematic liquid crystals giving 3D charge transport.

**Figure 2.5:** Discotic LC (1D) Smectic LCs (2D) Nematic LCs (3D)

**Figure 2.6:** Uniform compact CH$_3$NH$_3$PbI$_3$ 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 PeSC technology in the journal Nature Photonics. 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 PeSCs. The team provided compelling evidence for a non-excitonic charge generation mechanism (an exciton binding energy < 2meV which is amongst the smallest of any known semiconductors), 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 PeSC 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. The lack of any spectral dependence of the IQE rules out any hot exciton effects.

This work, published on-line in Nature Photonics in December 2014 and in print January 2015 has had immediate impact, receiving instant published citations and > 9000 downloads in its first 2 months. It has also led to a follow-up publication in Advanced Materials (front cover article in March, 2015) by the same team who used the electro-optics design rationale to demonstrate the first broadband visible perovskite photodiodes.

3D Printing of Perovskite Solar Cells

CSIRO has developed a solar coater based on a 3D printing platform as a research tool for solution processed 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 PeSCs. PeSCs are an emerging technology with rapidly increasing record efficiency (from 3.8% to 20% in the last 4 years), 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. A new scalable process, sequential slot-die coating, was developed for the PeSCs and high performance printed PeSCs were fabricated by the 3D printer-based slot-die coater. The scalable process was also translated to fabricate roll-to-roll printed PeSCs – a world first. CSIRO is currently further developing the scalable process to improve the reliability of the process. Two patents relevant to the process have been filed.

Figure 2.7: Cover of March 2015 issue of Advanced Materials featuring perovskite research from the University of Queensland ACAP node demonstrating that broadband photoresponse with low noise and high detectivity can be achieved.

Figure 2.8: Roll-to-roll printed organometal halide perovskite Solar Cell
The Australian Centre for Advanced Photovoltaics (ACAP) co-ordinates the activities of the Australian partners in the Australia-US Institute for Advanced Photovoltaics (AUSIAPV), 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 UNSW, ANU, University of Melbourne, Monash University, University of Queensland and CSIRO, plus our industrial partners Wuxi Suntech Power C. Ltd., Changzhou Trina Solar Energy Co. Ltd. (Abbreviated to Trina solar in this report), Bluescope Steel and BT Imaging. AUSIAPV links ACAP with US based partners, specifically the 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, Lawrence Berkeley National Laboratories, Stanford University, Georgia Institute of Technology and University of California, Santa Barbara. These national and international research collaborations provide a pathway for highly visible, structured photovoltaic research collaboration between Australian and American researchers, research institutes and agencies, with significant joint programs based on the clear synergies between the participating bodies.

AUSIAPV/ACAP targets 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 AUSIAPV/ACAP organisational chart is shown in Figure 3.1. The international activities of AUSIAPV are coordinated by an International Advisory Committee with membership drawn from ARENA, the US Department of Energy (DOE), ACAP and QESST and NREL. The International Advisory Committee is also charged with identifying opportunities for synergistic photovoltaic research initiatives between Australia and the US and for facilitating staff and student exchanges. Some examples of current international activities are reported in Section 6 of this report.

As well as these collaborative activities, the major partners in AUSIAPV, specifically 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 under the Head Agreement with ARENA. ACAP is managed by a Management Committee, which consists of the Node Directors or delegates from each of the nodes. The Committee takes advice from the National Steering Committee, with an independent Charter, but with membership including a representative of ARENA and NREL, the ACAP and QESST Directors, and other members drawn from industrial partners.
As indicated in Figure 3.1, the ACAP program is organised under five Program Packages (PP1-PP5), each supported by two or more 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, while maintaining or preferably, improving, energy conversion efficiency. The ACAP program focuses on three main areas: cells made from solar grade silicon, rear contact cells and silicon-based tandem cells, both monolithic and mechanically stacked.

Program Package 2 (PP2) involves collaborative research into a range of OPV, organic/inorganic hybrid cells, “earth abundant” thin-film materials, including Si and Cu$_2$ZnSnS$_4$ (CZTS), as well as more futuristic “third generation” approaches. Recently, the relatively new photovoltaic material, the organic-inorganic perovskites, has been included within the scope. The program has the overall goal of demonstrating efficiency above 15% for cells of above 1 cm$^2$ area and of demonstrating the feasibility of costs below the SunShot targets.

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 manufacturing 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.

Additional targets for PP1-4 relate to the established academic measures documenting research performance, specifically the number and quality of publications, with strong collaboration being encouraged by placing emphasis on publications involving authors from multiple nodes within the Australian based Centre or the Australia-US Institute, on invited keynote and plenary presentations, on patent applications and on indicators of commercial interest, such as the number of projects jointly supported by industry, with active commercialisation of key developments for at least one technology by Year 8.

PP5 involves education, training and outreach. ACAP has specific targets for the number of researchers in different categories benefitting from the infrastructural support it provides and for the quality and number of researcher exchanges. Additionally, a significant number of major outreach events are targeted for each year. As well as major events such as those reported in the PP5 section of this annual report, other outreach activities include 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 prepared and presentations to both policy developers and their advisors.

During 2014, the program was extended to include the production in 2015 of an Australian Solar PV Cell and Module Research Infrastructure Plan and Feasibility Study. This will produce a catalogue of desirable additional tools and facilities, and opportunities for rationalisation of existing tools and facilities, to support Australian solar PV cell and module research in the future (up to December 2020); a discussion paper describing how shared access to research tools and facilities is managed in other scientific and engineering disciplines, including preferred options for managing Australian solar PV research tools and facilities; and a discussion of the feasibility of comprehensive sharing of cell and module research infrastructure.

Figure 3.1: Organisational chart
4. Affiliated Staff and Students

**University of New South Wales**

**Academic Staff and Senior Researchers**
Green, Martin (Node Leader until Sep 14 and Centre Director)
Egan, Renate (Node Leader since Oct 14)
Corkish, Richard (ACAP Chief Operating Officer)
Bagnall, Darren
Barnett, Allen
Bremner, Stephen
Campbell, Patrick
Conibeer, Gavin
Edwards, Matthew
Ho-Baillie, Anita
Huang, Jialiang
Huang, Shujuan
Keevers, Mark
König, Dirk
Lennon, Alison
Mehvarz, Hamid
Mitchell, Emily
Perez-Wurfl, Ivan
Shrestha, Santosh
Sproul, Alistair
Teal, Anthony
Tronke, Thorsten
Uddin, Ashraf
Varlamov, Sergey
Watt, Muriel
Wen, Xiaoming
Wenham, Stuart
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5. Research Reports

Program Package 1 Silicon Cells

Overview

This Program Package (PP1) addresses silicon wafer-based cells and has efficiency targets, increasing over the eight-year period, for cells formed from solar-grade silicon, all-rear contact cells and tandem structures that include silicon.

The research into forming cells from wafers of low-cost upgraded metallurgical grade silicon wafers has been carried out within a strong and close collaboration between ANU and UNSW, also working with Apollon Solar (France), Institute for Solar Energy Research Hamelin and Fraunhofer Institute for Solar Energy Systems (Germany). Outcomes have included a modified cell fabrication process that allows high carrier lifetimes after phosphorus diffusion to be maintained through to the final device, development and application of advanced hydrogenation for bulk passivation, advances in deant and defect imaging, demonstration of carrier lifetimes in excess of 1 ms in solar-grade silicon wafers and fabrication of excellent cells on wafers sliced from Czochralski-grown ingots, for which the silicon feedstock was 100% solar-grade silicon. One PP1 highlight was a record efficiency of 19.8% that has been confirmed by measurements at the Calibration Laboratory at the Fraunhofer Institute for Solar Energy Systems (ISE).

Another highlight result for PP1 was a world record efficiency, confirmed in 2014, of 24.4% for an interdigitated back contact (IBC) silicon solar cell, a form of all-rear contact cell, developed at ANU with collaboration and support from PV Lighthouse, ACAP, Trina Solar and the Solar Energy Research Institute of Singapore. The performance was confirmed at Fraunhofer ISE. Work continues to increase laboratory IBC cell efficiency into the 25-26% efficiency range. Other approaches have included investigation of several possible avenues for passivating the metal/semiconductor contacts required to connect to all silicon solar cells. Ideally, these selective contacts should permit the passage of one type of charge carrier while perfectly blocking the other. This work has included the development of a novel scheme for passivation and contact of metal/silicon interfaces by ultrathin, tunnelling dielectric layers, the first-time demonstration of high quality surface passivation by gallium oxide and the successful development of polysilicon contact technology.

The third PP1 area involves silicon-based tandem stacks of cells, both monolithic and mechanically stacked, with a wide range of approaches being explored. For the monolithic approach, five different technologies are being pursued: three for stacking III-V cells on silicon, each with a distinct approach for matching to the smaller atomic spacing of silicon and two technologies involving materials that are either already lattice-matched to silicon or do not require good crystal quality for high performance. Good progress has been made, with 27.8±1.3% having been demonstrated for a 4-terminal silicon/GaAs tandem. Significant steps have been taken towards development of perovskite-silicon tandem stack cells. Ultimately, an efficiency of 32% is targeted for at least one of the approaches being studied, significantly higher than what is feasible with a single junction cell.
PP1.1 Solar Silicon

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Aim
The use of low-cost solar-grade silicon materials is seen as a promising route to further cost reductions for photovoltaic modules. However, to create a compelling case for the use of such solar-grade materials, it is necessary for the resulting cell efficiencies to be almost indistinguishable compared to those obtained when standard silicon wafers are used. The aim for 2014 was to push towards cell efficiencies of 20% using wafers grown from 100% solar-grade silicon, supplied by industry partners Apollon Solar. This would represent a world record efficiency for this class of material. To achieve this, a number of key areas were targeted with significant progress in 2014.

Progress
- High temperature process optimisation: Extensive tests have been carried out at ANU on the impact of a range of high temperature steps on the carrier lifetime of solar-grade wafers, including phosphorus and boron diffusions. This has resulted in a modified cell process which maximises the positive effect of phosphorus gettering, while minimising the negative impact of both boron diffusions and thermal oxidation steps. A key strategy has been to perform the phosphorus diffusion as the last high temperature step. As a result, we are now reaching carrier lifetimes of hundreds of microseconds after the full cell processing sequence.
- Post-diffusion lifetime recovery: During this project, it has been shown unambiguously for the first time that dissolved iron in crystalline silicon wafers can be passivated by hydrogen. This hydrogenation reduces the negative impact of the iron impurities, and can be achieved after cell processing, or during the final metal firing step (Liu et al. 2014). A key to understanding this process has been the recent discovery by the team at UNSW that the charge state of hydrogen plays a critical role in the hydrogenation process.

- Modelling of the advanced hydrogenation process: The UNSW team has developed a model for the simulation and manipulation of hydrogen charge-states, particularly for n-type silicon. This work and associated modelling, including innovative techniques for controlling these charge states has been published by Hamer et al. (2014). A strong collaboration exists between the teams at ANU and UNSW to further develop the advanced hydrogen passivation techniques and to apply them to the fabrication of even higher efficiency devices than the record devices already achieved. An important part of this work is the ongoing development and refinement of the models for predicting the behaviour of hydrogen when subjected to charge-state control. The original models developed by UNSW and referred to above have been further successfully developed and refined by researchers from ANU.

- Application of the advanced hydrogenation technology: In this task, the advanced hydrogen passivation techniques based on the control of the hydrogen charge states, have been applied to low cost solar grade silicon with impressive results. The main problem with such silicon is that the higher levels of impurities and defects can significantly reduce the minority carrier lifetimes and therefore device performance. The application of the advanced hydrogen passivation techniques has been demonstrated to remove the negative impact of such contaminants and defects and allow the achievement of minority carrier lifetimes equivalent to those achieved in silicon wafers normally costing as much as one hundred times. The impact of controlling the charge state of the hydrogen atoms is that it can greatly increase both their mobility and reactivity to apparently remove almost all recombination from even low quality silicon material. The effectiveness of these new techniques is demonstrated in the solar grade silicon wafer of Figure PP1.1.1 where the wafer, in the presence of a source of hydrogen, was heated to 250°C with only the circular region subjected to control of the hydrogen charge state. Importantly, the photoluminescent (PL) count indicated numerically and by the brightness of the colour, gives a measure of the resulting silicon quality, with the circular region being raised to a quality at least five times greater than the regions of the wafer where the hydrogen charge state was not controlled.

- Fabrication of high efficiency solar cells: Several batches of solar-grade silicon cells have been made using the optimised process developed above. The best solar-grade (UMG) silicon cell had an efficiency of 19.8%, as confirmed by measurements at Fraunhofer ISE CalLab, shown in Figure PP1.1.2.

- Fabrication of high efficiency solar cells: Several batches of solar-grade silicon cells have been made using the optimised process developed above. The best solar-grade (UMG) silicon cell had an efficiency of 19.8%, as confirmed by measurements at Fraunhofer ISE CalLab, shown in Figure PP1.1.2.

- The advanced hydrogen passivation technology has been described as a major breakthrough in silicon wafer-based photovoltaics and has received some of the most prestigious engineering awards internationally in 2014 including the A F Harvey Engineering Prize in the UK and the James N Kirby Award in Australia. The innovation embedded in the advanced hydrogen passivation techniques has justified filing for several patents including Wenham et al. (2014).

- Development of defect and imaging techniques: In the past months an established collaboration between ANU and UNSW in has further developed defect imaging techniques with numerous joint journal publications resulting, including the report by Mitchell et al. (2014). In particular, new vacancy-related defects in silicon wafers have been identified by the ANU team as being important recombination centres (Zheng et al. 2015). The team is currently working towards developing highly-resolved imaging methods for these defects and has found, surprisingly, that the well-known boron-oxygen defect, which we expected to be present in the solar-grade cells to a significant extent, appears to be entirely absent. This appears to be the result of in-situ hydrogenation of the defects during the final annealing of the contacts. This is a very positive result, but needs to be explored further in the coming months to fully understand and confirm the observations.

The most recent batch of ANU cells had a control efficiency of 22.0% (unconfirmed), indicating that there is scope to achieve higher efficiency devices than the record devices already achieved. The control cells made on electronic-grade float zone silicon reached a peak efficiency of 21.3%. The most recent batch of ANU cells had a control efficiency of 22.0% (unconfirmed), indicating that there is scope to increase the solar-grade efficiency above 20% in the coming year. Given new, improved solar-grade wafers received very recently from industrial partners, Apollon Solar, the team believes this is likely. These wafers show carrier lifetimes in excess of 1 ms, which promises cell efficiencies above 21% if this quality can be maintained during cell processing.

Figure PP1.1.1: PL count for an Apollon Solar wafer made from solar-grade silicon. The circular region represents the implementation of localised hydrogen charge-state control at 250°C to greatly improve the quality of this region via the passivation of contaminants and defects.

Figure PP1.1.2: Certified solar cell efficiency measurements from Fraunhofer ISE CalLab, for an n-type solar-grade ‘UMG CZ’ cell, and a control electronic-grade n-type ‘EG-FZ’ cell made at ANU under this project. The result for the solar-grade cell is the highest reported efficiency achieved to date with this class of material.
• Application of dopant imaging: In collaboration with partners at Fraunhofer ISE the ANU group has developed a powerful new method for imaging dopant concentrations and oxygen concentrations in silicon wafers, especially in relation to the presence of thermal donors, which are important in Czochralski-grown silicon ingots, such as the solar-grade ingots used in this project (Niewelt et al. 2014).

• Modelling of cell structures: Researchers at ANU are undertaking extensive modelling of solar cell properties to understand the main loss mechanisms in the solar-grade cells. In particular, analysis of the quantum efficiency of completed cells promises to reveal useful information about the impact of dopant compensation on carrier mobilities in the solar-grade cells. This knowledge will be fed back to the cell process design stage, to allow better optimisation of the cell process. The modelling work and the solar-grade cell results will be published in 2015.

Highlights

• Fabrication of a 19.8% efficient (independently confirmed) solar-grade silicon cell, the highest efficiency reported to date for this class of material.

• Development of a modified cell fabrication process that allows high carrier lifetimes after phosphorus diffusion to be maintained through to the final device.

• Demonstration of carrier lifetimes in excess of 1 millisecond in new solar-grade silicon wafers from Apollon Solar.

Future work

Future work will aim to achieve solar-grade cell efficiencies of over 21% within the next 12 months. In order to achieve this, we will need to continue to optimise the cell fabrication sequence, and further develop strategies and methods for minimising the impact of defects in this material, both during cell processing and post-processing. A key aspect will be the incorporation of the very successful hydrogenation work on wafers at UNSW into the cell fabrication process at ANU.

References

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PP1.2 Rear Contact Silicon Cells

The limiting efficiency for single-junction silicon cells is in the order of 29%. Several organisations are now fabricating cells at or above the 25% range and there is evidence that efficiencies above 26% are feasible using the current technologies, in particular cells fabricated with contacts on the rear offer improvements in performance through reduced shading.

Rear Contact Cells, or Interdigitated Back Contact (IBC) cells have the advantage of avoiding shading from the front metal grid, but at the cost of the need to move both electrons and holes to the rear surface. This places stringent requirements particularly upon front surface passivation and bulk lifetime and contact technologies. In back solar cells both the n and p contacts are removed to the rear surface to eliminate shading of the front surface by metal gridlines. Substantial reductions in resistive losses are also possible because the n and p contact metallisation can cover much or all of the rear surface, even overlapping, provided that an interposed pinhole-free insulating layer is used. Excellent front surface passivation is required because both the holes and electrons must be transported to the rear surface for collection without excessive front surface recombination. The minority carrier diffusion length must be at least several times larger than the wafer thickness in order to achieve high collection probability at the rear surface for electrons and holes that are mostly created near the front surface.

In 2014 a great deal of effort was directed at understanding and quantifying the loss mechanisms limiting cell efficiencies and developing processes to reduce or mitigate them, hence unlocking potential for higher cell efficiencies to be achieved in 2015.

Highlights

• Cells being fabricated using multiple lithography steps with an independently certified efficiency of 24.4%.

• Fabrication of cells having contact-opening lithography being replaced with masked UV laser ablation, with efficiency of 23.5% and with identical performance to co-processed cells which used photolithography to define contacts.

• A first batch of cells with all laser doping processes (no conventional high-temperature diffusions), fabricated with best efficiency of 19.1% and a best all ion-implanted cell efficiency of 22.1%, using patterned boron and phosphorus implants with co-anneal process.
Aim

Rear Contact Silicon Cells, or Interdigitated Back Contact (IBC) cells, have long been widely regarded as the most promising candidate for very high efficiencies. Indeed, Panasonic reported in 2014 a new world-record of 25.6% (for an aperture 125mm x 125mm cell) based on a combination of the heterojunction technology and IBC technology in the so called silicon heterojunction (SHJ) IBC cell, with Sharp also reporting at around the same time an efficiency of 25.1% (cell area approximately 4 cm²) based on the same SHJ-IBC architecture. Meanwhile SunPower reported last year 25.0% (125mm x 125mm) for IBC cells using more standard surface passivation methods and manufactured on an industrial pilot line, and remain the only company so far to commercialise the cell technology. However, IBC cells are now becoming increasingly considered as a promising route for large-scale industrial production, to continue the ongoing trend of increasing commercial efficiencies, with considerable attention now being paid to the technology by a number of cell manufacturers.

The development of IBC cells at ANU is targeted firstly at realizing the highest lab-scale cell efficiency practically possible, and secondly to use the knowledge gained to subsequently incorporate fabrication simplifications and industrially applicable processes to achieve high efficiency industrial IBC cells. IBC cell research activities at ANU fall typically into one of these two categories. Considerable progress has been made in 2014 along the path to achieving these goals.

Progress

Targeting very high efficiencies

A two-dimensional representation of an IBC cell design, fabricated to a size of 20mm x 20mm on 100nm diameter wafers in ANU’s laboratories, is shown in Figure PP1.2a.1. This is just one possible rear surface configuration (localized back surface field (BSF) and contact, broad area emitter and localized emitter contact, ‘contained’ n and p metal fingers), and corresponds to the cell design for the best cell manufactured to date at ANU, having an independently confirmed efficiency of 24.4%. This cell has been extremely well characterized at ANU (measurements of all physical, optical and electronic properties being made both throughout fabrication and subsequent to cell completion) such that each of the cell’s losses can be well described and quantified with the aid of 3D device simulation software. The resultant breakdown of losses for this cell, given in Figure PP1.2a.2, then provide guidance as to technology areas upon which to focus attention in order to realise further cell efficiency increases. As such, considerable effort has gone into understanding, quantizing and then developing processes to mitigate several of the key loss mechanisms for IBC cells, chief among them being optical losses owing to imperfect light-trapping, electronic losses due to bulk Shockley-Read-Hall recombination and rear surface recombination, and perimeter or edge losses due to carriers exiting laterally the relatively small active cell region. Resistive losses in the bulk, linked to the charge carrier transport mechanism from front surface/ bulk to rear current collecting contacts and representing a large fraction of overall losses, are simultaneously addressed via the mitigation or reduction of all recombination processes since this yields both higher electron and hole carrier densities and thus higher conductivity for both charge carrier types.

Light-trapping improvements have been assessed in 2014 by advanced ray-tracing simulations for a range of alternative front and rear surface treatments, to identify both the potential gain that could be made and to determine the most promising route to achieve this. With improved light-trapping via front and rear surface patterning and thicker substrates, an efficiency gain of between 0.2 and 0.3% absolute is targeted for 2015. To achieve this, a variety of new process steps must be introduced, many of which have been tested experimentally in 2014 with some further experiments required prior to implementation in new IBC cell designs.

Rear surface recombination using thermal oxide and low pressure chemical vapor deposition (LPCVD) SiN has been investigated in some depth in 2014 via the first of a two-part Design of Experiment process. Experimental work to date has led to the realization that thinner oxides combined with thicker SiN films can result, for a still not yet optimized LPCVD deposition parameter space, in a two-fold improvement in surface passivation on undoped silicon and similar
improvement on boron diffused surfaces. This efficiency improvement area, still a work in progress for 2015, will to some extent dictate rear cell geometries (for which a range of new mask patterns has already been designed and acquired in late 2014) which will yield highest efficiency for the best rear surface stack available. An efficiency improvement in the order of 0.2% absolute is targeted for this work.

However, it should be noted that other films for rear surface passivation (which must also satisfy other requirements – electrical isolation, chemical resistance) have also been and continue to be under investigation, not least because alternative light-trapping regimes may dictate them being required.

Bulk recombination losses are naturally closely correlated with material quality, and working with suppliers to ensure high quality wafers are supplied is critically important. However, it is the process itself which determines the final bulk lifetime and hence the impact on cell efficiency. It is well recognized that lifetimes in the order of 10 ms or greater are needed under most circumstances in order to exceed 25% efficiency. Work in this area of bulk material quality in 2014 has been directed at understanding the impact of various fabrication processes on bulk lifetime and in developing alternative process recipes to maintain or improve bulk lifetimes through the cell fabrication steps. Lifetimes of greater than 10 ms have been achieved in test structures, and improved annealing conditions are anticipated to deliver higher lifetimes still. Total efficiency improvements in the order of 0.2% (realistically achievable) up to 0.7% (for approaching ideal bulk material) are being targeted.

Finally, considerable work has been done in 2014 to characterize and quantify, via advanced PL imaging techniques, the edge losses due to carriers that are generated within the illuminated active cell region diffusing out of the active area and into the non-illuminated perimeter region where they combine. Losses which are considerable for small area cells on high lifetime substrates will, if unchecked, become even more noticeable as some of the other efficiency improvement measures are adopted. Therefore, work had been undertaken in 2014 to develop novel edge structures designed to suppress lateral carrier diffusion out of the active cell area and thus reduce losses. Considerable work is still required to ensure reliable implementation in fabricated cells. It is anticipated that edge losses (typically between 0.2 and 0.4% absolute under most circumstances) could be reduced by at least 50% when edge loss mitigation is implemented in cells.

Targeting industrially relevant cells
Work in the area of reducing fabrication complexity and implementing simplification of processes by employing novel processing technologies has largely consisted in 2014 of successfully introducing laser ablation, laser doping and ion implant technologies. These technologies offer the opportunity to perform localized processes without complex and costly patterning / masking processes, and to do away with many or all high-temperature processes, thereby eliminating costly tools while also adding flexibility in terms of thermal budgets required to maintain high material lifetimes on industrially relevant materials.

Laser ablation, performed at ANU via a masked 248 nm nanosecond excimer laser, has been shown to be capable of damage free removal of SiN films, thus making it a suitable process to replace photolithography in high-efficiency cell fabrication, in particular for the crucial contact opening step. Highlights in 2014 included fabrication of independently certified 23.5% efficient IBC cells, with evidence to show that the laser ablation step itself had no impact on the limit to efficiency. Laser ablation will be implemented in 2015 with expectations of 24% efficient cells.

Contact opening via laser ablation was also employed in a two-step all laser doped cell fabrication design at ANU in 2014. This was a first attempt to fabricate IBC cells with laser patterning and doping only, yielding a result of 19.1% efficiency but with known limitations. Work has continued in 2014, and is ongoing, to find the best laser parameters and cell design using such a process in order to achieve reasonable efficiencies. It is expected that all laser doped IBC cells with efficiency in excess of 22% will be fabricated in 2015.
PP1.2b Passivated contacts

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Aim

The objective of this subproject is to investigate several possible avenues for passivating the metal/silicon contacts required by all silicon solar cells. Ideally, these selective contacts should permit the passage of one type of charge carrier while perfectly blocking the other type. In most common implementation of silicon solar cells, electron and hole selectivity is partially achieved by diffusing dopants into the silicon wafer, forming n⁺ and p⁺ regions. These regions cannot block minority carriers completely, even when optimised. The main reason is that recombination at the contact between the metal and the n⁻ or p⁻ semiconductor is practically unavoidable with conventional technology. In this sub-project we will investigate different avenues to passivate the contacts, aiming to produce proof-of-concept results.

Progress

The initial phase of the work has identified passivated contact technologies of particular promise and developed one of them to full device level. We studied and obtained good results for contact passivation by PECVD amorphous silicon, but even better results with amorphous silicon/dielectric stacks, in what we call an a-Si:H enhanced MIS contact structure, achieving 21% cells. On the other hand, work on sputtered a-Si:H came up against the roadblock of not being able to dope it to a sufficiently high level, due to the limitations of the targets available to us. To compensate for that, we had success in developing a simple technology for polysilicon contacts that exhibit very good transport and recombination properties. A more ambitious, longer term approach based on Ga₂O₃ had its first breakthrough in 2014 with the demonstration of effective surface passivation. This opens the path to further planned research on this material.

Contact passivation by PECVD amorphous silicon

Carrier recombination at the metal contacts is a major obstacle in the development of high-performance crystalline silicon homojunction solar cells. To address this issue, we inserted thin intrinsic hydrogenated amorphous silicon (a-Si:H(i)) passivating films between the dopant-diffused silicon surface and aluminium contacts. We found that with increasing a-Si:H(i) interlayer thickness (from 0 to 16 nm) the recombination loss at metal-contacted phosphorus (n⁺) and boron (p⁺) diffused surfaces decreases by factors of ~25 and ~10, respectively. Conversely, the contact resistivity increases in both cases before saturating to still acceptable values of ~50 mΩ·cm² for n⁺ and ~100 mΩ·cm² for p⁺ surfaces. Carrier transport towards the contacts most likely occurs by a combination of carrier tunneling and aluminium spiking through the a-Si:H(i) layer, as supported by scanning transmission electron microscopy - energy dispersive x-ray (STEM-EDX) maps. We explained the superior contact selectivity obtained on n⁺ surfaces by more favorable band offsets and capture cross section ratios of recombination centers at the c-Si / a-Si:H(i) interface.

Figure PP1.2b.1: Illuminated I-V curve comparison of alike n-type cells with an a-Si:H enhanced MIS rear contact and directly metalized partial rear contact.

Amorphous Silicon Enhanced Metal-Insulator-Semiconductor Contacts.

A thorough experimental investigation produced the proof-of-concept of a procedure to reduce contact recombination by means of enhanced metal-insulator-silicon (MIS) structures. Lightly diffused n⁺ and p⁺ surfaces were passivated with SiO₂ / a-Si:H and Al₂O₃ / a-Si:H stacks, respectively, before the MIS contacts were formed by a thermally-activated alloying process between the a-Si:H layer and an overlying aluminium film. Transmission / scanning transmission electron microscopy (TEM/STEM) and energy dispersive x-ray (EDX) spectroscopy were used to ascertain the nature of the alloy. Idealized solar cell simulations revealed that MIS(n⁺) contacts, with SiO₂ thicknesses of ~1.55 nm, achieve the best carrier-selectivity producing a contact resistivity of ~3 mΩ·cm² and a recombination current density of ~40 mA/cm². These characteristics were shown to be stable at temperatures up to 350°C. The MIS(p⁺) contacts failed to achieve equivalent results both in terms of thermal stability and contact characteristics but may still offer advantages over directly metallized contacts in terms of manufacturing simplicity.

Solar cells with a-Si:H enhanced MIS contacts

This work implements the experimental demonstration of silicon solar cells that incorporate an enhanced MIS passivated contact scheme on a phosphorus diffused surface. By depositing intrinsic a-Si:H on an ultrathin SiO₂ layer and alloying with an overlying aluminium layer, the interface passivation has been vastly improved over that of conventional MIS contacts, whilst maintaining a low contact resistance. We have optimised the Al / a-Si:H alloying process and the influence of the tunnelling SiO₂ layer thickness. A conversion efficiency of 21.0% has been achieved for n-type cells fabricated with a front boron diffusion and a full area rear MIS passivated phosphorus diffusion. The cells exhibit a high open circuit voltage (Vₜₚₜ) of 666 mV and fill factor (FF) equal to 0.805, whereas the Jₒₜₚ of 39.3 mA/cm² is relatively low due to a non-optimal antireflection coating and a low back surface reflection, and hence should be easily improvable.
We have demonstrated the first application of gallium oxide ($\text{Ga}_2\text{O}_3$) thin films to crystalline silicon solar cells. Effective passivation of n- and p-type crystalline silicon surfaces has been achieved by the application of very thin $\text{Ga}_2\text{O}_3$ films prepared by atomic layer deposition (ALD) using trimethylgallium (TMGa) and ozone ($\text{O}_3$) as the reactants. Surface recombination velocities as low as 6.1 cm s$^{-1}$ have been recorded with films less than 4.5 nm thick. A range of deposition parameters has been explored, with growth rates of approximately 0.02 nm per cycle providing optimum passivation. The thermal activation energy for passivation of the Si-$\text{Ga}_2\text{O}_3$ interface has been found to be approximately 0.5 eV. De-passivation of the interface was observed for prolonged annealing at increased temperatures. The activation energy for de-passivation was measured to be 1.9 eV.

Phosphorus-diffused polysilicon contacts for silicon solar cells

An ultrathin dielectric layer capped with a doped polysilicon layer can form a very effective selective carrier contact for silicon solar cells. We have performed an experimental optimisation of SiO$_x$/n$^+$ polysilicon/metal contacts, where a thermal POCl$_3$ diffusion process is used to dope PECVD deposited intrinsic polysilicon, and two methods are trialled to create the oxide: thermal and chemical. The phosphorus diffusion temperature and time were optimised for a range of thicknesses of the two component layers. The oxide thickness is found to be critical to obtain both a low recombination parameter $J_{oc}$ and a low contact resistivity $R_c$, with an optimum of 1.2 nm for the thermal oxide and 1.9 nm for the chemical one. By adjusting the diffusion and drive-in conditions it is possible to achieve very low $J_{oc} < 6 \text{ fAcm}^2$ for polysilicon thicknesses in the range 32-60 nm. Nevertheless, $R_c$ increases with polysilicon thickness, due to its bulk resistivity. The optimum trade-off between recombination and transport is $J_{oc} = 4.5 \text{ fAcm}^2$ and $R_c = 0.019 \Omega\text{cm}^2$, for 32 nm of polysilicon with 1.2 nm of thermal silicon oxide. Alternatively, a 1.9nm chemical oxide with polysilicon layers of 32-44 nm produce an only slightly higher $J_{oc} = 6 \text{ fAcm}^2$ and a very similar $R_c$.

**Highlights**

- Development of a novel scheme for passivation and contact of metal/silicon interfaces by ultrathin, tunnelling dielectric layers.
- First-time demonstration of high quality surface passivation by gallium oxide.
- Successful development of polysilicon contact technology.

**References**

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PP1.3a Silicon Tandem Cells (monolithic)

Five strands are run under Program Package PP1.3a aim, for the first time, to successfully mate the most successful PV technology based on silicon solar cells with the III-V and chalcogenides technologies.

Of the III-Vs of interest, only GaP offers a lattice match to silicon, with the III-Vs used in the best III-V cells having about 4% mismatch, being better matched to Ge. One strategy PP1.3a(i) is to take advantage of the miscibility between Si and Ge to grow a series of SixGe1-x buffer layers on Si, with x steadily decreasing. In this way, the lattice constant can be changed from that of Si to that of Ge after growth of a micron or more of buffer material. High quality III-V cells can be grown on the Ge surface.

A parallel approach PP1.3a(ii) with some success demonstrated in 2013 is to take advantage of the similar miscibility of GaP and GaAs by growing a series of GaP,GaAsx buffer layers on Si with x again steadily decreasing, allowing a transition from the Si lattice constant to that of GaAs. An advantage in this case is that the material in the buffer layer has a much higher bandgap than silicon, allowing the silicon substrate to participate as an active cell in the stack.

Working with US- and Australian-based collaborators, with additional project support leveraged beyond that able to be provided from SRI funding, an efficiency of over 24% with one or more of these approaches is anticipated in the first 4 years of the Australian Centre operation. Options for reducing the thickness and cost of any buffer layers or otherwise reducing costs will be the target of the second phase of activities during years 5-8, with a targeted cell efficiency of 32%.

Two more adventurous approaches to building high quality tandem cells on silicon wafers are also being explored. PP1.3a(iii) utilises an atomically abrupt Si/Ge transition, where the lattice mismatch is taken up in a single atomic layer, which is thermodynamically feasible since it is a low energy configuration. UNSW has filed patent applications on approaches that have given promising results of this type. This would allow the Ge layer to be very thin, creating negligible absorption loss, or thick enough to be used as an active cell in a novel “out-of-sequence-tandem”.

The second of these more adventurous approaches (PP1.3a(iv)) is the investigation of silicon tandem cells using chalcogenides as the upper cells in the stack. Although the established chalcogenide cell materials (copper indium gallium selenide (CIGS) and CdTe) have shown high efficiency potential, they are not lattice-matched to silicon and have problems arising from the use of toxic and/or scarce materials.

More promising for the long-term are devices made from materials based on the CZTS system. Despite the relatively small effort yet devoted to its development, devices made with these materials have already demonstrated energy conversion efficiency above 12%. Moreover, its lattice constant and that of related alloys are a close match to silicon and the CZTS bandgap, at circa 1.5 eV, is almost ideal for the lower cell in a 2-cell stack on silicon. Moreover, alloying with related compounds with, for example, Zn or Sn replaced by lighter elements such as Fe(ii) or Si will increase the bandgap making values such as the 1.7 eV required for a 1-cell stack or the circa 2 eV required for the top cell in a 2-cell stack on silicon also accessible in a highly compatible materials system.

The final strand of activity (PP1.3a(v)) involves investigation of material systems that do not require lattice matching to silicon. Work in 2013 has been restricted to Si quantum dot cells, with the crystalline quantum dots dispersed in an amorphous matrix.
The primary technology used for device fabrication in this research is photolithography. Figure PP1.3a.2 illustrates the fabricated 3-T structure with an anti-reflection coating (ARC). The process has been improved and summarised as follows:

The rear and front metal contacts are deposited using thermal evaporation. The contacts are then annealed using rapid thermal processing (RTP). Isolation of the top devices is performed using a wet chemical method. The middle contact is deposited on the III-V back surface field layer to facilitate analysis of top and bottom cells separately. Bottom cells are isolated using reactive-ion etching (RIE). The final step is the application of the ARC, deposited by plasma enhanced chemical vapour deposition.

Materials characterizations for III-V and Si$_{1-y}$Ge$_y$ have been carried out both optically and electrically. Optical constants of GaAs$_{0.84}$P$_{0.16}$, Ga$_{0.59}$In$_{0.41}$P and Al$_{0.65}$In$_{0.35}$P have been measured and used to estimate non-zero collection probability in the window layer (Conrad et al. 2014a). Window layers have been optimized to enable broadband double-layer ARC (Conrad et al. 2014b). Hall mobility of GaAs$_{0.84}$P$_{0.16}$ has been measured and used for predicting device performance using a 1-D diode model (Soeriyadi et al. 2014). A highly accurate approach has been proposed and the absorption coefficient of Si$_{1-y}$Ge$_y$ film grown on silicon substrate with germanium compositions of 78%, 82%, 85% and 88% from around 1000nm to 1400nm at 297K have been obtained (Li et al. 2014). Material compositions of Si$_{1-y}$Ge$_y$ are confirmed with energy-dispersive X-ray spectroscopy and electrochemical capacitance voltage profiling (Zhao et al. 2014a).

Device performances have been improved for GaAsP top solar cells and SiGe bottom solar cells individually, thus leading to progress for the tandem solar cells. The efficiency of the GaAsP top cell has been improved to 18.4% by improving $J_{sc}$, $V_{oc}$ and FF with the use of ARC, by improving material quality during growth and by reducing $R_s$ through device engineering. The measured band gap voltage offset ($W_{oc}$) of this top cell is 0.48V and 0.31V under 1X and 20X, respectively (Wang et al. 2014b). Numerical and analytical methods have been introduced to demonstrate the SiGe solar cells’ performance limits and examine the trade-offs between IV performance, cell’s structures and material composition. An efficiency of 1.7% has been achieved with the Si$_{0.18}$Ge$_{0.82}$ cell under a GaAsP top cell. The measured $V_{oc}$ is 435 mV with 425 mV $W_{oc}$ under 20X illumination (Zhao et al. 2014b). EQE integrated $J_{sc}$ of the top cell and bottom cell has been increased to 19.3 mA cm$^{-2}$ (300-740nm) and 10 mA cm$^{-2}$ (740-1400nm), respectively, as presented in Figure PP1.3a.3. By integrating this improved SiGe bottom cell, the efficiency GaAsP/SiGe tandem device on silicon has been boosted from 18.9% under 1X (Diaz, M. 2014) to 20.6% under 1X and 20.2% under 20X illuminations, respectively. JV performance is shown in Figure PP1.3a.4. Current matching scenario has been realised by improved bottom cell structure, additional active bottom cell area and adjustable light spectrum.

**Figure PP1.3a.1:** Simplified diagram of improved GaAsP on SiGe/Si tandem structure showing the key layers

**Figure PP1.3a.2:** Cross-sectional graph of GaAsP on SiGe/Si fabricated 3-T tandem device structure (with ARC)

**Figure PP1.3a.3:** Quantum efficiency of top and bottom solar cells with and without ARC

**Figure PP1.3a.4:** JV curve of tandem device with ARC under 1X and 2.2X illuminations
Highlights

- Low TDD of $2.8 \times 10^6 \text{cm}^{-2}$ in III-V layers by SiGe graded buffers between III-V and Si
- Current matching between GaAsP top cell and SiGe bottom cell
- Tandem efficiency on Si of over 20%

Future work

Achieve current matching of 21 mA cm$^{-2}$ for each solar cell under AM1.5G by light trapping techniques and better optical design.

Further improve material quality by reducing TDD to increase $V_{oc}$

Minimise series resistance and reduce ideality factor close to 1 to improve fill factor

With these, a GaAsP/SiGe tandem efficiency of over 25% and 30% under 1X and 20X illumination of AM1.5G is expected to be achieved.

References

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PP1.3a (ii): III-V Cells on Silicon Using Gallium Phosphide Buffer Layers

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Aim

This approach exploits a number of advantages of using GaP as a bridging layer from the silicon substrate to high potential efficiency III-V materials. Foremost is the demonstrated ability to grow very high quality GaP on Si, the ability of the high band gap GaP to act as a window layer, as well as favourable band alignments for carrier flow in multi-junction solar cell.

Progress

First structures with 1.8 eV GaAsP layers on top of silicon via step grading of the alloy content from GaP were successfully grown. The high quality material confirmed that UNSW processing is compatible with subsequent epitaxial growth and that no modification to the pre-growth processing of substrates is required.

The performance of the bottom silicon cell structures, designed and fabricated by UNSW, was tested. Of particular interest was the long wavelength performance of the silicon sub-cell.

Results (see Figure PP1.3a.5, taken from Grassman et al. (2014), indicated the UNSW-developed passivated emitter, rear totally diffused (PERT)-like structure performed significantly better than more standard structures in the long wavelength portion of the spectrum, confirming our previous modelling results Almansouri et al., 2014).

Simulations to try and optimise the III-V cells series connected and stacked on top of silicon were also undertaken during 2014. Exploiting a heavily doped rear buffer the predicted performance was improved for material with relatively large densities of deleterious threading dislocations. Figure PP1.3a.6 shows the proposed structure and the impact of using this design on performance.

Figure PP1.3a.5: Internal quantum efficiency (IQE) measurements for the UNSW prepared bottom silicon sub-cell in comparison to an in-situ epitaxially formed junction approach. Results confirm the UNSW prepared silicon substrates performed markedly better at longer wavelengths making them ideal for use in a III-V/Si multi-junction device.
An alternate structure for the silicon solar cell was initially explored in 2014, with the location of the pn junction close to the rear surface being explored via computer simulation. Suitable silicon wafers have been acquired and the first UNSW processed structures will be sent to Ohio State University for III-V growth in the near future.

**Highlights**

- Demonstrated superiority of UNSW silicon solar cell for use in final multi-junction solar cell
- First growth of GaAsP layers via step graded metamorphic layers on top of GaP

**Future work**

Future work will focus on the processing of complete devices, with several iterations expected in order to optimise the integration of the different processing steps required for contacting to III-V materials and silicon. This will initially be focused on the more conventional front junction design, but will also be applied to the alternate rear junction design.

**References**


Progress

A patent application on the laser annealing of Ge to minimise crystal defects has been filed through NSi, UNSW (NSi 2015). This will allow the Ge layer to be very thin, creating negligible absorption loss, or thick enough to be used as an active cell in a novel “out-of-sequence-tandem”.

Experiments were designed with EPISAR to develop III-V cell growth and fabrication on Ge/Si and reference Ge substrates. Promising voltages but lower than expected currents and fill factors were achieved. Key limitations are under investigation.

As part of further optimisation and comparison, III-V cell structures different from the one by EPISAR have been grown and fabricated by collaborating with Korean Advanced Nano Fab Centre (KANC) on Si substrates as well as virtual Ge substrate. With optimised III-V design, the former gave the performance with conversion efficiencies exceeding 12%. Without the incorporation of super lattice layer designed for direct growth of III-V on Si, the devices with Ge buffer layer yields poorer performance, indicating the III-V structures need to be optimised for virtual Ge substrate.

Numerical study of III-V structures was carried out in parallel as a feedback to industry partners for improving the performance of Si/III-V tandem cells.

Highlights

• Filing of a provisional patent on a new approach that can yield high-throughout crystal defect cleaning. This would allow the Ge layer to be very thin, creating negligible absorption loss, or thick enough to be used as an active cell in a novel “out-of-sequence-tandem”.

• Fabrication of operational GaAs cells on sputtered thin Ge layers deposited on silicon wafers during 2014 by collaboration with Epistar and KANC (see Figures PP1.3a.8 and PP1.3a.9).

• Fabrication of 12% GaAs cells on bare Si wafers, in collaboration with KANC.

Future work

The aim in 2015 is to optimise the laser defect-annealing process, polarity engineering of heteroepitaxial Ge/Si as well as developing optimised III-V cell structure suitable for virtual Ge substrate.

References


![Figure PP1.3a.7: Cross-sectional TEM images of (a) Ge on Si before annealing; (b) after cyclic thermal annealing; (c) after diode laser annealing.](image)

![Figure PP1.3a.8: J-V and EQE curves of III-V cells on sputtered Ge/Si and GaAs substrates (by collaboration with Epistar).](image)

![Figure PP1.3a.9: J-V and EQE curves of III-V cell on Si and sputtered Ge/Si substrates.](image)
PP1.3a (iv): Chalcogenide Cells on Silicon

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Aim
Chalcogenide semiconductors are promising as absorber materials for solar cells due to their direct band gaps and high absorption coefficient (>10^4 cm^-1). As an ideal candidate to substitute for toxic and rare elements in CIGS, CZTS, a quaternary absorber material with a band gap of 1.5 eV has been identified. This band-gap energy is close to the optimal band gap for a single junction solar cell of 1.35 eV and is also optimal for a middle cell in a 3-cell tandem with a Si bottom cell. Bandgap tuning of CZTS by substituting a lower atomic number group IV element for some of the Sn, Ag for Cu, allows exploration of CZTS-based cells for the top cell in a CZTS/Si stack for a 2 or 3-cell tandem. The lattice parameters of Si and CZTS, aSi=0.5431 nm, aCZTS≈0.543 nm, c≈1.086 nm(c≈2a), with respect to crystallographic symmetry, demonstrate that cubic silicon as a substrate material should be suitable for epitaxial growth of a tetragonal kesterite CZTS thin film. The combination of optimal bandgap as a middle cell and tunable bandgap as top cell for a 3-cell stack and low lattice mismatch shows that this material system well suited for the top cell on Si cells. Epitaxial layers of quaternary CZTS related compounds on silicon can combine the advantages of a direct semiconductor with those of the well-known and established silicon technology for novel tandem photovoltaic devices.

The aim of the present project is to work with NREL, which has world-leading expertise on I-II-VI chalcogenide solar cells, to exploit the complementary synergies with UNSW to develop a new generation of Si wafer cell technology, with performance of the Si cell substantially improved by deposition of thin layers of high performance CZTS based cells on its surface to produce tandem devices.

Progress
The general design concept for this approach is shown in Figure PP1.3a.10.

High quality CZTGS (Cu₂ZnSn₁₋ₓGeₓS₄) thin films with tuneable bandgap in the range of (1.5-2.0eV) have been synthesised and associated optical and electrical properties have been investigated. With the incorporation of Ge into CZTS, the lifetime is enhanced (Figure PP1.3a.11). In addition, the electronic band structure varies with the Ge addition, with modification mainly in the conduction band (Figure PP1.3a.12). A working CZGS solar cell was also demonstrated.

Figure PP1.3a.10: Tandem cell stack (left) and limiting energy conversion efficiency (right), with (green) and without (red) the bottom cell constrained to be silicon.

Figure PP1.3a.11: Time-resolved photoluminescence of CZTS with different levels of Ge doping.

Figure PP1.3a.12: Estimated conduction band offset between CZTGS series and CBD-synthesized buffer material options (CdS, InₓSᵧ, and Zn(S,O) by CBD method) and ZnS taken from the reference (M. Bär, and et al., Physical Review B 84, 035308 (2011)).
Epitaxial growth of CZTS was realised on sapphire, ZnS and Si substrate for the investigation of tandem solar cells, among which the work of epi-CZTS on ZnS was selected as the cover of Physica Status Solidi Rapid Research Letters. (Figure PP1.3a.13)

A 1.8% efficient bifacial CZTS solar cell on indium tin oxide (ITO) coated glass was achieved for 4-terminal tandem cells. (Figure PP1.3a.14) and a working CZTS/Si heterojunction was demonstrated (Figure PP1.3a.15).

CZTS solar cells from CZTS nanocrystals were realised with a record efficiency of 4.4% by a novel solution method, which utilises high throughput rapid thermal processing sulfurization, providing an alternative method for creating low-cost, high-throughput chalcogenide/Si tandem cells (Figure PP1.3a.16).

Ag nanowire was investigated as an alternative transparent front contact for chalcogenide/Si tandem solar cells. Finite difference time domain (FDTD) simulation was carried out to identify the optimised combination of Ag nanowires and ITO for maximised transparency and conductivity. Ag nano-wires were synthesised using the dip-casting and spin-coating method (Figure PP1.3a.17).

**Highlights**

- Working chalcogenide solar cells demonstrated on Si and on ITO glass
- Investigation of two-terminal chalcogenide/Si tandem cells and four-terminal chalcogenide tandem cells
- Numerical and experimental studies carried on front transparent contact, chalcogenide solar cells, and Si bottom cell.

**Future work**

The future work in 2015 is to optimise current developed top chalcogenide solar cells and integrate with Si for tandem solar cells.
5. Research Reports

PP1.3a (v): Non-epitaxial Tandem Cells on Silicon

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Aim
To investigate material systems where epitaxial growth on a crystalline template is not required for good cell performance. One such material system is organic metal halide perovskite.

Progress
One of the major outcomes of this work was determination of the optical constants and dielectric properties of CH$_3$NH$_3$PbI$_3$ perovskite materials for informed optical modelling for design of single junction PeSCs or tandem structures using perovskite as one or more sub-cells (Figure PP1.3a.18). This aspect was published by Jiang et al. (2015). See.

The project also determined the exciton binding energy of CH$_3$NH$_3$PbI$_3$ and CH$_3$NH$_3$PbBr$_3$ perovskites, with consideration of exciton-polaron interaction and evaluation of bandgap (Soufiani et al. 2014) as shown in Figure 1.3a.19. It also calculated solar energy conversion efficiency limits for dual junction perovskite/silicon tandem cells (Almansouri et al. 2014a,b). See Figure 1.3a.20.
One- and two- photon photoluminescence imaging of perovskite material by Wen et al. (2014) illustrated by Figure 1.3a.21, fabrication of higher bandgap PeSCs (Sheng et al. 2015). Figure 1.3a.22 and Table 1.3a.1) and improved scanning probe microscopy of perovskite grain boundaries (Yun et al. 2015). (Figure 1.3a.23) were additional advances.

Tasks PP1.3a (iv) and (v) are conducted under the ARENA RND075 program in collaboration with Australian National University, Arizona State University, Wuxi Suntech Power Co. Ltd., and Trina Solar.

**Future work**

- Determination of higher bandgap perovskite optical constants and dielectric properties
- Various photoluminescence characterisations of various perovskite materials fabricated using various methods
- Scanning probe microscopy of grain boundaries of various perovskite materials fabricated using various methods
- Fabrication of perovskite / Si tandem cell under various terminal configurations
- Stability study and encapsulation strategies for perovskite / Si tandem technology.

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PP1.3b Silicon Tandem Cells (mechanically stacked)

An alternative approach to silicon tandem cells is mechanical stacks with independent wiring. This removes constraints in relation to matching of current, lattice constant and thermal expansion coefficient, albeit at the cost of additional mounting and interconnection costs. The best available silicon and wide bandgap cells can be separately optimized and mounted together.

Current proof of concept work is focused on reflector based architectures to direct long wavelength light to the Si cell. This will enable the use of commercially available conventional GaAs as the top cell. Design of the mounting, optics and interconnection is critical to maximising performance. Longer term design preferences are for transparent top cells which offer more flexibility in the application of the tandem structure within field applicable devices.

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Aim
Efficiency is a major driver for cost reduction in photovoltaics, decreasing modularization and balance of systems costs. Although silicon continues to dominate the photovoltaics market, the efficiency of the best laboratory devices has been capped at 25% for 15 years. While large area cells with efficiency greater than 24% have recently been demonstrated, for photovoltaic performance to exceed 30% the silicon device needs to be combined with another, ideally higher bandgap cell.

This work focuses on four terminal tandem devices with silicon as the low bandgap device where modelling shows that a broad range of semiconductor materials are capable of delivering efficiencies >30%. This work looks at a practical implementation of this modelling to demonstrate the potential of four terminal tandems with silicon as the bottom cell. Rather than requiring devices that are transparent to sub-bandgap light or expensive optics, the high bandgap cell is used as a reflector of the sub-bandgap light onto the silicon cell.

Highlights
• Development of concentration and non-concentrating architectures for reflective tandems
• Preliminary modelling of the economics of silicon-based tandems

Future work
Reflective tandem arrangements
The reflective tandem arrangement would lead to considerably different architecture than for a conventional module. Any configuration is likely to require the range of directions on the light to be constrained in one axis. Fortunately, one axis roll trackers are capable of meeting this requirement. Such systems are already cost effective for flat plate modules due to the increased energy collection and are economic even for moderate efficiency modules such as those produced by First Solar. The tracking cost would be reduced for high efficiency tandems.

One potential approach would be to have a 45° saw tooth superstrate on which the high bandgap cells are placed (Figure PP1.3b.1). The high bandgap cells could be deposited directly on the superstrate or formed separately and then mounted. Bifacial silicon cells, such as SLIVER cells, would be placed in slots formed at the peaks of the saw tooth. Light reflected from the high bandgap cells would then strike the silicon devices as per the arrangement in the earlier measurements. One advantage of this arrangement is that the light intensity on the silicon cell is doubled, requiring only half the silicon cell area and increasing light intensity closer to one sun. This approach would be well suited to any high bandgap thin film cell.

The use of narrow (of the order of 1mm) silicon cells such as SLIVER cells ensures that the module thickness would be similar to conventional modules. Given that the entirety of the module is covered with the high bandgap material, it would be best suited to lower cost thin film approaches.

Another approach better suited to enabling more expensive high bandgap cells such as GaAs to have lower electricity costs is represented in 1.3b. A linear concentrating element is placed in front of the cells reducing the area of cells required (Figure PP1.3b.2). By using a linear concentrating element, the use of the same relatively simple one axis rolling tracker option mentioned earlier is still practicable. This approach is best suited to regions with high ratios of direct to global light insolation. Even moderate levels of concentration can bring significant increases in the amount that can be spent on the high bandgap
Program Package 2 Thin-Film, Third Generation and Hybrid Devices

Overview
Program Package 2 (PP2) encompasses research into a range of organic solar cells, organic/inorganic hybrid cells, “earth abundant” inorganic thin-film materials, including Si and CZTS, organic/inorganic perovskites and more futuristic “third generation” approaches, with the overall goals of demonstrating efficiency above 15% for cells of above 1cm² area and of demonstrating the feasibility of significantly reduced costs.

The work on thin-film organic photovoltaics (PP2.1) involves all but one ACAP node and addresses roadblocks currently preventing economic mass manufacture of modules. The work involves investigation of a wide range of different device structures, materials and manufacturing processes as described in the body of the report. Ultimately, lower costs are targeted compared to those of conventional cells or, alternatively, applications such as flexible or partly transparent cells for which conventional cells are not well suited. Research at University of Melbourne has developed a new class of block copolymers consisting of p and n-type organic semiconductors, synthesised with side-chains, which will provide solubility in industrially relevant solvents.

Preliminary economic modelling work
Tandem cell cost can increase more than proportionally with efficiency due to the fixed area costs of a system, including the module and installation costs. Figure PP1.3b.3 compares cell efficiency to cell cost per square metre assuming typical modularisation costs of $60/m² and installation costs of $120/m² for a fixed PV system at latitude 20.3°S.

This demonstrates that costs for a 30% efficient cell can be approximately 4x higher than a conventional cell ($227/m² vs 60/m²). It appears extremely unlikely that a module based Si based tandem would be economic as it is likely to require an ~25% efficient Si base cell ($150/m²) to achieve 30% tandem efficiency, leaving relatively little money available for the top cell (length of red arrows).

Concentrators such as that shown in Figure PP1.3b.2 provide increased flexibility for cell costs. Optical models have been used to determine the efficiency of the concentrator to direct and indirect radiation. Annual global and direct solar insolation data for fixed plane at latitude and one axis is extracted from Australian Solar Insolation tables. Efficiency losses including inversion losses, dust, system degradation, temperature over time etc results in ~75% of the DC capacity energy translating to annual alternating current output. Installation costs are assumed to be $120/m² for standard systems and $160/m² for one axis roll tracking. Inverters are assumed to be $0.25c/Wp.

Port Hedland was chosen as a location with very high direct insolation fraction. The model was first considered for a typical silicon based module with a single axis roll tracker. Flat plate module costs were assumed to be $60/m² for 18% efficient cells and $60/m² for a standard module. This results in a levelised cost of electricity (LCOE) 9.7c/kWh. The increased cost of the roll tracker (~$40/m²) is more than offset by the benefit of the increased energy production (28%). This is the bench mark which we used to compare the results for low concentration cells.

The LCOE for this system is presented in Figure PP1.3b.4. For reference, the green star on the chart represents the standard module with $60/m² for 18% efficient cells and standard module and the yellow star represents the $150/m² for 25% efficient cells from Figure PP1.3b.3. The red arrows indicate the additional money that could be spent on the module for the target LCOE from scenario 2 (9.7c/kWh). For example, the solid arrow indicates that it would be reasonable to spend about 3 times more on the module ($180/m²) and about $400/m² for the cells. Alternatively, if the module could be delivered for around double the price (120/m²) then around $800/m² would be available to be spent on the cells. If modules could be built to the left of this line, then they would have an economic advantage. These results indicate that there could be a very interesting space for tandem and/or III-V cells in combination with and low concentration modules on roll trackers.

References
Work on thin-film inorganic, earth-abundant cells involves both non-silicon (PP2.2) and silicon (PP2.3) materials for the thin-film devices under investigation. The compound semiconductor Cu2ZnSnS4 forms the focus of PP2.2. In 2014, the efficiency of CZTS thin film solar cells on glass at UNSW was improved to 6.7%. A working CZTS thin film solar cell on stainless steel was demonstrated, with an efficiency of 2.1%, and a strategy was developed for high-throughput barrier material. Good progress was also made with silicon thin film devices under PP2.3, with significant enhancement of light absorption achieved by combining glass-silicon and rear silicon texturing and 10.5% efficient liquid-phase crystallised silicon on glass (LPCSG) solar cells were fabricated. As with PP2.1, lower costs than those possible with conventional cells are targeted, or integration of these thin-film styles to form thin-film tandem cell stacks.

A highlight of the PP2 work is that researchers at the Monash node have developed uniform, compact CH3NH3PbI3 organic/inorganic perovskite films for solar cells with a conversion efficiency of 17% by controlling the morphology of the pin-hole free films of ~300nm thickness. Two high impact papers were published in Angewandte Chemie International Edition and Nano Energy, attracting significant interest around the world.

Work on advanced third-generation devices forms the focus of PP2.4. Hot carriers cells are a topic of particular interest with efforts directed to understanding fundamentals as well as to implementing the different elements required for their successful implementation. Advances in work on both absorbers and contacts are reported in this section. Silicon based nanodots and their potential application to photovoltaics forms a second key area of activity. A 2014 highlight was the fabrication of first tandem Si quantum dot (QD) devices, one on a Si wafer cell, the other on a thin film crystalline Si cell.

### PP2.1 Organic Photovoltaic Devices

#### Background

Advanced PV concepts envisaged or developed originally for conventional semiconductor photovoltaics can be applied to organic photovoltaic (OPV) and dye sensitised solar cell (DSC) devices to boost their performance and manufacturability. In this Program Package, we will aim to develop and characterise new photovoltaic materials, implement novel device concepts and develop nanomaterials for application in improved hybrid photovoltaic devices.

For organic solar cells being developed within AUSIAPV, key materials properties are; 1) high power conversion efficiency (>10%), 2) material stability during processing, 3) scale-up and processability in industrial relevant solvent systems, and 4) new device architectures requiring new materials.

For organic solar cells it is expected that efficiencies for printed modules of between 8-10% power conversion efficiency would provide a commercial performance.

#### PP2.1a Organic Bulk Heterojunction Solar Cells

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ACAP, ARENA, ARC, UNSW

**Aim**

The overall aim of the organic bulk heterojunction work is to fabricate high efficiency solar cells in the Organic Photovoltaics laboratory at UNSW

Although OPV conversion efficiency has improved significantly in recent years, progress in materials optimization still occurs largely by trial and error. This is because, in part, much of our basic understanding of how nanoscale morphology affects the optoelectronic properties of these heterogeneous organic semiconductor films has to be inferred indirectly from macroscopic measurements. In 2014, the project aims to control the morphology on a molecular scale to improve the efficiency of charge separation and transport.

**Progress**

Work is now underway on improving the understanding around fundamental issues of morphology optimization for organic films for OPV devices, such as control of the electronic structure at film interfaces, exciton dissociation and carrier transport for photovoltaic operation. First principles density functional theory (DFT) methods are used as a valuable tool to obtain insight into the charge separation and transport process as well as the photochemical stability of organic molecules. This helps to identify robust and electronically suitable molecules that ultimately determine the morphology of OPV devices.

Furthermore, we have investigated the plasmonic enhancement of poly(3-hexylthiophene); phenyl-C61-butyric acid methyl ester (P3HT:PCBM) bulk heterojunction OPV cells with an incorporated thin silver (Ag) film. Such
films consist of plasmon-active and size-variable Ag nanostructures. Incorporation of a plasmon-active Ag nano-material is shown to enhance light absorbance in the photoactive layer resulting in the enhancement of the external quantum efficiency at red wavelengths. This plasmonic enhancement needs to be optimized to further improve the photo conversion efficiency of OPV cells.

A new inverted OPV device structure has been designed and developed to overcome the challenges of low conversion efficiency and lifetime as shown in Figure PP2.1a.1. We have achieved over 8% efficiency for bulk heterojunction OPV cells and an enhanced lifetime without any encapsulation. While traditional bulk heterojunction OPV device lifetime is around two/three days without any encapsulation, our new inverted OPV device lifetimes exceed three months.

The organic active layer in organic solar cells is composed of donor and acceptor blended materials. The concentrations of donor and acceptor materials are an important parameter for the cell operation. We have systematically investigated the effects of solvent additive on inverted-structure bulk heterojunction organic solar cells. By incorporating solvents into the polymer solution, an approximately 40 nm red-shift of absorption peak at long wavelengths, resulting in an enhanced overall optical absorption, an improved EQE spectra of the device and an increase in the device current from $9.89 \text{ mA cm}^{-2}$ to $12.14 \text{ mA cm}^{-2}$.

A reduction in device performance, caused by the residual solvent, was observed as the additive concentration was increased beyond the optimum. We found that a vacuum drying process can greatly improve the device performance without changing the optical absorption profile and surface morphology. As an example of the improvement of device performance the IV characteristics were shown in Figure PP2.1a.2.

Additionally, a nanometer-scale, interpenetrating network with suitable domain sizes smaller than the exciton diffusion length (10 – 20 nm) is necessary for highly-efficient organic solar cells. Generally, these conditions do not occur in OPV devices, thus causing poor device performance. We have demonstrated ternary bulk heterojunction organic solar cells by incorporating P3HT into a conventional host system to overcome this limitation. P3HT in this ternary system behaves as a sensitizer and morphology control agent.

The absorption, carrier mobility and crystallinity of the active layer film were all improved by adding a small amount of P3HT, thus contributing to an improvement in $J_{sc}$ and FF. Additionally, the $V_{oc}$ of the ternary blend solar cells was improved. The combination of these effects led to a 10% increase in efficiency by adding 1 wt% P3HT to the active layer blend. We have proposed that P3HT may also act as recombination centres, which caused a reduction in device performance at higher P3HT concentrations.

Through careful optimization, we conclude that ternary blend photovoltaics can be a simple and effective way to achieve efficient organic solar cells. As an example the IV characteristics of OPV devices are shown in Figure PP2.1a.3 for different concentrations of P3HT.

![Figure PP2.1a.1](image1.png)

**Figure PP2.1a.1:** (a) A schematic diagram of the inverted structure of OPV device on ITO electrode. (b) Average lifetime of inverted structure OPV devices without encapsulation.

![Figure PP2.1a.2](image2.png)

**Figure PP2.1a.2:** Current density ($J$) – voltage ($V$) curves of the reference devices and the device with 1, 2, 3 and 4 vol.% 1,8-ODT concentration.

![Figure PP2.1a.3](image3.png)

**Figure PP2.1a.3:** Current density–voltage curves of reference Si-PCPDTBT:PC71BM and Si-PCPDTBT:PC71BM solar cells with varying concentrations of P3HT from 1 to 5 wt%. The inset shows the dark current density–voltage curves of the device. The best improvement is coming for the 1 wt% of P3HT.
Highlights

- Developed our understanding of donor/acceptor morphology in bulk heterojunction solar cells
- Investigated low band-gap donor materials
- Investigated materials components in ternary bulk heterojunction organic solar cells

Future work

- Continued investigation into morphology control of donor/acceptor materials in bulk heterojunction solar cells
- Continue lifetimes study of OPV devices
- Study light trapping by plasmonic nano-particles

PP 2.1b Organic-Inorganic Base Solar Cells

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Aim

Organic – inorganic hybrid systems are an emerging thin-film photovoltaics technology that has the potential to transform electronics and manufacturing because they combine advantages of both the organic and inorganic systems. Recently, there has been increased interest in application of the perovskites material group in photovoltaics, with a dramatic improvement in conversion efficiency reported when using perovskites in the absorbing layer. The performance of a TiO$_2$ solar cell sensitized with lead-iodide perovskite (CH$_3$NH$_3$PbI$_3$) has been shown by multiple groups to attain an overall power conversion efficiency of 20%.

The aims of the organic-inorganic hybrid solar cell project are:

i. to test novel materials including polymers for improved photon harvesting, improved infiltration properties, or better compatibility with inorganic material, better metal oxide nanostructures, self-assembled materials for surface modification and quantum dots.

ii. to fabricate and characterise devices

iii. to establish reproducible benchmark devices against which future improvements can be evaluated

iv. to increase short circuit current through improved light harvesting, increased interfacial area or reduced charge recombination, and to increase open-circuit voltage through improved energy level alignment at the interface

The device structure is shown in Figure PP2.1b.1.

Progress

Devices were fabricated with the structure shown in Figure PP2.1b.1. A variety of novel materials were investigated, including novel TiO$_2$ pastes and new dyes with improved properties in materials modification.

In 2014, a novel TiO$_2$ paste, provided by DyeSol Ltd., was tested. This paste allows larger pores to be formed, to aid polymer infiltration. It was found that the thickness of the nanoporous film from this paste could be increased to improve device efficiency without compromising the fill factor.

A novel dye (C106) also provided by Dyesol was investigated as an interface modifying monolayer. The TiO$_2$ surface is extremely hydrophilic, and thus incompatible with the polymer. Modification of the TiO$_2$ surface to reduce its hydrophilic nature and convert the surface to a more hydrophobic one would aid compatibility with the polymer. This would then encourage the polymer to infiltrate the TiO$_2$ film pores, resulting in increased current. Therefore an increase in $J_{sc}$ by applying the C106 to the TiO$_2$ surface is expected.

The dye monolayer was applied at the TiO$_2$/P3HT interface. Both $J_{sc}$ and $V_{oc}$ were found to increase with this modification. Another frequently used dye (Z907) was also applied as a comparison, with the results shown in Table PP2.1b.1.

Table PP2.1b.1. Performance of cells with different dye monolayers, showing improvement in performance with the addition of novel dyes.

<table>
<thead>
<tr>
<th>Dye Monolayer</th>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>$V_{oc}$ (V)</th>
<th>$FF$</th>
<th>$FF$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Dye</td>
<td>0.6</td>
<td>0.4</td>
<td>0.5</td>
<td>0.20%</td>
</tr>
<tr>
<td>Z907</td>
<td>2</td>
<td>0.4</td>
<td>0.5</td>
<td>0.60%</td>
</tr>
<tr>
<td>C106</td>
<td>3.6</td>
<td>0.6</td>
<td>0.55</td>
<td>1.10%</td>
</tr>
</tbody>
</table>

The Z907 dye showed an improved performance, compared with the control, consistent with earlier reports. The use of C106 resulted in a further significant increase in current. The observed increase in $J_{sc}$ is not due to extra absorption by C106 alone, as C106 is applied only as a monolayer on the TiO$_2$ surface and excess material is removed thoroughly by repeated rinsing in the solvent. Further, dip coating in the dye solution did not result in any significant coloration of the film. The increase in $J_{sc}$ is therefore inferred to have arisen from the improved surface compatibility. The new dye monolayer C106 used here, contains thiophene units (the main unit in P3HT) which results in an improved compatibility of the modified TiO$_2$ surface to P3HT.

The increase in $V_{oc}$ would be a result of increased spatial separation between the polymer and TiO$_2$ surface, slowing down recombination of the separated charges. The long
alkyl insulating side chains in the dye may increase spatial separation between the polymer and TiO$_2$ surface, and could be responsible for slowing down recombination, resulting in increased $V_{oc}$. Transient absorption spectroscopy was used to compare recombination kinetics in the unmodified and modified interfaces to confirm this conclusion.

Perovskite, a material with superior light absorption, was investigated in the organic-inorganic hybrid structure. The structure studied was TiO$_2$/Perovskite/P3HT. In the current literature, the highest reported efficiencies for TiO$_2$-perovskite-P3HT devices are just over 6% and the world record efficiency for any type of Perovskite device is just over 16%. Progress was made in 2014 through investigation of the device layer thicknesses and processing conditions with materials processed through to complete device structures. Future work will include a systematic study of varying processing conditions and device design, aiming at improved device performance.

A variety of characterisation techniques were used in these studies. These include transient absorption spectroscopy to investigate the TiO$_2$-polymer interface with/without modifications. The recombination dynamics indicate the level of recombination of charges occurring at the device interface. This technique was used through collaboration with Imperial College London (Professor Jenny Nelson’s group). A variety of other characterisation techniques were used in the studies, including current-voltage, spectral response (EQE), ellipsometry and dektak profilometry available at UNSW.

Plasmonic nanoparticles were included in the structure (and a protective over-layer applied) to introduce light trapping in the device. Gold nanoparticles (~5 nm) and TiO$_2$ overlayers (amorphous ~2 nm or anatase ~6 nm) were coated over the nanoporous TiO$_2$ layer. The techniques for applying nanoparticles and overlayers were sputter-coating and atomic layer depositions. An increase in $J_{sc}$ was observed for Perovskite devices. However the current was reduced in TiO$_2$-dye-P3HT devices. It was concluded that optimising the thickness of the overlayer is important in this application. A very thick film would obstruct infiltration and would reduce effective plasmon enhancement. However a very thin layer would result in charges recombining at the nanoparticles.

The techniques for fabricating Au nanoparticles coated with thin film Al$_2$O$_3$ have been developed. Further work will include optimisation of the structure and improved device efficiency.

### Highlights
- Investigation of novel materials in the structure
- Use of a variety of characterization techniques
- Application of plasmonic light trapping in the device

### Future work
- Establish reproducible benchmark devices against which future improvements can be evaluated.
- Test novel materials including polymers for improved photon harvesting, improved infiltration properties.
- Investigate better compatibility with inorganic material, better metal oxide nanostructures, self-assembling materials for surface modification, quantum dots etc.
- Increase short circuit current through improved light harvesting, increased interfacial area or reduced charge recombination, and increase open-circuit voltage through improved energy level alignment at the interface.

## PP2.1c Printing and Scale up

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### Industry Partners
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(iv) ARENA

### Aim
(i) Photocurrent mapping: Redesign photocurrent mapping device to accommodate A3 modules and strips (300 mm x 500 mm)
(ii) Scale up: Small scale field trial of fully printed solar cells with Aramax
(iii) Novel coating processes for prototypes and discovery: Produce organic photovoltaic (OPV) modules using spray and 3D coating
(iv) Low Temperature IPCE and photocurrent characterisation of photovoltaic devices.

### Progress
(i) Photocurrent mapping system designed and installed last year has been widely used to evaluate the quality of printed OPV modules and, more recently, has also been used to assess degradation of OPV modules during lifetime assessment. In particular, the photocurrent mapping system was used to evaluate performance of different encapsulation architectures under outdoor conditions using our weathering station, OSCAR, shown in Figure PP2.1c.1.
The photocurrent mapping of the printed modules shown in Figure PP2.1c.2 was able to verify possible moisture ingress paths in each encapsulation method.

(ii) Scale Up: OPV modules for the Aramax roofing panels were fabricated in Q2 2014. Some 12 metres of 30 cm wide ITO-PET substrate was printed on the µCoater. This included printing of zinc oxide, the active layer (P3HT:PCBM) and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS). The silver electrode was applied using the Essemtec batch screen printer in roll to roll mode. Upon completion, the modules shown in Figure PP2.1c.3 were encapsulated and laminated to the previously supplied Aramax roofing panels.

An installation trial was carried out (See Figure PP2.1c.4) by the Aramax team at their Carcoar site in NSW. Feedback from the trial was positive as securing the panels was very straight forward.

(iii) Spray/3D coating: CSIRO has developed a mini slot die coater based on a 3D printing platform as a ‘lab-to-fab’ research tool for solution processed solar cells. Solar cell fabrication parameters can be first optimised on this laboratory scale printer before being easily transferred to large scale industrial printers. Figure PP2.1c.5 shows the solar cell structure and the reproducibility of the cell performance.

(ii) Scale Up: OPV modules for the Aramax roofing panels were fabricated in Q2 2014. Some 12 metres of 30 cm wide ITO-PET substrate was printed on the µCoater. This included printing of zinc oxide, the active layer (P3HT:PCBM) and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS). The silver electrode was applied using the Essemtec batch screen printer in roll to roll mode. Upon completion, the modules shown in Figure PP2.1c.3 were encapsulated and laminated to the previously supplied Aramax roofing panels.

Figure PP2.1c.1: Organic Solar Cell Assessment Rig (OSCAR) – Outdoor Testing System

Figure PP2.1c.2: Image of Photocurrent mapping of OPV modules with “partial” and “complete” encapsulation architectures after 10 weeks in outdoor conditions.

Figure PP2.1c.3: 12 meter roll of 30cm wide printed OPV modules.

Figure PP2.1c.4: Installed OPV panels on a Aramax ‘Neo Roman’ roofing material (image courtesy of Aramax).

Figure PP2.1c.5: (top): Schematic drawing of a module with 5 cells in series connection on a 10x10 cm² substrate. (bottom): J-V curve of a module with 47.3cm² of active area and a single cell with 0.1cm² of active area. Both devices were fabricated using the same coating conditions.
Another approach to process optimisation is the use of an in situ optical thickness monitoring system in a spray deposition process. Inspired by thickness monitoring found in vacuum deposition systems, the CSIRO has developed a spray deposition system coupled with an LED-photodiode couple (shown Figure PP2.1c.6) which allows rapid process optimisation of the OPV active layer.

(iv) Temperature and light dependent electrical characterisation of solar cells provides valuable insight into the device physics, including the dominant recombination and loss mechanisms that limit device performance. We have developed a versatile, fully automated setup (shown Figure PP2.1c.7) that can investigate various temperature and light dependent characteristics (e.g. IPCE and I-V). The setup has been validated using commercial silicon solar cells (Figure PP2.1c.8) and is now being applied to 3rd generation solar cells such as CZTS(Se) and OPV cells.

**Future work**
- The photocurrent mapping system is fully operational and this characterisation tool can be used to support ACAP research activities.
- Following up the conclusion of the ARAMAX activities within the VISCOSC consortium lead project, discussions will take place to develop a follow-up proposal.
- The laboratory scale printers such as the spray coater and the 3D coater have proved to be a reliable tool to predict process performance for large scale printing. The next stage is to use these tools routinely for material evaluation instead of using the traditional spin coating, a non-scalable technique.
- Consistent results have been obtained for commercial silicon solar cells. The next step is to apply these measurements more extensively to organic and inorganic thin film solar cells. This will aid in understanding how the underlying device physics is impacted upon by processing conditions. The results will guide their further improvement.

**References**

**PP2.1d Industrially relevant solvent systems**

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**Aim**

Commercialization of emerging technologies requires performance profiles sufficiently high to allow confidence that translation to large scale modules will give commercial performance. For organic solar cells being developed within ACAP key materials properties are: 1) high power conversion efficiency (>10%), 2) material stability during processing, 3) processability in industrial relevant solvent systems, and 4) new device architectures requiring new materials.

For organic solar cells it is expected that efficiencies for printed modules of between 8-10% power conversion efficiency would provide a commercial performance. Therefore, lab-based devices with an efficiency of >10% power conversion efficiency will be required.

Research is focused on the development of high performance p and n-type organic semiconductor materials, triplet host materials, understanding degradation mechanisms in OPV devices, block copolymers for solvent compatibility and new materials for luminescent solar concentrators.

**Progress**

The synthetic path to new block copolymers has been optimised for new block copolymers with side-chains promoting solubility in industrially relevant solvents. Annealing conditions leading to the best phase separation in these new materials are being optimised, and this will be followed by device characterisation of OPV performance.

Water dispersible conjugated polymer nanoparticles have been made by reprecipitation and emulsion methods. The morphology and photophysics of these systems have been characterised and preliminary photovoltaic device data using these materials recorded. To date efficiencies obtained for the nanoparticle-based devices are lower than those made using films cast from organic solvents.

**Highlights**

- A new class of block copolymers consisting of p and n-type organic semiconductors has been synthesised with side-chains, which will provide solubility in industrially relevant solvents.

**Future work**

- The synthetic methodology leading to the new class of materials has been developed and the first examples synthesised. The annealing conditions remain to be fully optimised before device characterisation can be completed.
- The synthetic methodology will be translated to new materials incorporating high electron and hole mobility materials.

**Reference**


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*Figure PP2.1d.1:* The chemical structure of the first organic semi-conductor P3HT-b-PFTEGTBT block co-polymers soluble in industrially relevant solvents.

*Figure PP2.1d.2:* Preliminary annealing studies of P3HT-b-PFTEGTBT showing the development of a well defined morphology above 190oC.
PP2.1e OPV High performance materials

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Aim
For organic solar cells it is expected that efficiencies for printed modules of between 8-10% power conversion efficiency would provide a commercial performance. Therefore, lab-based devices with an efficiency of > 10% power conversion efficiency will be required.

Research is focused on the development of high performance p and n-type organic semiconductor materials, triplet host materials, understanding degradation mechanisms in OPV devices, block copolymers for solvent compatibility and new materials for luminescent solar concentrators.

Progress
A new high performance polymeric p-type material (PBDT-BT) was developed, with a peak efficiency of 9.4% (Subbiah et al. 2014). The polymeric material is being scaled up for further studies.

A new nematic crystalline p-type molecular material (BTR) has been developed with excellent transport properties (Sun et al. 2015). 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 synthetic challenges in the formation of new porphyrin containing triplet host materials have been overcome and new materials are currently being synthesised for examination.

Synthetic approaches to a high yielding regiospecific synthesis of bis-functionalised fullerenes is ongoing. The value of the research has been demonstrated by isolating single fullerene isomers of bis-indene adducts from a complex mix of isomers. One single isomer was demonstrated to have a higher performance than the normally available mixture of isomers (Wong et al. 2014).

A series of water soluble interlayer materials has been synthesised and is currently being examined in devices.

Figure PP2.1e.1: The chemical structure of a) PBDT-BT with b) J-V curves of the best performing materials.

Figure PP2.1e.2: Single crystal structure of the nematic liquid crystalline BTR hole transport molecule. a) BTR chemical structure, b) Side view of BTR aggregation. BTR molecules aggregate into stacked dimers by further stacking, with an average interplaner separation of 3.62Å, and c) The parallel planes of the stacked BTR molecules are held together by weak van der Waals interactions between the interpenetrating alkyl side chains and are arranged down the z-y direction (alkyl chains omitted for clarity).
Highlights

- A new class of nematic liquid crystalline p-type molecular organic semi-conductors has been described leading to high performance OPVs, up to 9.6% PCE.
- A high performance p-type polymeric organic semiconductor (PBDT-BT) has been reported in work completed in collaboration with CSIRO, up to 10% PCE.
- A single isomer of a fullerene bisadduct derivative was obtained by controlled synthesis and the material gave enhanced performance in devices.

Future work

- Capitalising on the success with developing new high performance materials for OPV at the University of Melbourne during 2014, future work will focus on the development of these new high performance materials.
- The use of the nematic liquid crystalline BTR organic semiconductor, a single molecule material, has demonstrated the advantages of self-organising materials in OPV devices. Structure-property analysis will be undertaken on the BTR molecule to understand its performance profile. Changes will include electron acceptor unit variation, central core substitution and conjugation length.
- The development of high yield synthetic routes to fullerene bis adducts will continue. The target materials have been designed to improve the performance of OPV devices.
- The development of block copolymers, soluble in industrially relevant solvents, will continue with new classes of n and p-type materials. Annealing conditions will be optimised to deliver the best performance OPV devices.
- In a new direction, the synthesis of new perovskite analogues will be targeted. Specifically we will develop materials that will enable theoretical models of perovskite function to be fully tested.

References

Highlights
• It has been demonstrated that aggregation induced emitters can be used as donors in devices with a secondary emitter better matched to the traditional silicon solar cell’s band-gap.

Future work
• Build more LSC silvery devices and test stability.
• Design, synthesise and test more stable dye systems.

PP2.1g OPV Characterisation
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Georgia Institute of Technology

Industry Partner
Agilent

Funding Support
ARENA, ACAP, University of Melbourne

Aim
Research is focused on the understanding of the performance profiles of the OPV devices, spectroscopic characterisation and degradation studies.

Progress
High performance materials are being synthesised for degradation studies, including the high performance PBDT-BT polymer.

The synthetic path to new block copolymers has been optimised for new block copolymers with side-chains promoting solubility in industrially relevant solvents. Annealing conditions leading to the best phase separation in these new materials are being optimised, and this will be followed by device characterisation of OPV performance.

The synthetic challenges in the formation of new porphyrin containing triplet host materials have been overcome and new materials are currently being synthesised for examination. The generation and transport of triplets will be examined in detail.

Spectroscopic instrumentation has been established that allows (i) PhotoCeliv charge mobility measurements, and (ii) femtosecond energy and charge transport in semiconducting materials. This instrumentation has been applied to investigate charge separation processes in triblock conjugated donor:acceptor block copolymers.

Highlight
• Instrumentation to enable transient spectroscopy over a broad wavelength range and charge mobility of photovoltaic materials has been established.

• High performance PBDT-BT photovoltaic polymers have been synthesised for stability testing.

Future work
• PBDT-BT polymer has now been synthesised for inclusion in degradation studies. The causes for degradation in OPV device performance during thermal processing will be examined.

• New solar cell materials, including conjugated polymer, block copolymers and semiconducting nanoparticles will be characterised by charge mobility and time-resolved spectroscopy methods.

Reference
PP2.1h: Elucidating the role of donor and acceptor in photocurrent generation

Lead Partner
University of Queensland

UQ Team
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NREL (USA) Team
Dr Nikos Kopidakis

Funding Support
ARENA ACAP, University of Queensland

Aim
The aim of this program is to understand how light absorption in acceptor materials can contribute to current generation in organic solar cells. This will facilitate the development of the concept of complementary junctions and contribute to the overall objective of simplifying OPV module structures and thereby reducing costs.

Progress
We have made progress in the following two areas during the reporting period:

Alternative (non-fullerene electron acceptors): The development of both polymeric and non-polymeric materials has been investigated. More than ten new non-fullerene acceptors have been prepared. The materials differ in their dimensionality (pseudo one- to three-dimensional). The compounds have differing functionality to enable tuning of the optical gap, electron affinity, and dielectric constant. Non-fullerene acceptors with optical gaps as low as ≈1 eV have now been achieved. In addition, materials with static dielectric constants of up to ≈8 have also been prepared. These compounds are now the focus of film morphology, transport, charge generation, and device studies.

Defining Channel I and Channel II charge generation efficiencies: We report the first example of an organic solar cell, and the first observation and measurement of differing Channel I and Channel II efficiencies. We postulate the differing channel efficiencies were due to the relative energy offsets between the acceptor and donor ionisation potentials and electron affinities which define the driving for PET and PHT. Figure 2.1h.1 illustrates this key finding and the work was published in the prestigious Journal of the American Chemical Society (Armin, A. et al. 2014).

Highlights
• Non-fullerene acceptors: Materials with optical gaps approaching ≈1 eV and dielectric constants of around 8.
• Defining Channel I and Channel II charge generation efficiencies: We report the first example of an organic solar cell where the Channel II process (acceptor absorption) is more efficient than the conventional Channel I process (donor absorption), leading to an excitation energy dependence of the internal quantum efficiency not related to hot exciton effects.

Future work
• Testing of alternative new electron acceptors
• Understanding the charge generation and extraction physics in low donor and low acceptor “homeopathic” organic solar cells

References
PP2.1i: Characterising the factors that affect photocurrent collection in sub-module cells

Lead Partner
University of Queensland

UQ Team
Dr Hui Jin, Dr Mike Hambsch, Mr Ardalan Armin, Prof. Paul Burn, Prof. Paul Meredith.

UQ Students
Ardalan Armin

Funding Support
ARENA ACAP, University of Queensland

Aim
The aim of this program is to understand how photocurrent can be effectively collected in sub-module organic and earth abundant solar cells to facilitate the development of new materials and device architectures. In particular, this work will facilitate the development of monolithic large area cells with effective apertures >20 cm².

Progress
The thick junction concept: In the previous reporting period we demonstrated that organic solar cells lose efficiency when scaling from small (<1 cm²) to large (sub-modules >20 cm²) areas because of two key factors: i) large anode sheet resistances suppressing the fill factor and producing parasitic series resistance; and ii) the defect density in thin junctions scales exponentially with area (shorting defects also reduce fill factor). To ameliorate point i) we developed a back metallic grid concept which only marginally reduced the illumination aperture but maintained fill factor to 25 cm². The back grid also required conformal coating of the junction and this led us to the “thick junction” concept (<400 nm) which also helped address the second issue of defect density. However, not all organic solar cell bulk heterojunction materials are suited to the thick junction architecture; some only function in the thin junction limit and suffers loss of fill factor due to transport limitations. We were able to demonstrate a system which maintained its fill factor in the thick junction limit and, with new innovations in processing, were able to conformally coat a metallic grid and demonstrated the first 5% monolithic organic solar cell sub-module (Armin, A. et al. 2014a).

Balanced carrier mobilities and the maintenance of fill factor at large areas in thick junctions: We undertook a detailed study of why some bulk heterojunction materials could maintain their fill factors in the thick junction limit. We applied state-of-the-art charge transport measurement techniques, notably a new unipolar technique called Metal-Insulator-Semiconductor Charge Extraction with Linearly Increasing Voltage to measure both electron and hole mobilities as a function of junction thickness in several systems. We found that the systems that maintained their fill factors in thicker junctions also had balanced electron and hole mobilities. This appears to be a necessary condition to maintain the charge extraction efficiency for junction thicknesses >100 nm. Figure PP2.1i.1 and Table PP2.1i.1 demonstrate this concept for a number of systems, including high and low molecular weight solutions where a high casting solution viscosity (in the base of the high molecular weight polymer) is required to not only conformally coat the grid, but also develop the morphology required for high hole mobility. This work has attracted significant attention and was published in the high ranking international journal Advanced Energy Materials (Armin, A. et al. 2014a). The work was extended to create state-of-the-art organic photodiodes with broadband, flat spectral responses and performance metrics equivalent to commercially available crystalline silicon diodes (Armin, A. et al. 2014b).

Highlights
• Efficient, large area and thick junction solar cells with balanced carrier mobilities and low defect density
• New understanding as to the necessary conditions for maintaining organic solar cell fill factor in large areas
• Application of this new thick junction understanding to create state-of-the-art broadband organic photodiodes with flat spectral response and performance metrics matching commercial inorganic diodes

Figure PP2.1i.1: Organic solar cell fill factor as a function of bulk heterojunction layer thickness. Maintenance of the fill factor to thickness >100 nm is seen in two systems, P3HT (poly-3-n-hexylthiophene):PC70BM and high molecular weight DPP-DTT:PC70BM, which both possess balanced electron and hole mobilities as shown in Table 2.1i.1.

Table PP2.1i.1: Electron and hole mobilities for different acceptor: donor combinations. A mobility ratio of 1 indicates balanced transport and this is characteristic of the P3HT:PC70BM and DPP-DTT:PC70BM systems. The mobilities were measured in unipolar devices with device relevant structures using the new technique of MIS-CELIV.
Future work

- Understanding whether the same scaling physics for organic solar cells translates to large area organo-halide perovskite solar cells
- Demonstration of a >1 cm² organo-halide perovskite or organic solar cell with efficiency >7%

PP2.1j Hybrid Devices

Aim

Advanced PV concepts that were envisaged or developed originally for conventional semiconductor photovoltaics can be applied to organic photovoltaic (OPV) and dye sensitised solar cell (DSSC) devices to boost their performance and manufacturability. In this task we aim to implement a number of novel device concepts. In addition, we will develop nanomaterials for novel and improved hybrid photovoltaic devices for deposition on rigid and flexible substrates. Work in this area will be closely tied to activities at the Molecular Foundry and other parts of Lawrence Berkeley National Laboratory, NREL, Stanford University and Georgia Institute of Technology, as well as the related inorganic “Third Generation” strand at UNSW (PP2.4).

Work at Monash in 2014 focused on the new type of organic-inorganic hybrid solar cell, the organometal halide PeSC, and also studied DSSCs. Organometal halide perovskite solar cells have shown extraordinary efficiency improvements in the last five years, from about 3% in 2009 to over 20% (certified) in 2014. The devices are made of earth abundant materials and can be produced by solution processes. They have, therefore, great potential for the development of a low cost and high efficiency photovoltaic technology.

Conventional DSSC devices contain solvent-based electrolytes, which would be unstable at high temperatures and result in relatively short lifetimes for the devices. The Monash team is developing alternative solid-state or gelled electrolytes to replace the liquid electrolyte in order to improve the device stability as well as the device efficiency.

The aim of Monash’s work is to achieve low cost, high efficiency and solution processed solar cell technologies.

References


PP2.1j(ii): Organic/Inorganic Hybrid Solar Cells

Lead Partner

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Academic Partners

UC Berkeley/Lawrence Berkeley National Laboratory, NREL, University of Melbourne, CSIRO

Funding Support

ACAP, ARENA, VICOSC, ARC, Monash

Spectroscopy study of perovskite solar cells

In this study, the impedance spectroscopic (IS) response of various planar perovskite solar cell assemblies was measured and evaluated. The single impedance feature observed in the symmetric ITO/perovskite/ITO cell is attributed solely to the interface between the two materials, with no evidence from IS measurements to suggest a transmission-line response or a distribution of traps within the perovskite layer. This single impedance feature of the symmetric ITO/perovskite/ITO cell was unique with all other asymmetric configurations, displaying both high-frequency and low-frequency impedance response features. Using a theoretical foundation that accounts for the impedance response of the dielectric relaxation of the perovskite, the equivalent circuit parameters for p-i-n, p-i and i-n cells were determined. The high-frequency feature associated with the charge separation at the perovskite contacts was observed to be largely independent of the charge-carrier density, whereas the low-frequency dielectric response showed a strong dependence on the carrier concentration. This flat high-frequency capacitance, as a function of the open-circuit potential, revealed that the high-frequency feature is not dominated by the chemical capacitance of the perovskite layer, C_p, but rather by the double-layer capacitance immediately at the perovskite/contact interfaces.

A comparison of photoluminescence decay constants and IS time constants revealed that it is unlikely that IS measurements can provide any information on recombination rates within the perovskite film. However, open circuit voltage decay (OCVD) data indicated that the high-frequency time constants correlate well with recombination rates across the perovskite/contact interfaces. The prominent slow component of the OCVD curves observed for the p-i-N and i-n devices was not observed in the IS measurements due to the impedance response being dominated by the perovskite/Spiro-OMeTAD interface. The extremely slow photovoltage decay found for the p-i-n and i-n devices implies that the dense TiO₂ layer plays a pivotal role in the characteristic delayed dielectric response of PSC devices.

This work presents a solid foundation, not only for the analysis of planar PSC devices using IS, but also for the comparison of different planar assemblies and the comparison of IS measurements with complementary characterization techniques. The results of this study provide further evidence for the potential value of IS as a diagnostic tool for PSC technologies.
Flexible perovskite solar cells

Constructing efficient flexible photovoltaics on polymer substrates remains difficult due to the substrates’ intrinsic low-temperature limitation. In the past year, attention has been drawn towards photovoltaics utilising inorganic-organic perovskites, offering amongst many others the advantage of a low processing temperature. Nevertheless, the majority of the perovskite solar cells constructed on glass employ a high temperature processed inorganic blocking layer (≥450 °C), non-compatible with flexible applications. In this regard, a method to produce efficient and reproducible perovskite solar cells on plastic substrates has been developed, with the entire device fabrication process conducted at 150 °C or below. Power conversion efficiencies over 13% have been attained for small flexible devices, with an average efficiency of 11.8 ± 1.8 %. The polymer substrates offer the photovoltaic devices light weight and flexibility, broadening their potential applications. In addition, practical industrial concerns such as the stability and the manufacturing processability of these devices are currently under investigation. This work was conducted in collaboration with Dr Rachel Caruso of The University of Melbourne.

By controlling the nucleation and crystal growth rates, the team successfully prepared pin-hole free perovskite films of ~300nm thickness. Monolayer films consisting of single crystals were first reported by the Monash team. This structure would facilitate charge transport due to lack of grain boundaries. Two high impact papers were published in Angewandte Chemie International Edition and Nano Energy, respectively. The study has attracted significant interest around the world. The Nano Energy paper has been downloaded more than 2,600 times since it appeared on line in September 2014, while the Angew. Chem. paper has been cited 29 times (according to Google Scholar), in the short period since its publication in mid 2014.

Development of Uniform Compact CH$_3$NH$_3$PbI$_3$ Films For High Efficiency Perovskite Solar Cells

A remarkable power conversion efficiency of 17% has been achieved at Monash by controlling the morphology of the CH$_3$NH$_3$PbI$_3$ film. The quality of the perovskite film is extremely important for perovskite solar cells, especially for planar structured devices. The team 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, the team successfully prepared pin-hole free perovskite films of ~300nm thickness. Monolayer films consisting of single crystals were first reported by the Monash team. This structure would facilitate charge transport due to lack of grain boundaries. Two high impact papers were published in Angewandte Chemie International Edition and Nano Energy, respectively. The study has attracted significant interest around the world. The Nano Energy paper has been downloaded more than 2,600 times since it appeared on line in September 2014, while the Angew. Chem. paper has been cited 29 times (according to Google Scholar), in the short period since its publication in mid 2014.
PP2.1j (iii): Impedance Spectroscopy

Lead Partner
Monash

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Funding Support
ARENA & AUSIAPV. The researchers also acknowledge the useful contributions of Prof. Udo Bach, Prof. Leone Spiccia and A/Prof. Chris McNeill.

Background

Hybrid organic-inorganic perovskite-based solar cells have displayed a rapid ascension in performance since first reported 5 years ago. Efficiencies of PSC devices are currently nearing the benchmarks of mc-Si based photovoltaics, which presents an important milestone in terms of the progression of the technology. In association with these high reported efficiencies, PeSCs boast some enviable advantages in terms of their manufacturing requirements. The low-temperature, solution-based processes used to fabricate devices may ultimately lead to greatly reduced processing costs, thereby increasing the economic viability of the technology. Recently reported device architectures have also been able to dispense with costly metal contacts while still preserving relatively high conversion efficiencies. These benefits, coupled with the trending improvements in device performances, bode well for the future commercialization of PeSC technologies.

Aim

Impedance spectroscopic (IS) analyses of PeSC devices have revealed some important information concerning device operation. Previous impedance studies have largely focused on a mesoscopic cell architecture, although there have also been preliminary studies into the impedance response of planar-structured devices. Despite some clear similarities between the previously reported impedance spectra for both planar and mesoscopic devices, the interpretation of these results has presented some notable discrepancies. The observation of two or three distinct impedance features has been a common finding to most studies using a mesoporous TiO$_2$ scaffold. The low/intermediate-frequency feature has been attributed to the accumulation of charge within the perovskite/TiO$_2$ layer. This feature typically has been fitted using an RC component or a transmission-line model, as the revealing 45° transport feature is observed in the absence of the hole-transport layer, and has been distinguished by a characteristically slow time constant. The high-frequency feature has previously been attributed to the charge accumulation at the interface between the perovskite and TiO$_2$ scaffold. This feature has also been able to dispense with costly metal contacts while still preserving relatively high conversion efficiencies. These benefits, coupled with the trending improvements in device performances, bode well for the future commercialization of PeSC technologies.

Progress

Impedance Spectroscopic Analysis

The impedance response of the simplest measurable PeSC configuration was determined by fabricating a cell consisting of a perovskite film sandwiched between two transparent ITO contacts as shown in Figure PP2.1j.4.

From the Nyquist plot in Figure PP2.1j.4(a) a solitary high-frequency feature is observed for the ITO/perovskite/ITO symmetric device. The impedance spectra for this device display no evidence of the transmission line response reported previously, and seems to resemble a single RC element. The impedance spectra measured for the device incorporating both Spiro-OMeTAD and perovskite layers, enclosed between two ITO contacts, are shown in Figure PP2.1j.4(b). In this instance the Nyquist plot reveals two distinct features; one occurring at high-frequency and the onset of a second feature at low-frequency. These high-frequency and low-frequency impedance features are again observed when measuring the ITO/TiO$_2$/perovskite/ITO device, as shown in Figure PP2.1j.4(c). Our results imply that the high-frequency feature is due to charge separation at the interface between the perovskite layer and its adjacent contacts.

Figure PP2.1j.5: Nyquist impedance spectra for a symmetric ITO/perovskite/ITO device (a), a ITO/perovskite/Spiro-OMeTAD/ITO device (b) and a ITO/TiO$_2$/perovskite/ITO device (c). Impedance measurements were performed under illumination (270 W m$^{-2}$) with applied bias in the 4 MHz to 100 mHz frequency range.
The low-frequency feature evident in Figures PP2.1j.5(b) and (c) was not observed in the simplified ITO/perovskite/ITO device, and only occurred when a third material was included as a layer adjacent to the perovskite film. The low-frequency feature is not unique to either the perovskite/Spiro-OMeTAD or perovskite/TiO₂ interfaces as it is evident for a variety of different PSC assemblies.

To further investigate the characteristics of these two features, impedance spectroscopy was performed on the p-i-n, p-i and i-n cell types under varying illumination at open-circuit conditions. For the complete PIN device it is apparent that the $R_{rec}$ and $R_{dr}$ resistive elements display an essentially exponential dependence on the open-circuit potential. This log-linear trend of the $R_{rec}$ and $R_{dr}$ elements is also shared by the ‘incomplete’ p-i and i-n devices.

The low-frequency capacitance $C_{dr}$ values also displayed a direct dependence on the charge-carrier density, as shown by the log-linear correlation in Figure PP2.1j.6 (b), (d) and (f). However, this is not the case for the capacitance of the adjacent contact layers, $C_{con}$, as this parameter appears to be effectively independent of the $V_{oc}$. The high-frequency feature, which determines the $C_{con}$ value, is linked to the charge separation at the interfaces between the perovskite layer and the neighboring interfacial materials. From these results, it appears that the capacitance at the perovskite contacts is analogous to the Helmholtz response of an electrical double layer.

The PL decay curves illustrate the rapid charge transfer between the perovskite and the Spiro-OMeTAD layers, which occurs on a time scale that is significantly faster than the radiative recombination of charges within the perovskite material. The recombination time for charges within the pristine perovskite films studied in the present work was observed to be in the order of $\tau \approx 250$ ns, which was calculated by measuring the PL decay at an emission wavelength of 770 nm.

The high-frequency time constant $\tau_{hf}$ for all three measured assemblies displays an approximately exponential dependence on the open-circuit potential. These $\tau_{hf}$ values are on the order of 0.01 – 1 ms which does not correlate well with PL-based recombination rates within the perovskite layer itself. It is, therefore, unlikely that the impedance spectra for a planar PSC device can provide information regarding the recombination of charges within the perovskite layer, particularly given the fast quenching by the neighbouring materials shown by the TRPL decay.

The fast and slow processes observed in the impedance measurements are equally represented in the open-circuit voltage decays, shown in Figure PP2.1j.7. This technique involves the generation of charges under illumination at open-circuit, followed by the decay of the potential as the illumination is switched off and charges recombine. The voltage decays of the complete p-i-n device (blue), the p-i device (red) and the i-n device (black) display an initial fast component which then gives way to a slow decay at the lower potentials. If we assume a mono-exponential decay for the fast open-circuit voltage decay component, we are able to estimate the time constant for this process. The time constant associated with the fast component of the decay is determined to be in the order of 0.1 – 10 ms for the three PSC devices, which is comparable with the magnitude of the time constant for the high-frequency feature obtained from impedance measurements. This provides further evidence that the high-frequency feature in planar PSC devices relates directly to the charge transfer at the interfaces between the perovskite and its bordering materials.

**Future Work**

- The proposed impedance model must be applied to PeSCs comprising a broad variety of different materials to examine the effect of different contacts on the high-frequency and low-frequency impedance features. This will further strengthen the prospects of impedance spectroscopy as a tool for the characterisation of PeSCs.
PP2.1j(iv) Flexible Perovskite Solar Cells

Lead Partner
Monash

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MAMF is acknowledged for electron microscopy access

Funding Support
ARENA, AUSIAPV, VICOSC, MRGSS.

Overview
The development of photovoltaics employing solution processable inorganic-organic hybrid perovskites, such as \( \text{CH}_3\text{NH}_3\text{PbX}_3 \) (\( X = \text{Cl}, \text{Br}, \text{I} \)) has seen a plethora of publications in recent years, indicative of the great interest these materials have raised in the scientific community. The emerging technology combines low-cost materials and processing techniques, thus offering a cheap alternative to existing solar technologies. In addition, the perovskite photoactive layer is commonly produced at 100°C, allowing its deposition on polymer substrates. The use of lightweight, flexible substrates broadens the potential applications of these photovoltaic devices to consumer electronics and power-generating textiles.

Progress
In 2014, we developed a device fabrication method to efficiently produce CH\(_3\)NH\(_3\)PbI\(_3\) based planar PeSCs on polymer substrates with the entire process conducted at 150°C or below. The hole blocking layer employed was a solution processed mesoporous TiO\(_2\) layer. A gas-assisted perovskite deposition method was used to produce excellent coverage of the hole blocking layer by a \( \sim \)350 nm thick CH\(_3\)NH\(_3\)PbI\(_3\) film (Figure PP2.1j.8), resulting in high device performance reproducibility. After optimisation of the TiO\(_2\) layer thickness, we show that an average efficiency of 11.8 ± 1.8 %, and a maximum efficiency of 13.4 % have been attained for flexible PeSCs.

First, a titania film was deposited by spin coating a suspension of 20 nm crystalline titania particles onto an indium doped zinc oxide coated polymer substrate (IZO-PET) and subsequently treatment at 150°C for 1 h. For glass-based devices, the TiO\(_2\) blocking layer is commonly obtained via a spray pyrolysis process at 450°C or above, producing a 30 nm dense layer. Here, spin coating a suspension of crystalline titania nanoparticles resulted in a fully covered transparent conductive oxide. However, TEM analyses (Figure PP2.1j.9) showed that the TiO\(_2\) layer was mesoporous, which is unexpected for an efficient hole blocking layer. It is worthy to note that a 70 nm thick film was necessary to prevent contact between the perovskite and IZO layers.

A great deal of effort has been directed towards the development of perovskite deposition methods, all with the aim to produce uniform perovskite layers enhancing the efficiency and reproducibility of the resulting devices. In this work, we employed a gas assisted method (Huang 2014), developed in house, to prepare the CH\(_3\)NH\(_3\)PbI\(_3\) film. Figure PP2.1j.10 shows a perovskite film spin-coated onto the TiO\(_2\) coated IZO without applying a gas flow. The normal slow crystallization method resulted in large dendritic perovskite crystals leaving large uncovered areas of titania. These large voids promote charge recombination and are thus detrimental to the performance of these solar cells. As depicted in Figure PP2.1j.10, the one-step gas-assisted deposition method resulted in a highly homogeneous perovskite film with excellent coverage of the TiO\(_2\) coated IZO substrate.
After deposition of the perovskite and hole transport material according to a published protocol (Dkhissi 2015), a thin layer of gold was thermally evaporated under high vacuum to complete the device fabrication process. The impact of the blocking layer thickness on the photovoltaic performance of the devices was investigated. With a 100 nm TiO$_2$ layer, the devices showed on average an open-circuit photovoltage, $V_{oc}$, of 979 ± 27 mV, a short-circuit photocurrent, $J_{sc}$, of 16.1 ± 0.5 mA cm$^{-2}$, a fill factor of 0.65 ± 0.07, and a power-conversion efficiency, PCE, of 10.6 ± 1.2 % (Table 2.1j.1). A 50 nm TiO$_2$ layer was found incapable of efficiently blocking the holes and led to a loss in the performance and reproducibility of the resulting devices (Table 2.1j.1). The optimum thickness for this solution processed TiO$_2$ layer was 70-80 nm and resulted in the best performing solar cell, with a PCE of 13.4 % when scanning from forward bias to short-circuit, Figure PP2.1j.11. To accurately evaluate the performance of the photovoltaic device, its steady state power conversion was measured with a forward bias of 0.84 V, as depicted in Figure PP2.1j.11.

Finally, preliminary bending tests were conducted on a flexible planar PeSC on a polymer substrate, using a home-made bending device (Figure PP2.1j.12). The tests consisted of shortening the distance between two metal blocks, thus resulting in bending of the flexible substrate, followed by relaxing the polymer substrate to its flat form, hence completing one bending cycle, which was repeated to undergo hundreds of cycles. The flexible device performed well under moderate stress (curvature radius of 15.8 mm); the device maintained 80% of its initial photovoltaic performance after 500 bending cycles, Figure PP2.1j.12. Unfortunately, higher stress or bending angle (curvature radius of 8.7 mm) resulted in device failure after 300 cycles, Figure PP2.1j.12.

### Future Work

- It is well understood now that investigating the degradation mechanisms and producing stable devices will constitute the next milestone in the field of perovskite photovoltaics. This is particularly true when applied to polymer substrates. The stability of these devices is currently under assessment.

### References


Dkhissi, Y. et al. 2015 J. Power Sources 278, 325
Aim

Recently, PeSCs have attracted intense attention due to their rapid rise in power conversion efficiency up to 20%. There are two general device architectures for PeSCs: a mesoporous structure and a planar structure. As a much simpler structure, the planar PeSC is easier to fabricate. In a planar structure, the perovskite should be pin-hole free to avoid possible shunt. Snaith et al. employed a dual-source vapor deposition method to fabricate a planar device with a homogenous perovskite layer and efficiency above 15%. However, to reduce the manufacturing cost, a solution-based process that is compatible with printing technologies would be desirable.

Progress

Nucleation and crystal growth study

In general, the conventional spin-coating method results in a very porous perovskite \( \text{CH}_3\text{NH}_3\text{PbI}_3 \) film. By investigating the precipitation of the perovskite crystals during the spin-coating (Figure PP2.1j.13), we found that the dendrite structure is attributed to a slow nucleation rate and fast crystal growth rate. To induce the growth of a compact perovskite layer, the nucleation rate should be much larger than the crystal growth rate. This can be achieved by a rapid increase in the super-saturation degree.

Solvent Induced fast deposition

We have developed a simple one-step solvent-induced fast deposition-crystallization (FDC) protocol that also results in flat, highly uniform \( \text{CH}_3\text{NH}_3\text{PbI}_3 \) thin films. This method involves the spin-coating, followed the immediate exposure of the wet film to a second solvent, such as chlorobenzene, to induce crystallization (Figure PP2.1j.14). The chlorobenzene serves to rapidly increase the super-saturation degree. This FDC spin-coating protocol offers the advantage of single-step processing and short deposition time as the film formation is complete within 1 min. SEM analysis indicated that perovskite thin films of controllable thickness can be prepared with large grain structures that fully cover the substrate (Figure PP2.1j.15).

Flat polygonal grains with triple junction grain boundaries are a predominant microstructural feature in our films, suggesting close packing of similarly sized perovskite grains perpendicular to the electrode surface. This characteristic may lead to improved charge transport properties for photovoltaic devices. The planar devices made using the FCD method showed a stabilized power conversion efficiency of 13.0% as shown in Figure PP2.1j.16.
Gas-assisted spin-coating

Fast removal of the solvent is another method to increase the super-saturation degree. Here we developed another novel facile method to fabricate the compact perovskite film for the planar PSC. A dry gas (here Argon) was blown over the wet film during the spin coating process as shown in Figure PP2.1j.17. The gas will rapidly remove the solvent inducing a high super-saturation degree and drastically increasing nucleation. The nuclei grow into a compact film similar to that made by FCD. In addition, the prepared perovskite film is a monolayer of single-sized grains. The electron diffraction patterns at different locations on a single grain are almost identical. This indicates that each single grain is a single crystal as shown in Figure PP2.1j.17.

The single crystal monolayer grain structure is favourable for the fast charge transport. The best device efficiency achieved for the gas-assisted perovskite film was 17.0% after the film was annealed at 100 °C as shown in Figure PP2.1j.18. The steady-state power output measurement at a forward bias of 0.86 V (Figure PP2.1j.18) showed a quite stable PCE of ~ 16.5%. Furthermore, 16 devices prepared by the gas-assisted method showed an average PCE of 15.7 ± 0.7% with a very small variation in the efficiency.

Future Work

• The new methods formed a compact CH₃NH₃PbI₃ film which is extremely important for a high efficiency planar PSC. The methods will be applied for fabrication of other type perovskite, eg. MAPbBr₃, MASnI₃, and FAPbI₃.
PP2.2 Thin film Inorganic (CZTS)

Background

All successfully commercialised non-concentrating photovoltaic technologies to date are based on silicon or the chalcogenide (semiconductors containing Group VI elements, specifically Te, Se and S). As indicated by Figure PP2.2.1, the successful chalcogenide materials, CdTe and Cu(In,Ga)Se2, 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. Cd and Se are toxic while Te and In are amongst the twelve most scarce elements in the Earth’s crust. These factors would seem to clearly limit the long-term potential of the established chalcogenide technologies. However, as indicated in Figure PP2.2.1, 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 earth-abundant, non-toxic elements.

Kesterite Cu2ZnSn(S, Se)4 (CZTSSe) compound semiconductor has emerged, based on such reasoning, as a promising candidate for use in absorber materials for thin film solar cells. Analogous to the chalcopyrite structure of CIGS, CZTS shares similar optical and electrical properties. CZTS has a band gap of 1.4-1.5eV, a large absorption coefficient of over 10^4cm^-1 and is composed of non-toxic and earth abundant elements. Notable is that the bandgap of the CZTS family can be tuned to span a wide range beyond 2.25eV, even above the accessible range of the highest efficiency III-V cells. This makes the material suitable for tandem cells (see Section PP1.3a). For thin film solar cells, energy conversion efficiency up to 12.6% and 8.5% have been achieved so far for CZTS(e) and CZTS solar cells, respectively. However, the 12.6% record CZTSSe solar cell was obtained through a hydrazine solution method. Hydrazine is a highly toxic and very unstable compound that requires extreme caution during handling and storage.

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Funding Support
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Aim
The Centre’s work in the CZTS area takes a different fabrication direction, aiming for the development of a low-cost, high-throughput and up-scalable manufacturing process for high efficiency CZTS-based solar cells. Work in this strand includes the development of CZTS solar cells on soda lime glass as well as stainless steel and continuation of established collaborations with and financial support from industry partners.

Progress
In 2013, all constituent layers necessary for a complete CZTS cell were investigated and optimised. The efficiency of CZTS thin film solar cells on soda lime glass was driven up to 4.5%. This 4.5% CZTS was made from the metal only stacked precursor, which is comparable to the reported CZTS solar cells from metal precursors by the sputtering method from other groups (5%), except Solar Frontier (>9%).

In 2014, the efficiency of CZTS thin film solar cells on glass at UNSW has been improved to 6.7%. Various strategies for dealing with the problematic heterojunction and back contact interfaces have been developed, leading to improvement in all aspects of CZTS cell performance, as well as several patents and publications.

Figure PP2.2.1: “Synthetic silicon” – portion of the Periodic Table showing pathways to engineering semiconductors with four valence electrons per atom.

PP2.2a: Infrastructure upgrade

A new RTP sulfurization furnace, allowing versatile chalcogenide heat treatment recipes was commissioned in Feb 2014; a sputter machine dedicated for CZTS absorber fabrication was commissioned in Sep, 2014; and a new XRF characterization facility to enhance fast characterisation on chemical composition of CZTS absorber and associated precursor materials was commissioned in 2014.
PP2.2b CZTS cells on soda lime glass

CZTS absorber
The team developed and improved on strategies for the optimization of the CZTS absorber layer and key interface engineering. Producing a significant number of publications (see reference list below).

Progress in energy conversion efficiency of CZTS solar cells
As shown in Figure PP2.2.2, a base-line CZTS solar cells energy conversion efficiency of 6.7% was obtained without the use of an antireflection coating (ARC), which is comparable to the current certified record of 8.5% (with an ARC). This efficiency improvement is obtained by only optimising CZTS absorber chemical compositions.

Figure PP2.2.2: Progress chart of energy conversion efficiency of CZTS solar cells.

Intermediate layer
The use of an innovative intermediate layer between Mo back contact and CZTS absorber was found to significantly increase short circuit current without sacrificing open circuit voltage ($V_{oc}$) and fill factor. Its effectiveness has been confirmed to be reproducible, regardless of the CZTS absorber fabrication methods. One relevant patent is to be filled, with details to be disclosed in next year’s report.

Figure PP2.2.3: Schematic of band alignment between CZTS and CdS (a) and between CZTS and In$_2$S$_3$ (b) estimated by synchrotron XPS and XAS.

Innovative hybrid buffer for CZTS solar cells
Our previous synchrotron studies show that there is an unfavorable cliff-like band alignment between CZTS and traditionally adopted CdS, while other buffer options such as In$_2$S$_3$ and ZnS give spike-like band alignment (see Figure PP2.2.3). To achieve an appropriate optimum spike-like band alignment, we developed a novel hybrid buffer of CdS/In$_2$S$_3$. By using this hybrid buffer, a 6.7% efficient CZTS solar cell was achieved, comparable to the current record of 8.5% (with ARC). As the band alignment is improved from cliff-like to spike-like, the open circuit voltage was increased from around 650 mV to 714 mV (see Figure PP2.2.4). This $V_{oc}$ improvement was verified to be reproducible. In addition to the improvement in $V_{oc}$, the combination of CdS and In$_2$S$_3$ also improves the short circuit current, in particular in the UV range.

Figure PP2.2.4: J-V (a) and EQE (b) curves of CZTS devices with different buffer options.

Sulphurisation of CZTS nanocrystals
An innovative method was developed to successfully synthesise micro-sized large grain CZTS absorber from sulfurization of CZTS nanocrystals, overcoming the limitation of present CZTS solar cells from CZTS nanocrystals. By this method, a 4.4% pure sulphur CZTS solar cell was achieved (see Figure PP2.2.5), higher than the previous best 1.94% reported.

Figure PP2.2.5: 4.4% selenium-free CZTS solar cells from CZTS nanocrystals.
PP2.2c CZTS-coated architectural stainless steel.

A working CZTS thin film solar cell on stainless steel was demonstrated with an efficiency of 2.14%, with the steel provided by industry partner Baosteel. Key requirements for choosing the stainless steel were identified and a strategy of high-throughput barrier material was developed. Detailed technical discussion was carried out with Baosteel for optimisation on both stainless steel and CZTS solar cells.

- Stainless steel types, suitable for CZTS solar cells were ranked according to such aspects as steel type, coefficient of the thermal expansion, surface roughness etc.
- Surface roughness of BA and 8K steel (provided by Baosteel) and its impact on CZTS devices was investigated. The surface roughness of 8K is less than that of BA steel (both less than 100 nm), however the surface pattern and origin of the roughness, significantly affects the CZTS device performance. See Figure PP2.2.6.
- Barrier layer options, preventing the Fe diffusion from steel to CZST absorber, were studied and screened in terms of their effectiveness as a barrier layer, roughness, and adhesion. Sputtered SiO$_2$ barrier with a thickness $>$1um was effective but found to have a low-throughput. An innovative Ti barrier layer was developed for a high-throughput process.
- A 2.14% CZTS solar cell was demonstrated by using a novel thin Ti barrier layer developed, with open circuit voltage comparable to that on soda lime glass (Figure PP2.2.7).

Highlights

- In 2013, all constituent layers necessary for a complete CZTS cell were investigated and optimised. The efficiency of CZTS thin film solar cells on solar lime glass was driven up to 4.5% This 4.5% CZTS was made from the metal only stacked precursor, which is comparable to the reported CZTS solar cells from metal precursors by the sputtering method from other groups (5%), except Solar Frontier (>9%).
- In 2014, the efficiency of CZTS thin film solar cells on glass at UNSW has been improved to 6.7%. Various strategies for dealing with the problematic heterojunction and back contact interfaces have been developed, leading to improvement in all aspects of CZTS cell performance, as well as several patents and publications.
- A working CZTS thin film solar cell on stainless steel was demonstrated with an efficiency of 2.14%, with the steel provided by industry partner Baosteel. Key requirements for choosing the stainless steel were identified and a strategy of high-throughput barrier material was developed. Detailed technical discussion was carried out with Baosteel for optimisation on both stainless steel and CZTS solar cells.

Future work

- Future work needs to be carried out to improve CZTS solar cell device performance on both SLG and stainless steel with a focus on both absorber quality and interface engineering.

References

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Li, W. et al. 2015c, J. Alloy and Compounds (in press)
PP2.3 Superstrate Liquid-Phase Crystallised Silicon on Glass Cells

Background
Thin-film crystalline Si PV technologies offer advantages in the use of less silicon and so offers a cost advantage, and from the reduced bulk recombination that occurs in the smaller material volume which can potentially lead to higher cell voltages. Further, thin-film PV manufacturing cost benefit from simpler manufacturing processes, allowing for glass-in-module out manufacturing for monolithic patterning. Full inline-compatible processing provides manufacturing economies and is adaptable to varieties of substrate sizes and shapes. Success with these approaches has resulted in significant cost savings and process improvements in CdTe solar module manufacture. For silicon thin films thus far, these advantages have been outweighed by relatively low efficiencies as compared to Si wafer cells. The thin film silicon strand aims at significantly improving the performance of thin-film Si devices to make them competitive with the main stream Si wafer PV.

The thin-film crystalline silicon on glass (CSG) technology that holds the record efficiency worldwide of 10.5% for a single junction thin-film silicon cell was originally developed at UNSW. The efficiency record has been maintained for some time, limited by a high defect density in the solid-phase crystallised (SPC) Si material produced. A breakthrough in the performance is expected from reducing the defect density by adopting liquid phase crystallisation for material fabrication.

Polycrystalline Si (poly-Si) films with a low defect density can be prepared by melting precursor films with a high power, line-focus diode laser and then letting them crystallise from the liquid phase. Initial experiments have already produced poly-Si films with a few orders of magnitude lower defect density than in SPC material and these films have been processed into cells with much higher voltages than the record CSG device. With a defect density comparable to that in the mc-Si wafers, the liquid-phase crystallised Si on-glass (LPCSG) cells have a potential to reach open-circuit voltages of at least 600mV and efficiencies of 15-16%, matching the performance of mc-Si cells, while having the advantages of thin-film processing.

Currently, the most direct way to increase LPCSG cell efficiency is to improve the front light-coupling, which is still inferior to that of the SPC CSG cells. A more advanced antireflection coating interface between the glass and Si needs to be textured in a way compatible with the laser crystallisation process. Furthermore, the LPCSG cells can also become the basis of the thin-film tandem structure by playing a role of a crystalline Si bottom cell. To make LPCSG cells compatible with the tandem structure, their configuration needs to be reversed from the current superstrate to the substrate configuration and a completely new metallisation scheme then needs to be developed. Providing the performance is maintained at the superstrate cell level, different materials can be then tried for their suitability for the top cell in the tandem. Potential candidates are the same as for Si wafer based tandem structures, such as CZTS and perovskite cells.

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Industry Partners
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Aim
In 2014 research on LPCSG cells focused on understanding of contacting issues responsible for stable performance; identifying approaches to stabilising the performance, improving cell optical properties and increasing the efficiency to above the record of 10.4% by CSG Solar for poly-Si on glass.

Progress
The initial efficiencies of LPCSG cells produced in 2013-14 range from 7% to maximum of 11.7%. All cells are unstable and their performance degrades by 1-3% within hours after the last contact bake (Dore et al. 2014). Both Voc and Fill factor decrease while Jsc remains unchanged. The degradation is reversible and the cells can fully recover, or even improve, after baking is repeated (Figure PP2.3.1). It is believed that the degradation is caused by the poor quality of contacts between aluminium and lightly doped (\(\sim 2\times 10^{16} \text{cm}^{-3}\)) p-type silicon absorber due to the formation of a Schottky barrier at the interface.

Two approaches have been developed to improve the contact quality: 1) selective doping of silicon under the absorber contacts; 2) laser firing of the absorber contacts.

In selective doping (Figure PP2.3.2), a fraction of the n-type emitter is removed and boron is diffused into an exposed absorber, after which Al contacts are formed to more heavily doped silicon (Dore et al. 2014).

It is demonstrated that LPCSG cells with such selective p+ metallisation exhibit stable performance. Although no high efficiency (>10%) cells were fabricated by this approach, it provided proof that stable LPCSG cells...
are feasible. Further development is still required. In particular, due to partial removal of the emitter, the cell current is reduced. A method for minimising the area required for selective doping needs to be found.

In laser firing (developed in collaboration with HZB), each absorber contact receives a few tens of pulses from a 532 nm neodymium-doped vanadate laser (Figures PP2.3.3a and PP2.3.3b) (Weizman 2014). The treatment results in reducing the contact resistance, increasing the cell efficiency by up to 0.7%, and stabilising it.

Films for LPCSG cells are deposited by means of ebeam evaporation on planar glass. This approach is fast and cost effective, but limits the light-trapping and light coupling properties of the superstrate devices, thus also limiting the cell current. To improve broadband light coupling and trapping, texturing of the glass-silicon interface has been developed to be compatible with the laser melting process (Pakhuruddin et al., 2014). Texturing is carried out by mechanical abrasion of the glass, followed by chemical etching (Figure PP2.3.4a). A laser crystallised silicon film applied to this textured glass is continuous and the planarised air-side surface is well-suited for further cell processing (Figure PP2.3.4b). The reflection losses from LPCSG films on glass textured in this way are significantly reduced and the light absorption is increased (Figure PP2.3.5 a,b).

Additionally, to further improve the light-trapping of weakly absorbed long wavelength light (>700 nm), a very rough micron order texture (called “shallow texture”) has been developed for the exposed, air-side silicon surface (Figure PP2.3.6), which results in a noticeable increase in long wavelength absorption (Figure PP2.3.5 b).

As a result of the aforementioned improvement, an LPCSG cell with a designated area efficiency of 10.52%, exceeding the record 10.4% CSG Solar cell, has been fabricated, with Fraunhofer ISE verifying its performance (Figure PP2.3.7).
Highlights

• The performance degradation of LPCSG cells is attributed to lightly doped silicon under the absorber contacts.

• Approaches to stabilising the performance by both selective contact doping and contact laser firing have been demonstrated.

• Glass-silicon interface light-trapping texture, compatible with ebeam evaporation and laser crystallisation, is being developed.

• Significant absorption enhancement has been achieved by combining glass-silicon and rear silicon texturing.

• 10.52% efficient LPCSG solar cells have been fabricated.

Future work

• Future work will be on identifying performance limiting factors and increasing the efficiency of LPCSG cells to about 12%. Diffused homojunction will be compared to heterojunction.

• The light-trapping approaches developed will be implemented for use in real cells. The feasibility of selective laser doping will be studied for both superstrate and substrate cells.

References


PP2.4 Third Generation Approaches

Third generation photovoltaics describes the development of materials that can be used to engineer performance by manipulating the bandgap, phonon response or light-trapping properties of the absorber materials.

• Hot carrier cells aim to capture the energy of above band gap photons in a device such as to either extract their energy at high voltage and high current or to optically boost the efficiency of a standard silicon cell in a down-converter configuration.

• Silicon based nanostructures are used to modify the band gap of a photovoltaic device for use as a top cell element in a thin film silicon tandem device or as the top cell on a c-Si solar cell.

These approaches of Si nanostructure tandems and hot carrier cells offer alternative ways to boost the efficiency of silicon cells or provide high efficiency cells in their own right. Both circumvent the Schockley-Queisser limit and so offer routes to devices in the high 25% or well over 30%.

PP2.4a(i) Model phonon dispersion in bulk materials and nanostructures

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Aim

Modelling of phonon and polaron interactions in InN/InGaN multiple quantum well superlattices, as candidate materials for hot carrier cell absorbers.

Progress

InN/InxGa1−xN multiple quantum-well superlattices (MQW-SL) with wurtzite crystal structure are studied for their role as the absorber material in a hot carrier solar cell. Such a structure will exploit both the significant hot-phonon bottleneck effects in these materials and the known slowed carrier cooling in MQWs.

Modelling of the interactions in the materials and layers in the MQW-SL reported here, allows for optimal design of the material composition and thickness of the well and barrier layers.

The calculation of the rate of polar interaction between hot electrons and polar phonons are based on the Frohlich-type
Hamiltonian and the 1-st order perturbation theory. A hot reservoir of electrons at 1000K is assumed, with heat transferred to the cold reservoir of lattice modes at 300K. The energy relaxation times referring to the polar phonon emission are illustrated in Figure PP2.4a.1, for all the MQW-SL configurations, i.e. for different well and barrier thicknesses and different barrier materials. 18×18 combinations of the thicknesses are sampled for representing all the possible structures from 2 to 9nm. The number of combinations comes from the fact that a complete well/barrier layer should include an integer number of unit cells. Figure PP2.4a.1 is generated by interpolating the relaxation time data of the sampling combinations.

The energy relaxation times of high-lying longitude optical phonons are demonstrated in Figure PP2.4a.2, for different combinations of well and barrier thicknesses. For indium mole fraction $x=0$ (left figure), the contrast of relaxation times are larger than that for the case for $x=0.2$ (right figure); this is reasonable as the higher indium content in the barrier layer would make the structure closer to bulk InN. Both figures show the same trend with different barrier/well thicknesses: the relaxation time increases with thicker well layers and thinner barrier layers, in spite of some irregular local variations. The regular variation mainly results from the change of numbers of InN-like modes and InGaN-like modes. Here a hot reservoir of high-lying modes at 1000K is assumed, with heat transferred to the cold reservoir of low-lying lattice modes at 300K. The non-equilibrium between the two systems is physical due to their significant frequency separation.

To explain the variation, we need to first examine the phonon dispersions of the MQW-SL. Taking $x=0$ as an example, the left figure in Figure PP2.4a.3 shows the dispersions of InN/GaN SL structure, with 6 layers of nitrogen atoms inside each layer (barrier or well). The right figure shows the phonon modulation function of a representative mode from each category of modes, computed from the eigenfunctions of the lattice dynamic equation. The transverse modes have similar modulation functions and hence only that part of the longitude modes is shown.
Considering all three-phonon processes only certain decay channels are allowed due to the laws of energy conservation. As in wurtzite-structured SL, the difference between the acoustic branches and the low-lying optical branches becomes almost indistinguishable. These low-lying branches can be separated into two categories: GaN-confined modes (red lines) and GaN-InN mixed modes (grey lines). In fact the InN-like low-lying modes sit within the allowed frequency band of GaN, hence vibrations in GaN layers are excited too. Therefore no InN-confined modes exist in the low-lying branches. Among all allowed three-phonon processes, GaN-like optical modes can decay into both types of low-lying modes (See the solid arrow and the dashed arrow in Figure PP2.4a.3, while InN-like optical modes can only decay into the mixed modes as they only overlap with the mixed modes. Besides, the energy gap between GaN-like LO modes and GaN-like TO modes is relatively large; hence the resulting low-lying phonons have relatively high energies, compared to the decayed low-lying phonons from the InN-like modes. Since the low-lying branches with high energies are generally flatter, leading to a larger joint density of states of transition, the decay rates of GaN-like LO modes could be enhanced further. Due to the two reasons explained above the GaN-like LO modes decay faster than the InN-like LO modes. Therefore with a thicker well layer (or a thinner barrier layer), the energy relaxation time of the high-lying LO phonon system becomes longer, for it introduces more InN-like modes (or fewer InGaN-like modes). According to Figure PP2.4a.2 the relaxation time of high-lying phonons could go up to 300ps, which is significantly longer than the bulk value of around 1ps. The relaxation time of hot electrons (if phonons are completely thermalized) can go up to more than 1ps, this is also much longer than the bulk value. Combining these two, an optimized MQW-SL structure should involve a thin barrier layer and a thick well layer. The contrast in phonon energies between the well and the barrier also needs to be large, indicating a small indium content in the barrier. In addition, such a structures could potentially prevent hot phonons diffusing out, which makes it even more attractive than bulk materials.

**Highlights**

- Modelled phonon modes of InN/InGaN MQWs
- Predicted slower cooling in MQW structures due to phonon confinement.

**Future work**

- Further development of phonon and polaron interaction modes.
- Development of model describing electron-phonon interactions and hence prediction of carrier cooling in these materials.

**References**


**PP2.4a(ii) Investigate HC absorber using bulk materials**

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**Funding Support**
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**Aim**

- Investigate HC absorber using bulk materials
- Determine appropriate bulk materials for slowed carrier cooling through reduced phonon modes
- Fabricate materials of high quality and characterise for carrier cooling

**Progress**

Hafnium nitride and zirconium nitride have been shown, both theoretically and experimentally, to have a large optical phonon - acoustic phonon bandgap (Saha 2010, Christensen 1979, Christensen 1983). This gap is big enough to prevent Klemens’ decay, the main route of carrier cooling. Abundance of Hf and Zr is also relatively high. Hence these materials are expected to show slow carrier cooling rates, suitable for the hot carrier solar cell.

Thin films of Hf and Zr nitride have been deposited by DC and RF sputtering, respectively using Hf and Zr targets in nitrogen atmosphere. Process parameters such as growth temperature and gas flow were varied to optimise the film quality. An XPS depth profile of a ZrN film deposited at 200 °C with 5% nitrogen partial pressure is shown in Figure PP2.4a.4. Besides Zr and N, the film contains some oxygen. The high level of oxygen at the surface can be attributed to the oxidation of the Zr which is highly reactive to oxygen. The oxygen content decreases with the film depth to less than 5% for etch time longer than 350s. The oxygen content in the bulk of the film is likely to be due to the residual oxygen in the growth chamber. Apart from right at the surface, the Zr and N content in the film are reasonably uniform. Results for HfN films also show that Hf and N content of the films are uniform through the film. Oxygen contamination in HfN films is insignificant. XPS result indicates that both ZrN and HfN films are typically metal-rich.

**Figure PP2.4a.4:** XPS depth profile of a ZrN film deposited at 200 °C with 5% nitrogen partial pressure. Compositional depth profiling of Zr, N and O are shown.
Slow carrier cooling properties of selected HfN and ZrN films were investigated by ultrafast transient absorption spectroscopy (Hartland 2010). Samples grown on quartz substrates were used to detect the transmitted signals. Crystal quality of the films grown on quartz substrates was inferior to those grown on silicon substrates which are expected to decrease carrier lifetimes by introducing additional phonon modes in the phonon gap allowing decay processes to occur. The fs pump-probe experiments were performed using 400 nm excitation pump source with 100 fs duration and 1 kHz repetition rate. White light continuum was used as the probe beam and detected by a polychromator CCD.

The phono spectra of a HfN film at various time delays are shown in Figure PP2.4a.6. The changes in optical density ∆OD before and after the pump are plotted as a function of probe wavelength. An excited state absorption peak around 440 nm and a bleaching peak 730 nm can be observed. In Figure PP2.4a.6 time evolution of the change in optical density at 485 nm is plotted as a function of time delays. Immediately after the pump a rapid change in optical density is observed which may be due to electron-electron scattering. Then it slowly decreases with delay time. The red curve is the single exponential fit which gives decay time constant of about 2 ns. For zirconium nitride films the decay constant is about 0.5 ns. Work is in progress to investigate if the observed slow cooling rates are related to hot carriers. Considering the hot carrier lifetime of 3 ns, hot carrier solar cell can theoretically achieve efficiency over 55% under 1000x concentration (Takeda 2009). However, in reality the efficiency may be slightly lower due to nonidealities such as contact losses and incomplete light absorption.

**Highlights**

- Characterisation of carrier cooling in HfN and ZrN by ultrafast transient spectroscopy

**References**


are also achieved by Langmuir Blodgett deposition at a suitable surface pressure as shown in Figure PP2.4a.7.

To confirm the formation of Langmuir Blodgett multilayers, AFM measurements were carried out on these multilayers. Figure PP2.4a.8 shows a 2-layer film. From the cross section profile, a film of ~12 nm thickness is detected, which shows that it consists of two layers of 6.2 nm nanoparticles. To further investigate multilayer growth, a set of 6.2 nm Si nanoparticle films with 3, 5 and 15 layers deposited onto quartz substrate were characterized Raman spectroscopy. Figure PP2.4a.8 shows that the first order Raman peak at ~518 cm\(^{-1}\) from 6.2 nm Si nanoparticles is much stronger in thicker films, evidencing multilayer deposition.

**Characterisation of hot carrier properties**

Carrier dynamic of Si nanoparticles was investigated for different sizes (2.2 nm, 3.8 nm and 6.2 nm). For this steady-state and time-resolved PL measurements on Langmuir Blodgett and drop cast films of Si nanoparticles were used. Steady-state-PL for both films showed blue shift of the emission peak positions with decrease of sizes of Si nanoparticles, as expected. To investigate the hot carrier behaviour within the Si nanoparticle Langmuir Blodgett films, 2-D time-resolved PL mapping was acquired, as shown in Figure PP2.4a.9. In this map, a high energy area ranging from 570 nm to 610 nm appears within 20 ns. Figure PP2.4a.9 shows that this PL peak vanishes within 50 ns. Considering the carriers’ energy states as a Fermi-Dirac distribution, a Planck-like distribution is applied to the high energy tails of the PL peak. In Figure PP2.4a.9 the data is re-drawn in log scale and exponential fitting is applied to the data from 2.27 eV. An example of the fit is shown in the inset of Figure PP2.4a.9. Temperature calculated from the fitting is shown in Figure PP2.4a.9. It indicates an average temperature ~550 K for Langmuir Blodgett films and ~450 K for drop casting films. This demonstrates that ordered, highly packed Langmuir Blodgett films have high carrier temperature, and are hence more promising as a hot carrier absorber material.

**References**

**PP2.4a(iv) Investigate Energy Selective Contacts**

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**Funding Support**
ARENA

**Aim**
- Investigate Energy Selective Contacts.
- Establish high quality resonant tunnelling structures.
- Move on to triple barrier structures with asymmetric wells for improved selection and carrier rectification.

**Progress**
Energy selective contacts based on crystallized Ge well and amorphous Al$_2$O$_3$ barrier resonant tunnelling diodes based on amorphous Al$_2$O$_3$ barriers and crystallized Ge are promising structures to show room temperature tunnelling due to a high band-offset between Al$_2$O$_3$/Ge. Moreover, crystallization of ultrathin Ge films by thermal annealing is easier than Si sandwiched in oxide layers.

Crystallisation of Ge/Al$_2$O$_3$ multilayer samples grown by RF sputtering at room temperature was investigated with conventional thermal annealing and rapid thermal annealing (RTA). Annealing was conducted in N$_2$ atmosphere. These samples are multilayer structures of alternating Ge and Al$_2$O$_3$ thin layers as shown in Table PP2.4a.1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Ge thickness (nm)</th>
<th>Al$_2$O$_3$ thickness (nm)</th>
<th>No. of Ge layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.9</td>
<td>1.5</td>
<td>5</td>
</tr>
<tr>
<td>B</td>
<td>3.6</td>
<td>1.5</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>7.2</td>
<td>1.5</td>
<td>2</td>
</tr>
</tbody>
</table>

Previous experimental results and theoretical analysis for ultrathin Ge films of thickness less than 10nm separated by oxides have shown that crystallization temperatures ($T_c$) are higher for thinner Ge layer, i.e. $T_c$ is 800°C for 7.2nm film whereas it is 950°C for 1.9nm film (Zacharias and Streitenberger, 2000). In this work however, thermal annealing at 700°C for 30min resulted in oxidation of Ge films. Thermal annealing at 600°C for 1hr and 2hrs have also oxidised all samples, except for the sample with 7.2 nm Ge film. Crystallisation did not occur with annealing at 500°C.

With RTA, the Ge layer in Samples B and C achieved optimum crystallisation at 900 °C. No further improvement in crystal quality was observed with annealing at higher temperature.

A partial oxidation of Ge layer in Sample A was observed up to 800 °C annealing. The film was fully oxidised for annealing above 900°C. In order to avoid the oxidation of thin Ge layers, 0.5nm Al intermediate layers are added to each Al$_2$O$_3$/Ge interface as shown in Figure PP2.4a.10. Raman spectra show that the 1.9nm Ge film does not suffer from oxidation and show similar behaviour as B and C, see Figure PP2.4a.10.

![Raman spectra showing temperature dependence of sample annealed by RTA for 10s.](image)

Double barrier resonant tunnelling device structures (Al$_2$O$_3$/Ge/Al$_2$O$_3$) were grown on highly doped n-type Si (100) wafer and the back metal contacts were of sputtered gold (Figure PP2.4a.11). The 90K I-V scan (Figure PP2.4a.12) demonstrates resonant tunnelling at 0.84V.

![DBRTD structure and I-V curves.](image)

**Figure PP2.4a.10**: (a) 0.5nm Al intermediate layer inserted at each Al$_2$O$_3$/Ge interface. (b) Normalized Raman spectra show the temperature (600~1000 °C) dependence of the sample of (a) annealed by RTA for 10s.

**Figure PP2.4a.11**: (a) DBRTD of 0.5nm Al$_2$O$_3$/4nm Ge/0.5nm Al$_2$O$_3$. (b) Top Al contact by photolithography and etch-back.

**Figure PP2.4a.12**: I-V curves of 0.5nm Al$_2$O$_3$/4nm Ge/0.5nm Al$_2$O$_3$ DBRTD annealed at 1000°C.
Energy Selective Contacts using colloidal-based Silicon Quantum Dots

In principle, quantum dots (QD) should show better resonant tunnelling due to 3D confinement. We have demonstrated resonant tunnelling through SiO$_2$/Si QD/ SiO$_2$ deposited by physical deposition (Shrestha et al., 2010). However, the quality of resonance was compromised by non-uniformity quantum dot sizes in the structure. Langmuir–Blodgett method allows deposition of monodisperse quantum dot nanoparticles (Huang et al., 2004). In this work this technique has been used to make Energy Selective Contacts using double barrier resonant tunnelling structures (RTDs). The RTD structure investigated is shown in Figure PP2.4a.13.

Samples were grown on highly doped Si substrates. The first Al$_2$O$_3$ layer was deposited by thermal Atomic Layer Deposition (ALD) at 200 °C; then a layer of Si quantum dot was deposited on the Al$_2$O$_3$ layer by Langmuir Blodgett method. Next, the samples were sintered at 200 °C for half an hour to dehydrogenate or desorb the surfactant of Si quantum dots. Finally, the second Al$_2$O$_3$ layer was deposited by ALD at 200 °C. The size of the Si quantum dot was 3.8 nm and Al$_2$O$_3$ barrier layers were 0.5 nm thick.

The Si quantum dots studied here were synthesized by a gas-phase non-thermal plasma-assisted approach developed by Kortshagen et al. and surface-functionalized in the liquid phase (Kortshagen et al., 2007). These Si quantum dots are roughly spherical in shape and relatively uniform with the Gaussian size distribution of standard deviation about 0.18 d, where d is mean size. Pt contacts on top of the Al$_2$O$_3$ layer were made by e-beam deposition under SEM monitoring. Back contacts at the bottom of highly doped Si substrates were made of sputtered gold.

References


PP2.4a(v) Fabricate complete hot carrier devices

Aim

The development of electrically coupled devices of slowed carrier cooling absorber with energy selective contacts.

Progress

Slow carrier cooling absorbers and energy selective contacts have been studied and reported in earlier sections of this report. Fabrication of complete hot carrier cell devices consisting of absorbers and energy selective contacts or with optical emission are topics for investigation later in 2015.

PP2.4b(i) Optimisation of homojunction Si QD device

Aim

The focus of our research activities during this period has been on characterisation and modelling to be applied on Si quantum dot (QD) materials and solar cells.

Progress

The first tandem devices have been demonstrated with a series connection of two solar cells:

- a large bandgap (1.8 to 2.0 eV) silicon rich oxide (SRO) pin diode on top of a pn junction solar cell on a silicon substrate and
• a medium bandgap device (1.4 to 1.6 eV) on top of a thin film polycrystalline pn solar cell.

These devices have at least a 30% greater efficiency than that of a single junction Si QD device.

The tandem structure demonstrated is a Si QD solar cell mechanically stacked on a silicon thin film solar cell on glass. The reason for choosing this device configuration is due to the bandgap of the Si-QD cell. According to its PL emission, the bandgap of the Si QD solar cell is around 1.4 eV. A silicon thin film solar cell was then used as the bottom cell and a working tandem device was successfully fabricated.

The open circuit voltage was improved in the tandem cell compared to the top Si QD by 56.5%. The short circuit current of the tandem cell was somewhat unexpectedly improved as well by 66.4%. The improvement of the efficiency of the tandem structure compared to the top Si QD cell was demonstrated to be 172%.

A diagram of the mechanically stacked solar cell is shown in Figure PP2.4b.1. Notice that the need for mechanical stacking is unavoidable in the case of the thin silicon on glass solar cell because the base and emitter contacts are on the same side of the cell just as in our QD solar cells.

The device performs as expected in terms of voltage; the open circuit voltage of the tandem structure is close to the sum of the open circuit voltage of each one of the cells individually tested. The short circuit current of the quantum dot cell, on the other hand, is actually improved by 66%. This is not an expected result as the Si-QD solar cell, ideally sets the limit of the short circuit current. However, when the current of the individual devices in a tandem structure is not matched, the device with the higher current boosts the current of the device with lower current. The improved short circuit current in this case is due to the higher current available from the bottom cell. When the tandem structure operates under an external short circuit condition, some of the excess photocurrent from the bottom cell is injected into the top cell through the top cell shunt. The top cell is then actually operating in a reverse bias condition and the bottom cell is forward biased with the exact opposite voltage compared to the Si-QD cell. The current of the tandem device is then the short circuit current of the top cell plus the excess current injected from the bottom cell. The overall result is an improvement of the short circuit current and ultimately a higher improvement in the performance.

The improvements demonstrated are however not sufficient to make this device competitive yet with other similar tandem structures such as the micromorph cell, also based purely on Silicon. The three key aspects to improve the technology are common to all other technologies, even those of very mature high efficiency technologies such as HIT or IBC cells. These key aspects are: improving fill factor, increasing the short circuit current of the top cell and improving the open circuit voltage of the top and bottom cells. These aspects are analysed in more detail to predict the potential benefits of improving the present limiting conditions.

Figure PP2.4b.1: Schematic diagram of the mechanically stacked Si-QD solar cell on a thin film Si solar cell. Top cell absorbs short wavelength photons, bottom cell absorbs mid range photons and partially absorbs long wavelength photons. Some of the reflected photons make it back to the top cell and improve the short circuit current compared to that of the Si-QD cell on its own.

Figure PP2.4b.2: (a) View of the Top cell Si QD cell (a) View of the rear showing the bottom thin film Si on glass cell.

Figure PP2.4b.3: I-V characteristics of the tandem structure compared to the Si-QD solar cell on its own. A working tandem structure is demonstrated here (Illuminated I-V Tandem).
Highlights

• Silicon nanocrystal photovoltaic device fabricated via photolithography and its current-voltage temperature dependence

• Characterization of in-situ boron doped silicon quantum dots in silicon dioxide

• Fabrication of first tandem Si QD devices, one on Si wafer cell the other on thin film crystalline Si cell.

Future work

• Optimise tandem cell design and fabricate improved tandem devices.

References


Wu, L. et al. 2014b, 40th IEEE PVSC, Denver


PP2.4b(ii) Develop heterojunctions devices

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Australia-India Strategic Research Fund (AISRF)

Funding Support
ARENA 2-A001 Tandem Silicon Quantum Dot solar cells

Aim
Develop vertical device structures through investigation of conducting transparent layers for bottom contacts.

Progress
This project aims to develop two different structures for vertical structured Si quantum dots (QDs) solar cells to avoid previously found current crowding effect in mesa-structures. The working mechanisms are demonstrated in Figure PP2.4b.4.

A vertical structure is expected to eliminate the lateral carrier transport since all current would flow perpendicular to the junction. Additionally, a vertical structure will be necessary in the future to stack single junction Si QDs solar cells in series to form full tandem structure. In this work, two approaches are currently under investigation: Approach 1, using molybdenum (Mo) as back contact interlayer; and Approach 2, membrane cells through rear vias method. Schematic diagrams for these two approaches are illustrated in Figure PP2.4b.5.

For the first approach, Si QDs solar cell is patterned and sputtered on Si or fused silica substrates that have a pre-sputtered metal interlayer as back contact. Mo is selected for this contact layer due to its high melting point, good electrical conductivity, and high optical reflectivity. As the Mo interlayer will be annealed under 1100°C along with the Si QDs bilayers to assist Si nanocrystal formations, the key task is to guarantee the thermal stability of the interface between the Mo interlayer and the Si QDs bilayers.

The silicon nanostructures were first deposited and then annealed. After annealing, the formation of Si nanocrystals was confirmed using both Raman and PL spectroscopy. From the Raman spectra in Figure PP2.4b.6 (left), sharp Raman shifts at 521.5 cm⁻¹ were identified from all n-i-p mesas with different device sizes. The 1.5 cm⁻¹ shift of this peak compared to the reference Si peak at 520 cm⁻¹ was within the resolution of the Raman station (1.7 cm⁻¹), which indicated the presence of Si QDs in n-i-p mesas. PL measurement was conducted using a violet-blue laser with 405 nm wavelength. Normalized PL spectra of these two devices were present in Figure PP2.4b.6 (right) and a peak at around 1.37 eV was found. The domain of the peak position in this work was in consistence with previous results (Lin et al. 2014a, b), which also verified the formation of Si QDs in the vertical devices.
IV characterizations were determined under both dark and 1-Sun illuminated conditions. Measurement connection and IV curves of device with 2500 μm² size are shown in Figure PP2.4b.7. The IV characteristics demonstrated rectifying feature and light response, indicating the existence of diode within the device. From the 1-Sun illuminated IV curve, \( V_{oc} = 40 \text{ mV} \) and \( J_{sc} = 2.7 \times 10^{-4} \text{ mA cm}^{-2} \) extracted respectively. It was noted that the device had a shunting issue, which limited its overall performance.

For the second approach, a membrane Si QDs cell is fabricated on a SiO₂ window deposited on Si wafer. The SiO₂ layer, which will be removed after annealing in order to allow metal evaporation from the back, serves as a mechanical support for the sputtered Si QDs bilayers; it also acts as a buffer layer that blocks the responses from the Si wafer substrates. As this structure allows post-metallization, there is no need to pre-sputter and anneal any back contact metals that have to withstand high temperature process, making the whole structure more sustainable.

By the end of this project, it is expected that working single junction Si QDs solar cells with vertical structures can be fabricated using both of the proposed schemes. Characterizations including Si crystallinity, interface properties, current-voltage characteristics will be conducted. Improvements in current output will be quantified and compared with the previous mesa-structured devices. It is also expected to see the possibilities of making real tandem Si QDs solar cells by stacking different single junction cells in series based on these vertical structures.

**Highlights**
- Fabrication of Mo back contact p-i-n devices.
- Demonstration of small photovoltaic effect. \( V_{oc} = 40 \text{ mV} \), \( J_{sc} = 2.7 \times 10^{-4} \text{ mA cm}^{-2} \)
- Design of new membrane devices on etched substrate.

**References**

PP2.4b(iii) Model absorption and electrical properties of materials and devices

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**Funding Support**
ARENA 2-A001 Tandem Silicon Quantum Dot solar cells
Aim

Modeling of absorption in Si quantum dots (QDs), application to device properties. Improve understanding of absorption and origin of photovoltage in order to optimise growth of good devices.

Progress

Optical models have been developed previously. (Jia 2013) Device models have also been developed and applied to existing cells (Perez-Wurl 2012). Further modelling on absorption and measurement and modelling of photoluminescence for an overall picture of photogeneration in these materials.

The main focus of work in this period has been to characterise silicon QD materials more thoroughly to better understand the parameters required to fabricate better performing devices.

We have focused on developing these key building blocks independently with the intention of putting them together in a device that will perform with improved properties. A significant amount of effort has gone into developing a better understanding of the material by means of developing models and characterisation techniques. The results of these efforts are now being assessed by the scientific community either as conference presentations, scientific papers submitted to technical journals or both. The details of these publications are listed in the section below on publications.

We have identified a key aspect to ensure an improved efficiency of these devices, namely, a contact layer compatible with high temperature processing. As such, we have made use of external facilities to investigate two possible solutions: molybdenum and aluminium zinc oxide. Both approaches have shown potential as the desired contact but will need to be tested on the actual device structure to confirm compatibility.

Our focus on modelling and characterisation has resulted in a strong framework to assess the material quality required to be deposited. With the models developed we are now capable of using photoluminescence (PL) as a characterisation tool well beyond its initial limited applicability. PL was originally used to identify a peak in the emission that was loosely linked to the size of the Si QD. Our current model allows us now to identify average Si QD size and its variation. This feedback will become a key factor when depositing Si QD material. PL measurements take only a few seconds so that our current model will allow us to optimise the material within a few weeks. PL has also been used to demonstrate the ability of reducing defects in the material with the use of boron. Using a combination of steady state, transient PL and electron paramagnetic resonance measurements we have confirmed that boron can be used to mitigate the effect of defects.

Ellipsometry is another characterisation technique that will be essential to calibrate and monitor thickness and composition of our films. An ellipsometry measurement also takes a few seconds to perform but it is only useful if a reliable optical model is available. We have developed a model that allows us to use this technique with complete confidence. We have also developed unique electrical models to identify the electronic quality of the Si QD material. Specifically, capacitance-voltage measurements and temperature dependent I-V properties can be used to determine doping, trap density and effective bandgap. The feedback to the fabrication using these techniques is much slower than PL and ellipsometry as they require the fabrication of devices. However, these electrical characterisation techniques along with the specific models we have developed, will allow us to optimise the devices in a much more effective manner.

In summary, we have put in place a set of characterisation tools and models to allow us to optimise the material in a short time once we get access to key equipment in our labs. We have also demonstrated two possible solutions to address the key issue of contacts compatible with high temperature processing.

Highlights

• Capacitance-Voltage characterization of in-situ boron doped silicon quantum dot in silicon dioxide
• Investigation into high temperature annealing of ZnO:Al as a prospective transparent conductive oxide window layer for superstrate silicon nanostructure solar cells

Future work

• Use of the models developed to optimise materials growth parameters and characterise and feedback into improvement of predictive power of model.

References


PP2.4b(iv) Investigate other materials based on Si or Ge QDs

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Progress

There are two activities in associated projects supported by ACAP: The use of Si rich silicon carbide grown by sputtering for photoelectrochemical photocathodes and the application of colloidal Si QDs to a range of applications.

Si Rich Silicon Carbide:
Sputtered Si rich silicon carbide (SiC) is deposited in a similar way to silicon rich oxide (SRO). This results in a material with modified bandgap between that of SiC and Si. It is predominantly cubic reproducing the 4c-SiC structure rather than the hexagonal forms. The material is usually doped p-type using Al or Sb doping but can be grown as n-type without any intentional doping. The main application is as the p-type photocathode in a photoelectrochemical cell.

Water splitting with evolution of hydrogen is achieved with a bias voltage of about 2.1V. This is seen to reduce to about 1.8V on illumination with white light.

One experiment carried out with a Si rich SiC photocathode and a Fe$_2$O$_3$ (hematite) photo-anode achieved spontaneous water splitting under illumination when measured with a three terminal potentiostat. Problems with parasitic reactions, usually oxidation of cathode and dissolution of anode are being further investigated.

Colloidal Si Quantum Dots:
Colloidal quantum dots (QDs) of highly monodisperse particle size, where the size can be either 5 or 10nm, are obtained from the University of Minnesota. These have been grown by a time of flight vapour CVD method and give high size uniformity. Typically the NPs are capped with chlorine to prevent oxidation although they can be capped with SiO$_2$.

These colloidal NPs are investigated for hot carrier properties and for multiple exciton generation. Long lifetimes of a few ns have been observed using transient absorption.

They have also been used in comparison of absorption measurements with photoluminescence to investigate the reasons for the difference between these measurements. The monodispersion of size removes one of the possible reasons for a difference (i.e. variable particle size).

Highlights

- Photo-cathodes of Si rich SiC, give water splitting under bias and illumination, and spontaneous water splitting when coupled to hematite photo-anode.
- Colloidal Si NPs have uniform particle size and are used in hot carrier cells and for absorption/PL measurements.

References


Program Package 3 Optics/Characterisation

Overview

PP3, optics and characterisation, targets experimental demonstration that previously accepted theoretical conversion limits can be increased by use of structures that have a high local density of optical states, with particular emphasis on thin film organic and inorganic solar cells. Of special interest are devices thinner than the wavelength of light where there are opportunities for much stronger absorption of light than would be normally expected from the device thickness involved.

There are two main themes in this Program Package. The aim of the first theme, PP3.1, is to develop methods and theories to better understand the structure-property relationships in thin film organic and earth-abundant solar cells. This activity will contribute to programs PP2a and PP2b and provide a valuable resource for the ACAP program overall. Highlights of this work in 2014 included a 16.5% hysteresis-free homojunction organo-halide PeSC, with a subsequent publication in Nature Photonics, and the first visible light, broadband organo-halide perovskite photodiode with silicon-like performance.

The second theme studies plasmonic and nanophotonic light-trapping for a range of cell structures. Work at ANU (PP3.2a) applies a photoluminescent spectroscopy method to compare a range of surface textures for Si wafers and to quantify their light-trapping performance against standard texturing methods. Absorption spectra extracted in that way for high-efficiency c-Si solar cells was shown to provide an accurate estimate of the cells’ external quantum efficiency at near-bandedge wavelengths. Complementary work (PP3.2b) at UNSW aims to measure the scattering properties of the surface plasmon structures proposed for light trapping. The group developed the capability to reliably fabricate the structures in a repeatable way. Further work at UNSW (PP3.3c) uses polystyrene nanospheres to pattern plasmonic light trapping arrays for as either a transparent conducting layers on the front or light-trapping layers on the rear of thin-film photovoltaics. Large area fabrication methods have now been established for reliable production. Small errors in the optical constants of silver can be magnified several fold if it is used in plasmonic structures, leading to inaccuracies in the modelling and interpretation of results if accepted values are used. Research in PP3.2c has developed novel measurement methods and produced revised values for the optical constants of this important metal. Finally, PP3.2e seeks to develop plasmonic light trapping for silicon wafer cells. This work has confirmed that surface tarnishing can affect the scattering properties of the silver nanoparticles and has determined that over-coating of the nanoparticles with a dielectric material, such as magnesium fluoride is an important design consideration.
PP3.1 Methods to characterize the optical and electrical properties of organic and other thin film earth abundant solar cell

Characterisation of the optical and electrical properties leads to a better understanding of the structure-property relationships in thin film organic and earth abundant solar cells. This work reports on the development of a sophisticated set of techniques for accurately measuring properties such as internal quantum efficiency, both carrier mobilities and recombination dynamics in organic solar cells under conditions and architectures as well as skills in neutron and x-ray structural techniques and the development of predictive structure-property relationships from the molecule to device level. This expertise is applied to new materials and architectures in OPV and other earth abundant technologies such as perovskites – and serves as a valuable resource among the ACAP partners by sharing learnings and techniques across the organic-inorganic spectrum in a coordinated approach to PV cell and module characterization and understanding. Finally, the scaling of organic and other earth abundant solar cells from the lab-scale to sub-modules will require new measurement techniques which will also be the remit of this program.

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Funding Support
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Aim
The aim of this program is to develop methods and theories to better understand the structure-property relationships in thin film organic and earth abundant solar cells – structural, optical and electrical. In so doing, UQ will contribute to programs PP2.a and PP2.b and provide a valuable resource for the ACAP program more broadly.

Progress
We undertook a comprehensive study of the electro-optics of high efficiency, planar organo-halide PeSCs. This required development of new methodologies to measure basic materials and cell level properties such as: dielectric constant (static-to-optical frequency); optical constants (n,k); internal quantum efficiency (IQE); and exciton binding energy. Our results indicated that, contrary to current thinking, CH$_3$NH$_3$PbI$_3$ planar solar cells are strongly non-excitonic with binding energies ~2meV. The material displays Jonscher Law (1/f) behaviour at low frequencies characteristic of ionic character. This is most likely the origin of the high static dielectric constant which produces strong Coulomb screening and drives non-excitonic behaviour. With knowledge of the optical constants we were also able to optimise the cell structure, maximising the $V_{oc}$ with work function modifying layers at the anode and cathode.

As shown in Figure PP3.1.1, the outcome was a 16.5% hysteresis-free device with a simple homojunction architecture and flat 100% IQE. These results were published in Nature Photonics (Lin et al. 2015). The electro-optical principles developed and elucidated in this work were used to create the first organo-halide perovskite broadband photodiodes (Figure PP3.1.2). These “PPDs” have high, spectrally flat responsivities, and performance metrics rivalsing commercial silicon diodes. This work was also recently published in Advanced Energy Materials as a front cover article (Armin 2014a).

Figure PP3.1.1: (a) Current density – voltage characteristics of a CH$_3$NH$_3$PbI$_3$ organo-halide perovskite homojunction solar cell (hero device 16.5% power conversion efficiency); and (b) associated external and internal quantum efficiencies.

Figure PP3.1.2 Schematic showing the structure of a broadband CH$_3$NH$_3$PbI$_3$ organo-halide perovskite photodiode with performance metrics rivalling c-Si diodes.
We have developed a comprehensive suite of methods to measure and understand the transport physics of organic semiconductors under conditions which are relevant to solar cell geometries. As described in the PP2.1h report, the new technique of MIS-CELIV has allowed us to measure both electron and hole mobilities in unipolar devices (Armin 2014b). This methodology is now being adopted broadly in the community and we use it as a matter of course to assess new materials. Augmenting MIS-CELIV, the team has also developed new methods based upon Resistance Dependent Photovoltage (RPV), which in combination with detailed drift-diffusion modelling also delivers accurate carrier mobilities and recombination coefficients in structures relevant to real, operating organic solar cells. These methods have been used to study the time independence of mobility in polymer:fullerene blends, the molecular weight dependence of bimolecular recombination, hot carriers and the impact of reduced bimolecular (non-Langevin) recombination in organic solar cells.

**Highlights**

- An understanding of the basic physics of organo-halide PeSCs
- A 16.5% hysteresis-free organo-halide PeSC with the simplest possible homojunction architecture

**Future work**

- Development of Intensity-dependent Photocurrent (iPC) methodology to accurately measure recombination losses
- Application of transport methodologies to study the fundamentals of transport physics in organo-halide perovskites
- Apply dielectric constant and optical-constants measurement techniques to new organic semiconductors (including high dielectric constant materials)
- Correlate transport measurements with alternative spectroscopies such as Transient Absorption Spectroscopy

**References**

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**PP3.2 Light Trapping**

As high efficiency solar cell technologies mature, harvesting the near-infrared (NIR) photons becomes essential in order to approach the theoretical limit of single junction solar cells. To capture this proportion of the light, light trapping structures are required to scatter light and increase the optical path length of photons within the solar cell.

UNSW and ANU have a long research history in the experimental demonstration of light-trapping schemes for crystalline Si and other thin film solar cells. In recent years both groups have developed novel approaches based on plasmonic and nanophotonic structures, which are compatible with a wide range of cell types. A key aim of the work at ANU in 2013 and 2014 was to compare the performance of these novel light-trapping schemes to conventional c-Si pyramidal surface textures. In 2013, we applied a technique based on photoluminescent spectroscopy (PLS) to extract the band-band absorption in Si wafers. This measurement technique is a useful way to calculate the absolute absorption within the active layer, as free carrier absorption and parasitic absorption can be excluded. It allows rapid comparison of a wide variety of light-trapping structures without the need to fabricate a complete cell.

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**Funding Support**

ARENA, ACAP, ANU

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**Aim**

The main aim in 2014 was to apply the PLS absorption extraction method to compare a range of surface textures on Si wafers, and to quantify their light-trapping performance against standard surface textures using a standard light-trapping figure of merit.

**Progress**

**Introduction**

In 2014 we carried out a systematic study and comparison of a range of novel Si surface textures with the aim of benchmarking their light trapping efficiency against standard textures. The use of photoluminescence rather than traditional reflection and transmission spectrum analysis allows us to measure the absorption due to band-to-band transitions only, excluding parasitic absorption from free carriers and other sources. By integrating the extracted band-to-band absorbance over the AM1.5G photon flux spectrum, we can calculate the effective $J_{sc}$ of the silicon wafer with each type of structure. We then compared the $J_{sc}$ of each sample to the $J_{sc}$ of an ideal Lambertian model to evaluate the LTE.

Four basic light-trapping structures were examined:

- Reactive ion etched texture (RIE)
- Metal-assisted etched texture (MET)
- Random pyramid texture (RAN)
- Plasmonic Ag nanoparticles with a diffusive reflector (Ag/DR).
We also compared two novel combined structures of front side RIE/rear side RAN and front side RIE/rear side Ag/DR. Figure PP3.2.1 shows a schematic of the double-side textured Si wafer geometry used in this study, and sample scanning electron micrograph (SEM) images of the different surface textures that were studied.

Results

Validation of PLS absorption extraction to predict performance of high-efficiency c-Si cells

The ability to separate band-band optical absorption in the active layer of a cell from other sources of parasitic loss allows a more accurate prediction of likely cell performance than is possible using standard measurement techniques (e.g. reflectance/transmittance with a spectrophotometer) which only measure total absorption. In order to validate the accuracy of the PLS technique, we extracted the absorptance of a high efficiency back-contact (BC) solar cell and compared it with the measured external quantum efficiency (EQE). Figure PP3.2.2 shows the band-band absorptance (ABB) and EQE of a BC solar cell. The circle represents ABB, while the triangle is the conventional 1-R-T absorptance measured with a spectrophotometer. The ABB value is very close to the EQE of the cell from 1000nm to 1200nm. The spectrometer 1-R-T measurement is significantly higher than the EQE in the range of 1000nm to 1200nm which clearly indicates the existence of parasitic absorption in the 1-R-T measurement. Therefore, the method of extracting ABB using the PLS method provides a more accurate current prediction than conventional methods which can easily overestimate the absorption in the region where light-trapping plays a significant role.

Comparison of different surface textures

Figure PP3.2.3(a) shows the absorptance spectra of the textured wafers extracted from R&T measurements from 300nm to 900nm. While all three textures notably reduce the front reflection losses, RIE texture provides a broadband excellent anti-reflection effect across both the ultraviolet and visible wavelengths. RAN and MET have wavelength dependent reflection loss, while MET performs better in the spectrum below 400nm due to the existence of a larger fraction of nano-scale textures, which are more effective at coupling short wavelength light into the silicon.

The extracted ABB of the samples in the long wavelength range are shown in Figure PP3.2.3(b). Black solid squares represent ABB of a 260μm wafer with planar surfaces, which serves as a baseline in this study with maximum $J_{sc}$ of 3.44mA/cm$^2$ from 990nm to 1200nm. The double side RIE sample shows excellent broadband anti-reflection properties but the lowest light-trapping contribution of the test structures ($J_{sc} = 4.89mA/cm^2$). Double side MET performs better than RAN in terms of overall photovoltaic performance.
anti-reflection in the range of 300nm to 900nm but has quite similar light-trapping properties. By combining RIE and RAN one can benefit from both excellent anti-reflection of RIE and light-trapping properties of RAN textures. As shown in Figure PP3.2.3(b), RIE/RAN performs the best (5.75mA/cm²) among all the structures clearly demonstrating low reflection loss of RIE and highly randomizing property of RAN. As an innovative structure alternative to RAN, Ag/DR also provides excellent light-trapping without increasing the surface recombination at the rear side. The combined structure of RIE and Ag/DR can also provide excellent light-trapping performance (5.65mA/cm²) comparable to RIE/RAN’s (5.75mA/cm²).

Light-trapping Efficiency Benchmarking

Using the maximum possible photocurrent calculated for each sample we evaluate the light-trapping efficiency (LTE) of each of the textured samples using the figure of merit proposed by Schuster et al (2014). The LTE is a relative measure of how close the absorption approaches that of ideal Lambertian light-trapping. The extracted LTE are compared with the LTE of other reported light-trapping structures in Figure PP3.2.4. The LTE of the combined RIE/RAN and RIE-Ag/DR textures are some of the highest reported for Si wafers.

Highlights

- A systematic analysis and comparison of different light trapping surface textures on crystalline Si wafers using photoluminescence spectroscopy was performed.
- Absorption spectra extracted from photoluminescence spectroscopy on high-efficiency c-Si solar cells was shown to provide an accurate estimate of cell EQE at near-bandedge wavelengths.

Future work

- In 2015 we will extend the photoluminescence spectroscopy method to study light absorption in a range of crystalline Si and thin film solar cells, and to quantify the light-trapping performance of various textures and nanostructures.
- In particular, we plan to apply this technique to study optical absorption and light-trapping in thin film PeSCs.

References

**PP3.2c Plasmonic Nanomesh Contacts for Thin-Film Photovoltaics**

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**Funding Support**  
ACAP, ARENA, UNSW

**Aim**  
We aim to investigate the use of nanosphere lithography (NSL) for the fabrication and characterisation of metal nanomesh films.

**Progress**  
NSL was successfully used to fabricate plasmonic structures – nanomesh arrays as well as hexagonal metal grating arrays. Improvements toward larger and more uniform nanosphere areas continue, with one of the SEM images in Figure PP3.2.5 showing a fairly uniform distribution of features. This initial phase of development has resulted in the ability to coat samples over areas extensive enough to measure with standard optical characterisation techniques as shown in Figure PP3.2.6. We have successfully extended this process to polystyrene nanospheres with diameters ranging from 1µm - 100 nm thereby enabling us to fabricate a range of structures. We aim to use this as either a transparent conducting layer on the front or a light-trapping layer on the rear.

**Highlights**  
- Demonstrated the capability to reliably fabricate films in a repeatable way.
- Established large area fabrication.

**Future work**  
- Determine the best approaches for integrating nanosphere-lithography-based nanostructures into experimental designs.

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**Figure PP3.2.5:** A scanning electron microscope image of one of the structures fabricated by our group, an array of nano-holes formed in a 100nm thick layer of Ag on quartz (SPIE copyright)

**Figure PP3.2.6:** Large-area coverage of nanosphere film on glass, showing diffraction on transmission of light from an LED lamp.

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**PP3.2d Optical constants of silver**

**Lead Partner**  
UNSW

**UNSW Team**  
Dr Supriya Pillai, Prof. Martin Green

**UNSW Students**  
Yajie Jiang

**Funding Support**  
ACAP, ARENA, UNSW

**Aim**  
We aim to prove that the most widely-used optical constant data sets in literature have deficiencies that could affect the accuracy of the many theoretical analyses based on them. Extracting the most accurate set of data for silver is important since most of the literature in plasmonic research cites questionable data. Accurate and reliable data is needed to optimise calculations for plasmonic applications.

**Progress**  
The accuracy of the published values has been brought to attention more recently with the widespread adoption...
of silver in plasmonic research. We revisited the most commonly used optical constants in literature: Palik (1985), Johnson and Christy (J&C) (1972) and Nash & Samples (N&S) (1996) and analysed their data.

We repeated the original experiments by J&C and used reflectance and ellipsometry measurements to characterise the samples, which were measured immediately after evaporation to minimise chances of contamination. Based on the measured reflectance, transmission and ellipsometry data, we were able to extract the optical constants of the silver films. These optical constants were then used to generate the various data. Drude-Lorenz oscillators in WVASE® were used for the purpose.

The newly extracted optical constants from the silver film with a thickness of 1μm, 30.4nm, and single crystalline bulk silver are compared with J&C’s data in Figure PP3.2.7. The extracted optical constants from our 30.4nm film do not agree with J&C values even though the films had very similar properties to that of J&C’s. The k value variations are small; however, the n values show a significant difference with n known to be highly sensitive to grain strain and crystal defects. The discrepancy between experimental results and generated values, based on Palik and J&C’s data, highlights drawbacks in their original data set.

The relaxation time $\tau$ (or scattering time) is the characteristic time for a distribution of electrons in a solid to approach or “relax” to equilibrium after a disturbance is removed. Relaxation time calculations were used as another check to validate the correctness of the optical constants. The Drude (1996) model and the Extended Drude model (EDM) (5) were used for the purpose. We also measured a single crystalline silver ([100] orientation) sample that has been polished to give good surface quality. The relaxation times for the three most popular silver data sets were calculated, as well as a single crystalline silver sample. It is expected that the values from single crystalline silver are slightly lower than the intrinsic value due to reduction by surface roughness due to polishing and tarnishing.

The relaxation times for the four data sets are calculated using the Drude model (Youn et al. 2007) and plotted as shown in Figure PP3.2.8. Palik, N&S and the single crystalline silver cases give constant relaxation times in the free electron region, whereas J&C’s data shows an unphysical fluctuating trend. Comparing the relaxation times deduced by different methods (not shown here), the AC relaxation times show fairly good agreement as deduced by the Drude and EDM methods for all data sets except for J&C’s. It is found that the AC and DC relaxation time values of J&C’s data deviate significantly from the other calculated values confirming the accuracy of their published data.

Anomalies in Palik’s data are very likely due to stitching of multiple data sets with different deposition and measurement conditions, especially in the lower energy region. While N&S data appears to be the most accurate, their tabulated data for a very small spectral region makes them unsuitable for most applications.

Figure PP3.2.7: Comparison of the optical constants of silver: (a) real part n (b) imaginary part k. (i) refitted optical constants by reproducing J&C’s experiment; (ii) extracted optical constants of opaque silver film; (iii) J&C’s data with error bars and (iv) extracted optical constants of single crystalline bulk silver.

Figure PP3.2.8: Silver relaxation time calculated by by Drude model expression $\tau = (1-\varepsilon r)/\varepsilon i \omega$.

**Highlights**

- We confirmed that a small variation in the optical constants can be magnified several fold in plasmonic work, leading to inaccuracies in the modelling and interpretation of results.

- We conclude that of the most widely used optical constant data sets for silver, published by Palik and by Johnson and Christy, have deficiencies that could affect the accuracy of the many theoretical analyses based on them.

- We have developed a novel way to way to measure the optical constants of silver at the interfaces, which are free from contamination and will be used to extract the optical constants of silver accurately in the near term.

**Future work**

Publish the tabulated data for silver optical constants using our novel method.

Study the effect of annealing and grain boundaries on the optical constants.

**References**

Drude, P., 1900, Ann. Phys. (Berlin) 1, 566


PP3.2e Novel Light-trapping in Si based solar cells

Lead Partner
UNSW

UNSW Team
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UNSW Students
Claire Disney, Qi Xu

Funding Support
ACAP, ARENA, UNSW

Aim
The aims of this work are to investigate the potential of using novel plasmonic structures on the rear of device structures and to study its potential as a light-trapping layer.

Progress
Using the nanosphere lithography (NSL) technology described in PP3.2c, we have demonstrated the fabrication of metal nanohole arrays and embedded spheres to form a grating structure. In this study the structures were investigated for their light-trapping ability when placed on the rear of cells. FDTD simulations were used to study the optimum design of such structures. A number of design parameters were varied for each of the structures simulated. These included the diameter of the holes or embedded spheres as well as the periodicity of the hemispherical array. Furthermore, the material and thickness of the absorber and metal layers was also considered. Additionally, the structures were compared with alternative rear reflectors. Contour plots, showing the idealized J_{ph} achieved for each array’s periodicity and feature size, are shown in Figure PP3.2.9 (nanohole arrays) and Figure PP3.2.10 (embedded nanosphere arrays) for Ag. In both cases, these values can be compared to the case of a rear Ag mirror, which yielded an idealized J_{ph} of 16.56mA/cm^2. The best enhancement achieved for the case of embedded spheres was an increase in J_{ph} of 3.58mA/cm^2 or 21.61% for a 2µm thick Si cell. In the case of an array of nanoholes, the maximum enhancement for the same thickness Si was an increase in J_{ph} of 2.27mA/cm^2 or 13.73%. It is promising to note that both structures showed improvement over the mirror.

Figure PP3.2.10: Photocurrent J_{ph} (mA/cm^2) for a variety of sphere diameters and array periods for dielectric spheres embedded in an Ag layer on the rear of 2µm Si. (SPIE copyright)

The degradation effect of the silver metal nanoparticle based system was also studied following on from the results reported last year. EQE measurements were used to compare the performance of the cells with time. A reference cell was used to monitor the changes. A clear degradation of up to 10% was evident for the case with silver nanoparticles exposed to the ambient as shown in Figure PP3.2.11. The samples where the particles were coated with MgF2 showed no degradation. Our results highlight the importance of overcoating the samples with a suitable dielectric immediately after deposition of silver to avoid tarnish and take full advantage of the scattering properties of the nanoparticles.

Figure PP3.2.11: Measured EQE degradation for cells with Ag MNP only and cells with Ag MNP + 150 nm MgF2 + Evaporated Al as rear reflector after 1.5 years storage.

Highlights
• Optimisation study undertaken using simulations, yielding promising results compared to a planar metal reflector.
• We have confirmed that degradation of the particles can impact the scattering properties of the silver nanoparticles and can conclude that over-coating of the nanoparticles with a suitable dielectric material is an important design consideration for plasmonic solar cells.

Future work
• Future work will look into fabricating and characterising such structures to isolate the absorption in Si from that in the metal. This is important to quantify the light-trapping capability of the proposed novel structures.
Program Package 4
Manufacturing Issues

Overview
The Manufacturing Issues program looks primarily at establishing a benchmark costing methodology that can be applied to the new technologies under investigation. The development of a methodology for costing of new technologies is intended to inform research directions and to assist in setting research priorities.

Cost targets are set to be competitive, with a benchmark comparison made to the US Government’s SunShot targets for photovoltaic costs, with the expectation that one or more of the technologies will be competitive. These cost targets are set with a view to ensure that the technologies developed are internationally competitive, taking into consideration all aspects of the costs for PV manufacturing. The relevance of these cost reduction targets is that their achievement would be recognised as a very major technological advance internationally and would provide the stimulus needed to encourage serious investment in the new technology.

PP4 Cost Evaluations

Lead Partner
UNSW

UNSW Team
Dr Anita Ho-Baillie, Dr Richard Corkish, A/Prof. Renate Egan, Prof. Martin Green

NREL, CSIRO, ANU, Monash, UoM, UQ Team

Input on processing sequences from all nodes will be mandatory for successful completion of this package

Aim
Driven by a need to provide a framework for costing of new technologies, the aim of the Manufacturing Issues package is to deliver a methodology for assessing manufacturing costs for the different technologies under investigation under the ACAP program. Modelling of cost and competitiveness, will inform decisions around priority areas for research with due consideration given to potential benefit, risk, scale and capital costs.

The Sunshot targets are used as benchmarks for comparison of the outcomes of the cost calculations. The target is to develop technologies with costs lower than the Sunshot targets to motivate further research and ultimately to provide the stimulus needed to encourage serious investment in the new technology developments.

Progress
In 2014, the manufacturing cost analysis activities included a review of past costing approaches, preliminary data acquisition and an evaluation of the current and historical costs of silicon and thin film manufacturing. In addition, ACAP partner manufacturers (Suntech and Trina) were consulted on the key manufacturing cost drivers for silicon based PV manufacturing and early collaborations were established with leading institutes including ACAP partner NREL on leveraging the existing knowledge base in costing methodologies.

Developing a costing methodology:
In assessing the costs of new technology developments, consideration must be given to

(i) cell level efficiency improvements, materials and device processing costs

(ii) module level efficiency, materials and process costs

(iii) risk, commercialisation costs and profitability

(iv) module durability, lifetime and balance of systems costs

ACAP will concentrate on technological improvements that target (i), reduction the $/Watt cost and the improvement of the energy conversion efficiency. Detailed costing methodologies will be developed in this work program for the innovative technologies. In addition, due consideration will be given to the other cost implications (ii) through to (iv) to assess the competitiveness of the technology. The costing analysis will include a first-stage evaluation of each.

Costing of the cell and module manufacturing process takes into account the sum of the direct costs including input materials, labour costs as well as the indirect costs including capex and/or depreciation, electricity and maintenance among others.

During 2014, costing methodologies for silicon wafer based PV manufacturing were reviewed and updated to reflect recent changes in processes and materials prices. Processes and input materials costs were updated to develop a first-pass analysis of current module manufacturing costs, shown in Figure PP4.1.2 with a comparison of the contributions of wafer, cell conversion and module
conversion to the current manufacturing cost for mono and multi-crystalline silicon module manufacturing.

In Figure 4.1.3, the cell manufacturing cost estimates are broken down into their contributing parts, showing the significance of metallisation and depreciation of capital, that together comprise around 50% of cell process costs.

Current and historical costs of silicon manufacturing:
A review of the literature, confirmed by the costing analysis by ACAP, shows that for silicon wafer module manufacturing the dominant factors are module efficiency, materials cost and equipment depreciation.

- Efficiency improvements drive down the $/W cost, but also leverage the balance of systems costs for an increased impact on total system costs.
- Materials costs are driven by market forces as well as technology developments that allow for lower cost materials to be used (as in PP1, Solar Silicon), small quantities or alternative materials (as in PP2, Thin Film)
- Equipment depreciation costs are influenced by market forces and by process improvements increasing the throughput and yield for a given capital investment.

From typical learning curve analysis, we expect that costs are likely to drop by 20% with every doubling in production capacity. A historical review shows that between end-2007 and end-2012 (5 years), cumulative production increased twelve-fold from 13 to 150 GWp. With this change and assuming cost reductions driven by learning, we would expect costs to have halved over the same time period. In fact, manufacturing cost dropped by 70% from ~$3.50/Wp to ~0.65c/Wp. The big drivers have been a significant drop in silicon feedstock, efficiency improvements, casting and wafering costs, with only small reduction in costs arising from cell and module processing Verlinden, 2014.

At a high level it is clear that opportunities lie in developing processes or new materials that address these key cost drivers of materials cost and efficiency improvement and much of the work in ACAP addresses these key areas. In particular the solar silicon project (PP1) aims at reducing the cost of the raw input material and at developing processes to enhance performance using low-cost, low quality silicon. The thin film, third generation and hybrid devices seek to develop technologies with new materials with lower cost paths to market through optimising material usage, manufacturing process streams and conversion efficiency.

Highlights

Future work
- In 2015, we will complete the development of a costing methodology for silicon module manufacturing with reference to the known cost and price structures of current multi and mono-crystalline silicon technologies. The more promising of the technologies developed under the ACAP program will be costed in detail. A sensitivity analysis will be used to assess near term opportunities for improvement.
- The methodology will then be developed to allow for high-level assessment of the cost-benefit of new technologies to guide research into areas of the highest potential for cost reduction. The outcomes of the cost analysis will be compared with the U.S. Department of Energy SunShot module price targets.
- A costing methodology for thin film technologies will be developed in 2015, with the aim of sharing this within the ACAP network for implementation in 2016.

References

Overview

Within the PP5 education training and outreach package, ACAP has specific targets for the number of researchers in different categories, who benefit from the infrastructural support it provides as well as from the quality and number of researcher exchanges. A significant number of major 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 2014 have included 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.

Of particular note for 2014 was the very strong international interest in the confirmed 40% efficiency result for the “Power Cube” power tower receiver (see Section 6.1 and Highlights in this report). Major news agencies and web portals all over the world have reported on this work. Other high impact work has been published in leading journals and generated citation numbers in the top 1% in their field, as listed in the Highlights section of this report. In general, interest in and citations of AUSIAPV/ACAP’s work have grown strongly through the year.

As a result of work throughout 2014, in January 2015 the Virtual Production Line, the interactive resource for teaching photovoltaics manufacturing, became, publicly available to engineering educators all over the world, in the form of the new PV Factory platform (see Section PP5.2a), through a partnership with PV Lighthouse. Educational interaction with AUSIAPV partner Arizona State University and the Science and Technology Education Leveraging Relevance program, in particular, grew strongly in 2014 (see Sections PP5.2a, PP5.2k, PP5.7).

The final report on the most detailed and intense review of the Australian education curriculum in this field, Renewing the Sustainable Energy Curriculum, was released in 2014 (see Section 5.1e). Other activities directed at improving photovoltaic education programs, already rated as amongst the best in the world, were advanced as a contribution to improving the competitiveness of renewable energy technologies in the Australian context.

PP5.1 ACAP Wide Activities

PP5.1a: Annual ACAP Conference

Lead Partner
UNSW

Oral presenters
Team
Prof. Martin Green (ACAP), Mr Hugo Llorens (US Consul-General, Sydney), Ms Veronica Heard (ARENA), Prof. Yi-Bing Cheng (Monash), Prof. Ken Giggino (UoM), Dr. Gerry Wilson (CSIRO), Prof. Paul Meredith (UQ), Prof. Andrew Blakers (ANU), A/Prof. Renate Egan (UNSW), Dr. Paul Basore (NREL), Prof. Christiana Honsberg (QESST), Dr Malcolm Abbot (PV Lighthouse), Dr Doojin Vak (CSIRO), Dr. Dani Lyons (UQ), Dr Wallace Wong (UoM), Dr Fuzhi Huang (Monash), Prof. Gavin Conibeer (UNSW), Prof. Andres Cuevas (ANU), Dr Greg Wilson (CSIRO), Dr Ardalan Armin (UQ), Dr Jegadesan Subiah (UoM), Dr Mark Keevers (UNSW), Dr Evan Franklin (ANU),

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ANU: Dr Andy Thomson, Dr Niraj Lai, Dr Fiacre Rougieux, Dr Soe Zin, Dr Igor Skryabin,
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Academic Partners
Ohio State University: Dr Tyler J. Grassman, Prof. John A. Carlin, Prof. Steven A. Ringel

Industry Partners
Amberwave: Dr Anthony Lochtefeld, Dr Andrew Gerger
Veeco: Dr Chris Ebert

Funding Support
ARENA/ACAP
Aim

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 one-on-one contacts between students and staff from the different nodes.

The program includes an oral summary of progress and plans for each node by its leader as well as oral and poster presentations of technical progress from staff and student researchers.

Progress

The 2014 conference was held at the Tyree Energy Technologies Building at UNSW on the 11th and 12th of December 2014. The dates and venue were chosen to coordinate with the inaugural Asia-Pacific Solar Research Conference, held from the 8th to the 10th of December 2014 on the same campus (see PP5.1b).

Participants were welcomed by the Director, Prof. Martin Green, who introduced two keynote addresses from the US Consul-General in Sydney, Mr Hugo Llorens and ARENA representative, Ms Veronica Heard. This was followed by a series of summaries of the progress of the various nodes, each director talking about their plans and talks from visitors from three partner organisations: Dr Paul Basore, representing Dr Gregory Wilson, Principle Investigator at Collaborating US Research Institution, NREL; Prof. Christiana Honsberg, Principle Investigator at Collaborating US Research Institution, QESST; and Dr Malcolm Abbot, on behalf of ACAP’s partner organisation, PV Lighthouse (see PP5.2a). Formal presentations were followed by an afternoon poster session, with 36 presentations. The second day comprised two technical presentations from each of the six nodes, and a wrap-up by Professor Green. Tours of the Solar Industrial Research Facility and the Tyree Energy Technologies Building, both on the UNSW main campus, were conducted in the afternoon. The Third ACAP National Steering Committee Meeting was held on the afternoon of the second day of the conference.

Highlights

• Uplifting and supportive address by US Consul-General
• 40% efficiency announcement (Mark Keevers)
• Promoted knowledge sharing and engagement between the nodes through a friendly, collaborative interaction.

Future work

• The next ACAP conference will again be held in coordination with the Asia-Pacific Solar Research Conference, at the St Lucia campus of The University of Queensland, 10 – 11 December 2015.
• The first day will overlap with the final day of the Asia-Pacific Solar Research Conference and the ACAP presentations on that day will form a special session of the more general conference.
PP5.1c: APVI Engagement

Lead Partner
UNSW

Team
Dr Muriel Watt, Dr Richard Corkish
UQ: Paul Meredith
Monash: Prof. Yi-Bing Cheng
ANU: Prof. Andrew Blakers
CSIRO: Dr Scott Watkins

Industry Partners
APVI: Muriel Watt/ Renate Egan,

Funding Support
APVI subscribers and supporters, including ACAP and ARENA

Aim
ACAP will continue as a member/subscriber of the Australian Photovoltaics Institute (APVI) and will increase engagement in its outreach and policy activities.

Progress
The Australian Photovoltaics Institute (APVI) is one of the more effective vehicles for Australian policy development through its focus on data, analysis and collaborative research. ACAP became a founding “Large Organization” member of the Australian Photovoltaics Institute (APVI) and ACAP partners have been active members of APVI throughout 2014.

ACAP collaborators contributed to and participated in a number of outreach events including

• the APVI Storage Workshop, held in Brisbane in March 2014
• the inaugural APVI Asia Pacific Solar Research Conference in Dec 2014 (see PP5.1b)
• the celebration of 40 years of Solar Research at UNSW by Prof. Martin Green and
• the production of the ‘Australia’s Bright Solar Future’ video.

This series of events and activities brought together solar researchers, industry partners and advocates and created media attention for ACAP and ARENA.

Highlights
• Australia’s Bright Solar Future video: https://vimeo.com/118539501 (Figures PP5.1.2, PP5.1.3, PP5.1.4)

PP5.1e: Renewing the Sustainable Energy Curriculum

Lead Partner
UNSW

UNSW Team
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ANU Team
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Academic Partners
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Queensland University of Technology: Dr Wendy Miller
University of South Australia: Prof. Wasim Saman

Funding Support
Australian Government Office for Learning and Teaching
Aim

This project aimed to scope and develop sustainable energy curriculum frameworks for Australian Higher Education Institutions that meet the needs of Australian and International student graduates and employers, both now and into the near future. The curriculum frameworks will enable the assessment of existing curricula, course content and delivery methods in Australian Universities and provide guidance on how they can be made more relevant to students’ and employers’ skills and knowledge needs. They will also provide guidance in the development of new sustainable energy courses and programs in this critical area.

Progress

Two nodes, UNSW and ANU, participated in and supported the major review of the Australian sustainable energy curriculum, led by Murdoch University and funded by the Australian Government Office of Learning and Teaching.

In 2013 the project surveyed graduates, employers and employer representative bodies to determine their views on the skills, knowledge areas and generic attributes required by professionals in this field and how to most effectively deliver them. It surveyed and interviewed key staff from international institutions with highly regarded sustainable energy programs in order to learn from their approaches to curricula and to learn how to promote internationalisation of the content. The survey and interview results were used to develop draft curriculum frameworks for engineering programs and multidisciplinary energy studies/sustainable energy programs. In 2013 and 2014 the project generated a catalogue of sustainable energy skills, knowledge and generic attributes using related reports and existing sustainable energy curricula, programs and courses in order to determine the skills and knowledge required and to fill the gaps already identified.

The final report and other results were delivered to the Office of Learning and Teaching in 2014 and, after review, published online and presented in conference papers. Inter alia, the deliverables supported and informed the undergraduate program stream revisions (see PP5.2) and development of the AQF Level 9 programs at UNSW (see PP5.21).

Highlights

• Provided a greater understanding of the skills, knowledge and generic attributes required by sustainable energy graduates, in order to deliver the most relevant sustainable energy education at tertiary level
• Delivered a consistent and internationally relevant set of curriculum frameworks for training sustainable energy students
• Provided improved engagement between employers and universities regarding skills and knowledge training for the sustainable energy industry

References


PP5.2 UNSW Led Activities

PP5.2a: Virtual Production Environment

See Section 6.5 of this report.

PP5.2b: Sunswift, Sunspint, MiniSprint, Solar Boat Race, Solar Pursuit

Lead Partner
UNSW

ACAP Team
Mr Robert Largent, Dr Richard Corkish

ACAP Students

Academic Partners
TAFE NSW, participating secondary and primary schools

Industry Partners
World Solar Challenge


Funding Support
ARENA, UNSW Faculty of Engineering, UNSW School of Photovoltaic and Renewable Energy Engineering, ARC@UNSW, UNSW School of Computer Science and Engineering
Aim

The Sunswift and Sunsprint and related activities enthuse and engage school and university students in science and engineering and are a major outreach activity for ACAP.

Progress

The UNSW student-led solar race car team, Sunswift, built, tested and raced a new car, eVe®*, in the 2013 World Solar Challenge race from Darwin to Adelaide in October 2013, winning line honours for its class. 2014 was the first year of preparation and fundraising for the 2015 World Solar Challenge to be held 18-25 October 2015.

On the 23rd of July 2014, Sunswift broke the Federale Internationale de l'Automobile (FIA) World Record for fastest electric vehicle over 500 km on a single charge. The record was broken at the Australian Automotive Research Centre near Anglesea, Victoria, where the card achieved an average speed of more than 100 km/h during the attempt, bettering the previous world record of 73 km/h. During a practice test run the car achieved its top speed to date of 132 km/h. The world record received extensive attention around the world, with the news reaching millions via social media, television and online media. Sunswift was featured in some of the world’s most prominent media channels and social media platforms. On Facebook, Twitter and Reddit alone it received over 15 million interactions.

The Sunswift schools and public outreach program were very active in 2014. The team exhibited the car at seven schools, where over 900 students engaged with the team and at the Youth Eco Summit at Newington, where an additional 200 students, approximately, participated. Sunswift gives two separate presentations to students. One is about building the car, life lessons learnt through Sunswift and stories from the World Solar Challenge and World Record events, and is usually presented next to the car. The other involves tailor-made educational content, tying in syllabus requirements with scientific principles applied in the solar car. Content includes the need for sustainable energy solutions, the theory behind photovoltaics and how advanced electric motors are used in the car.

In 2014 the team also participated in a range of public events, which have proven to be a huge success, offering exposure for ACAP and other sponsors and Sunswift to tens of thousands of people in Sydney, Melbourne, Bathurst and the Hunter Valley. These events have allowed team members to inform, educate and inspire the general public about solar energy and engineering education. Furthermore, conversations with a wide variety of demographic groups have given the team a strong understanding of the public’s perception of renewable technology and innovation in Australia. The feedback from members of the public has been overwhelmingly positive, and has been a strong motivator for team members.

Also in 2014, the Sunswift students took up seven opportunities to exhibit at UNSW events on behalf of organisations such as UNSW Faculty of Engineering, the School of Mechanical Engineering and the School of Photovoltaic & Renewable Energy Engineering.

At the end of 2014 the Sunswift team set out to raise $30,000 within 21 days to fund conversion of the car to “street legal" status and mounted a Pozible crowdfunding campaign. Beyond expectation, they reached their target in just 10 days. Donations continued to come in over the remaining weeks until they had a total of $36,420. Social media interaction with our campaign was a huge success with over 1600 shares on Facebook and retweets on Twitter. Media also provided us with support, with articles published by Business Insider, Science Alert, CNET, RE New Economy, Energy Matters and other technical and renewable energy websites.

The SunSprint Solar Challenge is a collection of age appropriate solar races designed for K-12 school students. The event encompasses the SunSprint Model Solar Car Challenge (grades 7-12), MiniSprint (two categories: K-6 and 7-12), Solar Boats (K-6 and 7-12) and the Solar Pursuit Race (using MiniSprint style cars and is open to all, teachers as well). The event is held on the first Saturday in September.

The SunSprint Solar Challenge is a photovoltaics project-based learning event designed for high school students. Solar cars are designed and built according to

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*Figures PP5.2b.1: Sunswift’s cruiser class solar race car, eVe, at Bondi Beach for a public exhibition in October 2014 (image courtesy of Sunswift). Figure PP5.2b.2: eVe on the “road” at the Honda Australia Rider Training track in St Ives (image courtesy of Sunswift). Figure PP5.2b.3: Senator Christine Milne visited to encourage the team at the Honda Australia Rider Training track in St Ives.
specifications provided by the Australian-International Model Solar Challenge (AIMSC), a national organization overseeing and linking all of the state events. These specifications provide design criteria that, when followed, allow students all over Australia to build model solar cars that are uniformly competitive with respect to design, cost and use of materials. The students contribute ideas, inspiration, time and money.

The average vehicle costs over $600 and takes the team over four months to design and build. Many schools throughout NSW have allowed final year design and technology students to adopt SunSprint as their year-long major project. High school physics and science teachers have also used SunSprint as a class-based teaching project, as SunSprint addresses several aspects of the curriculum.

The MiniSprint Model Solar Car Challenge and the Model Solar Boat Challenge are offshoot events allowing primary school students to design and build solar vehicles and then experience the thrill of competition. The MiniSprint competitors start with a kit containing all of the important parts of the solar car that can be constructed in an evening by means of soldering, glueing and taping.

The Model Solar Boat Competition requires much more student design than the MiniSprint category. The boats can be made of any material and can use almost any size or combination of solar cells and motors. The challenge for younger competitors is to get their boat to float right-side up and to move through the water successfully in competition with others.

ACAP also supports the national event of the Australian-International Model Solar Challenge which brings together winning teams from each state to compete for the national championship. In 2014, Strathfield South High School (NSW) won SunSprint and went on to win the AIMSC national championship.

**Highlights**

- FIA land speed world record for an electric vehicle over 500km
- Successful outreach
- Crowdfunding success

**Future work**

- Rebuild the car to be the first road-legal, solar-powered sports car in the world (complying to Australian standards)
- A demonstration drive around Sydney, including iconic locations such as the Opera House and Harbour Bridge, is planned for around April 2015
- An ‘Outreach Tour’ from Sydney to Melbourne and Adelaide
- Drive from Adelaide to Sydney in 2 days during the mid-year break in July
- Compete in the 2015 World Solar Challenge (WSC) to showcase the car whilst competing against teams from across the globe in the Cruiser Class - the WSC’s hallmark race, which pits practical solar powered cars against each other
- A launch event for the road-legal car, bringing together industry sponsors, academia, media, friends and family for networking and interaction
- An event for Sunswift alumni in June and another launch event prior to the World Solar Challenge in October
- Increase engagement with students on campus and to collaborate with other student groups by conducting entertaining, educational events in 2015
- Continue to exhibit eVe at industry trade-shows, UNSW conferences, public spaces, council events and company offices throughout the year.

**PP5.2c: Asia Pacific Solar Institute (APSI)**

**Aims 2015**

APSI aims to offer interdisciplinary training programs in solar photovoltaic energy to Professionals, who are looking to pursue or advance careers in solar energy. The solar industry is poised for unprecedented growth and needs leaders who understand both the most current technical and business topics in the field, in order to transform the solar industry. The programs are designed to help participants meet employers’ demands for sophisticated professionals, who can address science, policy and high-level business issues.

**Actions**

- The Asia Pacific Solar Institute (APSI) was initiated in 2013 by the Asian Photovoltaic Industry Association (APVIA) and founded in close collaboration with the University of New South Wales, National University of Singapore and Arizona State University.
- UNSW has initially offered entry into its Applied Photovoltaics Online Course
Aim
Broaden the availability of solar energy engineering training

Progress
The Asian Photovoltaic Industry Association has brought together three leading PV educational institutions in the Asia Pacific Solar Institute (APSI) to offer remotely accessible training programs in solar photovoltaic energy to professionals looking to pursue or advance careers in solar energy.

The programs, delivered by UNSW, Arizona State University and the National University of Singapore, are designed to help participants meet employers’ demands for sophisticated professionals who can address science, policy and high-level business issues.

Courses available:
• Applied Photovoltaics Online Course (UNSW)
• Solar Energy Engineering & Commercialization Certification Program (ASU)
• Characterisation of PV cells and modules (NUS)

References
APSI: www.apvia.org/about.aspx?gid=0ad2d52b-7029-4b7c-ad69-cbee795f8e96&i=1&id=118
PP5.2f: Lunchtime public seminar series

Lead Partner
UNSW

Team
UNSW: Dr Ziv Hameiri, Prof. Martin Green, Dr Muriel Watt
ANU: A/Prof. Kylie Catchpole, Dr Fiacre Rougieux, Dr Andreas Fell, A/Prof Klaus Weber, Dr Yimao Wan
NREL: Dr Dan Arvizu, Dr Gregory Wilson
Georgia Tech: Prof. Elsa Reichmanis

Students
UNSW: Ned Western, Phil Hamer, Brett Hallam, Pei Hsuan Doris Lu, Rhett Evans, Jie (Jason) Cui

Academic Partners
University of Lyon: Olivier Dupre
University of Texas at Austin: Prof. Brian Korgel
University of Uppsala and IMEC: Dr Bart Vermang
Macquarie University: Prof. John Mathews
Soochow University: Dr Jiansheng Jie
Yunnan University: Dr Zhu Liu
Sungkyunkwan University: Prof Sang Il Seok
Delft University of Technology: Dr Klaus Jäger

Industry Partners
Trina Solar: Dr Pierre Verlinden
Tempress: Dr Jan Marc Lucies
ePho Pty Ltd: Dr Oliver Hartley
Solar Citizens: Ms Claire O’Rourke
APVI: Dr Muriel Watt
Sungevity: Mr Danny Kennedy
Dissigno: Dr Dave Williams,
Megawatt Capital: Mark Schneider
PV Lighthouse: Keith McIntosh
Bloomberg New Energy Finance: Dr Kobad Bhavnagri

Figure PP5.2f.1: Dr Dan E. Arvizu, Director of NREL, presenting at the public lunchtime seminar series at UNSW in April 2014

Aim
• Public dissemination of research progress and results
• Foster collaboration between research institutes
• Allow researchers to be informed about relevant issues outside their narrow research topics

Progress
The UNSW School of Photovoltaic and Renewable Energy Engineering, with ACAP support and involvement, hosts a series of lunchtime seminars by visitors and local researchers. In 2014, a wide range of very interesting presenters from all around the world were involved. Many of the speakers consented to audio/video recording of their sessions and subsequent web access, thus creating a significant and persistent education and outreach resource.

Highlights
• 1 April 2014 - Dan Arvizu – NREL, “Renewable energy in an all-of-the-above world”

References
Public Research Seminars 2014 online. Available at www.engineering.unsw.edu.au/energy-engineering/public-research-seminars

PP5.2i: Program stream revisions

Lead Partner
UNSW

ACAP Team
Dr Santosh Shrestha, Dr Alison Lennon, Assoc. Prof. Alistair Sproul, Dr Anna Bruce, Dr Merlinde Kay, Dr Ivan Ivan Perez-Wurfl, Dr Stephen Bremner, Prof. Darren Bagnall

Funding Support
UNSW

Aim
Improve the quality of the Photovoltaics and Solar Energy Engineering undergraduate and postgraduate coursework programs at UNSW by better coordinating courses, avoiding repetition of topics and improving course content to enhance the quality of the programs.
Course offerings and knowledge progression in the undergraduate and postgraduate programs in the Photovoltaic and Solar Energy and Renewable Energy were reviewed to improve the quality of programs. Recommended study plans for the undergraduate programs were updated to help students choose appropriate courses in the different stages of the program.

Bachelor of Engineering (honours) streams in PV & Solar Energy (SOLAAH3707) and Renewable Energy (SOLABH3707) have been developed and have been approved by the UNSW Engineering Standing Committee. These streams will be offered from Semester 1, 2015. Details of these streams including their program requirements can be accessed through the following links:

SOLAAH3707 Photovoltaic and Solar Energy
SOLABH3707 Renewable Energy

The following four new postgraduate level courses have been developed and have been approved by the UNSW Engineering Standing Committee:

SOLA9101 Advanced Photovoltaics
SOLA9102 Advanced Solar Cell Characterisation
SOLA9103 RE System Modelling and Analysis
SOLA9120 Advanced Photovoltaic Manufacturing

These courses will be available to postgraduate students as well as high-achieving 4th year undergraduate students.

**Highlights**

- Development of 4 postgraduate level courses
- Development of two Bachelor of Engineering (Honours) streams

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**PP5.2k: Deliver ASU’s Advanced PV Manufacturing course at UNSW**

**Lead Partner**
UNSW

**UNSW Team**
Dr Alison Lennon

**Partner**
QESST (USA)

**Academic Partners**
Arizona State University (USA): Adjunct Professor Jeff Cotter

**Funding Support**
UNSW, ASU

**Aim**
To work with Arizona State University (ASU) to transfer the ASU course “Manufacturing Science of Solar Cells” (http://pv.asu.edu/node/77) from ASU to UNSW. In this course, first taught at ASU in 2012, students work in the Virtual Solar Cell Factory, an online solar cell factory simulation, applying manufacturing engineering science techniques to “save the company”. This course will complement the program at UNSW and mesh well with UNSW’s Virtual Production Line (see PP5.2a in this report). The aim for 2014 is to deliver the course for the first time during UNSW’s Summer Session 2014/2105.

**Progress**
Planning and promotion for the Advanced Manufacturing Course occurred throughout 2014 for the first run of the course at UNSW in the 2014/2015 summer semester. Dr Jeff Cotter of ASU worked with Dr Alison Lennon of UNSW to prepare the material. Lecture materials cover graphical models, population models and probabilities, confidence intervals, hypothesis testing, cost accounting, regression models, screening and design of experiment. Participants working in teams of four to manage production lines in the Virtual Solar Inc. fab and at the close of the course most teams had managed to turn around their production so that it was cashflow positive.

The course was run successfully for a total of 55 participants with 27 enrolled students and 2 external attendees, whose attendance was sponsored by ACAP. In addition to the course material, participants gained ‘real-life experience’ working in teams of 4 to manage production lines in the Virtual Solar Inc. fab and at the close of the course most teams had managed to turn around their production so that it was cashflow positive.

**Highlights**

- The use of PV Factory in Virtual Solar Inc. to apply learning in a manufacturing line
- A highlight of the course was the running of board meetings and technology and engineering review meetings so that attendees could gain an appreciation of how PV engineering operates in real commercial environments.

![Promotional brochure for the January 2015 Short Course on Advanced Photovoltaic Manufacturing](image)
PP5.2l: AQF Level 9 specialisation of The Master of Engineering Science

Lead Partner
UNSW

ACAP Team
Dr Santosh Shrestha, A/Prof. Alistair Sproul, Dr Anna Bruce, Prof. Darren Bagnall

Funding Support
UNSW

Aim
Improve program quality and consistency through compliance with Australian Quality Framework (AQF) Level 9 criteria.

Progress
In 2014 the UNSW School of Photovoltaic and Renewable Energy Engineering has obtained approval for two new postgraduate coursework streams (Photovoltaic & Solar Energy SOLACS8338 and Renewable Energy SOLADS8338). These streams will be offered within UNSW Faculty of Engineering Master of Science program and will be compliant with Australian Quality Framework Level 9 program criteria. They will be offered from Semester 1, 2015 and will replace existing Master of Engineering Science and Master of Engineering Science (Extension) programs in PV and Solar Energy.

In order to fulfil the requirements of the degree, students must complete a total of 96 units of credit (UoC) consisting of:

• 72 UoC specialisation courses (18-30 UoC of disciplinary knowledge courses, 18-30 UoC of advanced disciplinary courses and 18 UoC of enquiry based courses including 12 UoC project); and

• 24 UoC elective courses, including at least 6 UoC of Engineering and Technology Management courses.

In addition, two new Graduate Diploma in Engineering Science (Australian Quality Framework Level 8) programs, with specialisations in Photovoltaic & Solar Energy and Renewable Energy, have been created. Students must complete a total of 48 UoC, comprised of Disciplinary Knowledge, Advanced Disciplinary Knowledge, Engineering and Technical Management (ETM) and elective courses.

The description of these streams including course requirements are available in the online handbook:

Highlights

PP5.2m: WCPEC-6

Lead Partner
UNSW

AUSIAPV Team
Prof. Martin Green, Dr Richard Corkish
NREL: Dr David Ginley, Dr Larry Kazmerski, Dr Qi Wang
Stanford University: Prof. John Benner
University of Tokyo: Prof. Y. Okada

Academic Partners
A wide range of ex-AUSIAPV academic partners is also represented on the committees

Progress
The 6th World Conference on Photovoltaic Energy Conversion (WCPEC-6) was held from Sunday 23rd November to Thursday 27th November, 2014, amid the beautiful autumn leaves display at the Kyoto International Conference Center in Kyoto, Japan. In the same building, the Kyoto Protocol to the United Nations Framework Convention on Climate Change was signed on 11 December 1997. WCPEC-6 was a joint conference of the 24th Asia/Pacific PVSEC (PVSEC-24), the 41st IEEE PVSC and the 30th European PVSEC and covered the full scope of photovoltaic science and engineering.

The conference attracted 1256 attendees from 39 countries, with 10% from Australia or the USA, and a total of 1003 presentations. Three ACAP/AUSIAPV member organisations supported the conference with representatives on the organizing committees for this important summit.

One of the official conference highlights was the announcement of the new record 40% spectral-splitting, concentrating photovoltaic sub-module performance. This record resulted the partnership of UNSW, Raygen and NREL, described in section 6.1 of the present report. Further, ACAP Director, Prof. Martin Green, was invited to make a plenary presentation on “High Efficiency Crystalline Silicon Solar Cells: The Path to 25% Efficiency”.

Figure PP5.2m.1: Gavel from the signing of the Kyoto Protocol
ACAP Collaborating Industry Participant, Trina Solar, used the conference to announce its high efficiency (22.9%) mass production processes. Yifeng Chen, of Trina Solar, received a Young Researcher Award for the paper, “Assessment of Photovoltaic Learning Curves and Model Parameterization of Module Efficiency Trend for Industrial Crystalline Silicon and Thin Film Technologies”. A wide range of other reports at the conference confirmed the vibrant, competitive and positive state of photovoltaic research worldwide.

**Highlights**

- UNSW announcement of 40% spectral-splitting concentrating photovoltaic sub-module performance
- Trina Solar reported success with high efficiency mass production processes, where they achieve 22.9% in mass production

**Future work**

- This task has now been completed

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**PP5.2n: WIRE**

**Lead Partner**

UNSW

**ACAP Team**

Dr Richard Corkish, A/Prof. Renate Egan, Prof. Darren Bagnall

**Students**

Ms Naomi Stringer, Ms Roseline Tayeh, Ms Belinda Lam, Ms Wing Ki Kylie Chan, Ms Fangzhao Gao, Ms Kanyawee Keeratimahat, Ms Louise Walsh

**Funding Support**

ACAP, UNSW

**Aim**

The aim of WIRE is to inform, educate and empower current and future female SPREE students about career prospects and issues within the photovoltaic and renewable energy industries.

**Progress**

WIRE was established in 2010 to inform, educate and empower current and future female SPREE students. It provides a fun and casual environment for students across all stages of their degree programs. Members are able to socialise and support each other by means of various activities, such as fortnightly picnics, networking events and excursions, thus enhancing their perspectives on various renewable energy fields. These events foster strong friendship ties between industry associates and the School of Photovoltaic and Renewable Energy Engineering. Such ties provide members with a support system, both at university and once they enter the workforce.

In 2014, we were privileged to have tours of Infigen’s Operation and Control Centre and 1 Bligh Street, Sydney. We also held two networking events: one was held at UNSW, with the theme of Where renewable energy can take you, while the other was a more casual event to celebrate the end of 2014. Industry members from various companies and positions were invited to talk on their experiences at both events, and the nights ended with Q&A sessions.

Also in 2014, WIRE established, with ACAP’s assistance, a new web presence at http://wireunsw.nfshost.com/, complementing its Facebook site, https://www.facebook.com/groups/WIRE.UNSW/.

**Highlights**

- Web site established
PP5.3 ANU Led Activities

Lead Partner
ANU

Team
Prof. Andrew Blakers, A/Prof. Kylie Catchpole, Prof. Andres Cuevas, Dr Evan Franklin, A/Prof. Dan Macdonald, Dr Matt Stocks, A/Prof. Klaus Weber, Tom White, Prof. Ken Baldwin

Academic Partners
NICTA: Optimization Research Group.

Funding Support
ANU

PP5.3a New Course on Smart Grids:
Development of curriculum and course content for a new Masters level course on renewable energy grid integration and smart grid technology.

PP5.3b Energy update:
The ANU Energy Update provides Australian researchers, policymakers, industry and members of the public with the latest state of play in the world’s energy markets.

PP5.3c Solar Oration:
The ANU / ACT Government Solar Oration is an annual public lecture that focuses on the latest development in solar energy technology and policy.

PP5.3d Outreach events:
Public outreach events are aimed at raising the public profile of solar energy and recruiting students.

Progress
PP5.3a New Course on Smart Grids:
A new Masters-level course on renewable energy grid integration and smart grid technology was outlined in 2013 and finalized in 2014, including detailed curriculum development. The course will be an integral part of the ANU Master of Engineering Specialization in Solar Energy Technologies. The advanced topic course is scheduled to start in Semester 1, 2015.

PP5.3b Energy update:
The annual ANU Energy Update brings together Australian researchers, policymakers, industry and members of the public to provide an update on the latest world energy trends. On 9 December 2014, the ANU Energy Change Institute (ECI) was pleased to host Mr Ian Cronshaw from the International Energy Agency (IEA), co-author of the World Energy Outlook (WEO) reports. Speakers at the Energy Update included Nobel Laureate and former US Energy Secretary Professor Steven Chu as well as several panels made up of distinguished expert speakers who presented on the themes of nuclear energy and energy sector investment.

PP5.3c Solar Oration:
The Solar Oration series hosts lectures by prominent individuals in November each year. In 2014, the orator was Greg Bourne, Chair of ARENA, who spoke on the future of renewables from both a technological and commercial perspective. The event was well attended, with an audience of about 150.

PP5.3d Outreach events:
ANU undertook a wide variety of outreach activities in 2014, including seminars, public lectures, media events, VIP visits from which it obtained items in a wide variety of media.

PP5.4 UQ led activities

PP5.4a: Undergraduate course in Nanoscience: Synthesis

Lead Partner
University of Queensland

UQ Team
Prof. Paul Burn and other UQ Academic Staff.

Funding Support
University of Queensland

Aim
The aim of this course run by the UQ School of Chemistry and Molecular Bioscience is to provide students with an introduction to materials as well as to photovoltaic devices including linear and bulk heterojunction devices, and dye sensitised solar cells.
Progress
The course was run as expected in second semester 2014.

Highlights
- 33 students participated in the course.

PP5.5 UoM led activities

Lead Partner
University of Melbourne

University of Melbourne Team
Dr David Jones, Dr Wallace Wong, Prof Ken Ghiggino

CSIRO.Team
Dr Birendra Singh

Funding Support
ACAP, University of Melbourne, CSIRO

Aim
The University of Melbourne Masters Module in Organic Electronics Materials, from materials design, synthesis, characterisation through to device architecture and assembly was approved in 2013.

Future work
It is anticipated that the course will run in 2015 with essentially the same content in the area of photovoltaics.

Progress
The new Masters course module in Organic Electron Materials was delivered for the first time in 2014, to a class of 26 students.

Highlights
- The course enrolment of 26 was the highest for any of the modules on offer and was attended by a number of PhD students to supplement their knowledge in the area.

Future work
- The course will be offered each year from now on.

PP5.6 Monash led activities

Lead Partner
Monash University

Monash University Team
Prof. Yi-Bing Cheng, Prof. Udo Bach, Prof. Leone Spiccia

Partner
TEM Work

Funding Support
Monash

Progress
PP5.6a: John Monash Science School
An experiment on preparation of dye sensitised solar cells involving students from the John Monash Science School was carried out in 2013. The program finished in 2014 due to the change of the school's curriculum.

PP5.6b: DSC-OPV9 Conference
The 9th Aseanian Conference on Dye-sensitized and Organic Solar Cells (DSC-OPV9) was held in Sydney on 8-10 December 2014 as a satellite conference of the 2014 Asia-Pacific Solar Research Conference (see PP5.1b). The DSC-OPV conference has been an annual meeting in the last eight years, hosted in Japan, Korea, China and Taiwan and for the first time this year in Australia. Prof. Yi-Bing Cheng was the Organisation Committee Chair of the DSC-OPV9 conference and Profs. Udo Bach and Leone Spiccia were committee members. The conference attracted a very good number of local and international researchers. A total of 298 people from different countries attended the Solar Research conference, within which 159 people registered for the DCS-OPV9 conference, giving 32 invited presentations, 34 contributed oral presentations and 88 poster presentations. The conference was financially supported by ACAP and was attended by a large number of ACAP researchers.

PP5.6c: Visits by local companies
The Victorian Branch of the Australian Ceramic Society organised a function at Monash University on 30 July 2014. A group of visitors from local companies, including Morgan Technical Ceramics and Ceramic Oxide Fabricators, visited the solar cell labs at the New Horizons Building. Professors Yi-Bing Cheng, Udo Bach and Leone Spiccia were present. The visitors were highly impressed with the cutting-edge research being conducted and showed great interest in the experimental arrangements now set up in the New Horizons Building.
PP5.7 CSIRO led activities

Lead Partner
CSIRO

ACAP Team
Dr Gerry Wilson, Dr Scott Watkins, Dr Doojin Vak, Dr Fiona Scholes

Academic Partners
University of Technology, Sydney (UTS): Prof. Les Kirkup
Science and Technology Education Leveraging Relevance (STELR): Dr Peter Pentland

Funding Support
VICOSC consortium (for initial 50 modules), UTS

Aim
Pilot scale printing trials offer valuable information on process reproducibility and performance in a manufacturing environment. Running these trials to produce educational PV modules also contributes to public outreach/awareness on the benefits of renewable energy in the community. In this context, CSIRO has been involved with some educational organisations with the aim of advocating for solar energy and next generation solar energy technologies.

a) CSIRO and the University of Technology, Sydney (UTS) have co-developed an inquiry oriented laboratory-based practical class using OPV modules. This has been successfully trialled with a large proportion of first year students at UTS and is an important component of their broader Inquiry Oriented Learning effort.

b) The STELR (Science and Technology Education Leveraging Relevance) program is a hands-on, inquiry-based, in-curriculum program designed for Year 9 or Year 10 students, on the theme of global warming and renewable energy. The aim is to have third generation thin film solar cells (and their manufacture) included in the STELR curriculum.

Progress
a) The 50 printed modules supplied previously from the VICOSC consortium to UTS have been fully deployed in two of their undergraduate subjects: Physical aspects of nature for medical, biological and environmental sciences application and Foundations of physics for physical sciences application.

So far, the OPV modules have been used by approximately 900 students and Dr Fiona Scholes gave a virtual presentation in the second semester.

With the success of the program, further discussions are taking place to produce an additional 100 OPV modules. This would be an opportunity to expand the program to outdoor activities and more in-depth characterisation exercises.

Dr Peter Pentland, Program and Education Manager at STELR, visited the Flexible Electronics Laboratory at CSIRO in 2014 and plans to incorporate CSIRO solar cells in the curriculum. At present a new program is being developed for STELR for implementation into new curricula when complete.

Highlights
• The feedback from students participating in the practical classes and lectures at UTS has led to the request for more OPV modules.

Future work
• Discussion are taking place to produce twice as many modules as in the first trial. Given our progress in the field of printing, the performance of the modules is expected to improve, allowing a wider range of applications and longer lifetime.

Reference

Figure PP5.7.1: Students at UTS during practical lab course using OPV modules. Credit: UTS
6. International Activities

Overview

The Australia-US Institute for Advanced Photovoltaics (AUSIAPV) encompasses the local activities of the Australian Centre for Advanced Photovoltaics (ACAP) as well as international collaborations with US-based partner organisations. The AUSIAPV program is directed at the highest level through an International Advisory Committee, with representatives from the key partners in Australia and the US, with engagement fostered through the development of collaborative research programs and the annual AUSIAPV conference.

A highlight of the AUSIAPV collaboration for 2014 was the establishment of a new record of efficiency in excess of 40% in the Power Cube project, which was supported under the AUSIAPV program through the partnership with NREL for both measurement and certification of the record module efficiency. The outcomes of this work are summarized in PP6.1

Specific project activities that leverage the benefits of the AUSIAPV relationship also include key projects in Section 6.2 regarding the development of organic/inorganic solar cells in partnership with UC Berkeley and the Lawrence Berkeley National Labs and in Section 6.3 as part of the Foundation Program to Advance Cell Efficiency II (FPACE II) as well as a collaboration under the US Department of Energy Sunshot Initiative, in which UNSW is involved in a program led by Arizona State University.

The AUSIAPV collaboration described in Section 6.4 is a long-standing one that records the current status of a whole range of photovoltaic technologies in the maintenance and publication of Solar Cell Efficiency Tables as well as new developments in shared teaching program development in PV manufacturing, reported in Section 6.5.

In addition to the specific activities captured in this chapter, many of the reports already presented as detailed research reports also involve collaborations with US partners. These include the silicon tandem cell reported in PP1.3a, where well-established collaborations with Institutes such as NREL, QUEST, Ohio State University, Colorado School of Mines and Arizona State University are complemented by industry partner contributions from key players in the semiconductor foundry industries including Epistar Corp., Veeco and Amberwave.

The Monash ACAP node reports on working closely with the Molecular Foundry and other parts of Lawrence Berkeley National Laboratories, NREL, Stanford University and Georgia Institute of Technology on the development of novel materials for organic and inorganic solar cells.

Further, the education, training and outreach activities reported in PP5 include the ACAP conference and world conferences (WCPEC-6), 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 the US and Australia.
6.1 40% efficient ‘Power Cube’ power tower receiver

Lead Partner
UNSW

UNSW Team
Dr Mark Keevers, Prof. Martin Green

Students
Jonathan Cho Fai Lau, Nathan Tam, Jai Hashim

NREL Team
Dr Keith Emery, Larry Ottoson

Industry Partners
RayGen: Ian Thomas, John Lasich
Spectrolab: Dr Richard King

Funding Support
ARENA, AUSIAPV, NREL, Spectrolab (USA), RayGen (Australia), UNSW

Aim
This project uses spectrum splitting to improve the performance of a concentrator photovoltaics (CPV) receiver. By optimally dividing the solar spectrum between commercially available triple-junction (TJ) and Si solar cells, the overall amount of electricity generated can be increased by 10%. 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.

The aim of the Power Cube project was to design, fabricate and test a proof-of-concept, prototype spectrum splitting CPV module demonstrating an independently confirmed efficiency above 40%. With this achieved in 2014 as described below, the project has been extended to target 42% efficiency CPV module efficiency and 30% efficiency for a non-concentrating, flat-plate implementation of the approach. Independent testing of module performance has been performed by NREL within the AUSIAPV program.

Progress
Prototype design: The prototype design is based on reflective concentration optics, a custom bandpass (spectrum splitting) filter, and two 1cm² high efficiency commercial CPV cells, one silicon and the other a triple-junction III-V cell, each mounted on a concentrator cell assembly (CCA) and a water-cooled heatsink, with an optional reflective secondary optical element (SOE) to improve flux uniformity. The mechanical design, based on optomechanical components, was iterated to achieve a lightweight, robust and fully adjustable structure, enabling optimisation about all relevant linear and rotation axes. The cooling design was iterated to allow control of the CCA temperature, an approximation to the actual cell temperature, rather than simply the heatsink temperature. More design details were provided in the 2013 ACAP Annual Report. A photograph of the actual system under testing at UNSW is shown in Figure 6.1.2.
A schematic of the key prototype elements is shown in Figure 6.1.3a, with receiver details in Figure 6.1.3b. Both silicon and multijunction cells are located near the focal point of a 1m focal-length parabolic mirror. Reflective secondary concentrating mirrors were included in the design to allow better uniformity of light distribution on the cells, but were not used in the results reported since no significant advantage was observed. Irradiance concentration is nominally 365 suns.

Optical details are given in Figure 6.1.4a, showing the spectral photon flux in the standard airmass 1.5 solar spectrum, as well as cell spectral response curves, measured parabolic mirror reflectance and filter transmittance. The triple junction cell used in the prototype 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 antireflection coating applied at UNSW.

A unique feature of the present approach is the energy selective bandpass filter. Since operating under several hundred-times sunlight concentration, a non-absorbing illuminated-surface dielectric interference filter is used. As the multijunction cell is the primary contributor to high efficiency, it is important not to reduce sunlight intensity either on the III-V cells or on the Ge cell at energies below the Si bandgap. Since dielectric filters are more readily designed for near 100% reflection than for 100% transmission, an early design decision was to reflect light onto the multijunction cell, while transmitting the diverted light to the Si cell. Transmission is non-critical, since more light is potentially available for diversion to the Si cell than needed.

The filter was custom-designed by Omega Optical, Inc. Performance for off-angle light is relevant, both to accommodate the angular divergence of the incident beam and to allow fine-tuning of the filter passband, achieved by tilting from the 23° design point. Design specifications were refined in an iterative process based on simulations of specific designs by Omega Optical. The final design consisted of 158 alternating layers of Nb₂O₅ and SiO₂ (20 micron total thickness) deposited onto a UV grade non-absorbing silica substrate, with measured characteristics of filters supplied closely matching design values.
For the first time we report the use of a metal based hole-conducting material as charge transport layer in dye-sensitized solar cells. The special features of this metal complex allow the accessibility of different oxidation states of the metal center at much lower energy expense than the trivial metal complexes and are much more versatile in their application, providing choice in tuning their electronic and optical properties. Highly reversible redox processes at varying scan rates in solution phase electrochemistry make this metal complex an ideal candidate for studying solid state electrical properties and its application as a solid-state hole conducting material.

6.1.4c to the design value. Since the reported efficiencies are based on direct sunlight incident on the mirror, this high reflectance contributes to overall performance.

Figure 6.1.4b shows details of measured filter transmission at various incident angles for a typical filter. Since filters are essentially non-absorbing, these curves demonstrate close to 100% reflectance at all wavelengths for angles near 23°, except at wavelengths where only Si and Ge cells can both respond. The detailed filter response at these wavelengths is non-critical due to many more photons being available in this shared range than the number able to be diverted to the Si cell without upsetting the triple-junction cell current balance.

The other key optical component is the parabolic mirror simulating the heliostat field output. An "enhanced silver" coating (Ag plus a 2-layer Al₂O₃/Ta₂O₅, dielectric overlayer) was applied by Optical Coating Associates (OCA). Measured reflectance is compared in Figure 6.1.4c to the design value. Since the reported efficiencies are based on direct sunlight incident on the mirror, this high reflectance contributes to overall performance.

Highlights

- Prototype Testing: The prototype was initially tested in Sydney with 40.1% ±1.5% efficiency measured in a four-terminal configuration in outdoor testing on the afternoon of 22 October 2014 under an Airmass 2.3 spectrum.
- The system was then transported to the US National Renewable Energy Laboratory (NREL) in Golden, Colorado where it was reassembled and independently tested at NREL’s outdoor test facility, again in a four terminal configuration. An efficiency of 40.4% ±2.8% was certified for measurements made on the morning of 6 November 2014 under pressure-corrected airmass of 2.5 (direct normal irradiance of 883.7 Wm⁻²), referenced to 25°C cell temperature. The multijunction cell efficiency was 35.7%, while that of the Si cell was 4.7%, based on direct sunlight incident on the system aperture (the efficiency of the Si cell was calculated as a much higher value of 43.1% based on the energy actually striking it, since only a small fraction of the incident light is directed to the Si cell). The major contributor to the reported measurement uncertainty relates to uncertainties introduced in referencing the measured data to Concentrator Standard Testing Conditions (Direct normal AM1.5 spectral irradiance consistent with IEC 60904-3, referenced to 1,000 Wm⁻² irradiance and a cell temperature of 25°C).
- This represents the first certified conversion of sunlight to electricity with efficiency above 40% by any approach.

Future work

- Further refinement of the prototype design is expected to allow an efficiency of 42% to be demonstrated, increasing the margin over alternative CPV approaches.
- Applying a similar approach to a standard non-concentrating, flat-plate module is expected to significantly improve the performance of these modules with record 30% efficiency targeted for 2015.

6.2 Metal Complexes as Solid-state Hole Conducting Materials

Lead Partner
UNSW

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Funding Support
ARENA, AUSIAPV, ASU, UNSW, US Department of Energy

Progress

Solid-state dye-sensitized solar cells (SS-DSCs) are attracting huge interest in the scientific community due to their compatibility with robust and inexpensive manufacturing technologies like inkjet or roll-to-roll thin film printing. Classical SS-DSCs are based on a working electrode and an evaporated gold or silver counter electrode. The working electrode consists of a conducting glass, which acts as a substrate for mesoporous titania films to be printed. These printed titania films are then dipped into a dye solution to obtain a homogeneous monolayer of dye and a thin layer (4-6 micron thick) of hole conducting material (Spiro-OMeTAD) is then spin-coated onto the dye-coated substrates. A very recent revolution came in this field when a thin perovskite absorber replaced the dye component of the DSCs. However, all the solid-state devices use a hole-conducting layer for the efficient transport of charge across the working electrode and counter electrode.

For the first time we report the use of a metal based hole-conducting material as charge transport layer in dye-sensitized solar cells. The special features of this metal complex allow the accessibility of different oxidation states of the metal center at much lower energy expense than the trivial metal complexes and are much more versatile in their application, providing choice in tuning their electronic and optical properties. Highly reversible redox processes at varying scan rates in solution phase electrochemistry make this metal complex an ideal candidate for studying solid state electrical properties and its application as a solid-state hole conducting material.

Figure 6.2.1 shows the current density (J)- potential (V) curves for the best performing devices based on solid-state hole conducting material based solar cells, measured under simulated air mass (AM) and 1.5 G, 1000 Wm⁻². Devices based on metal-based hole conducting material show efficient charge transport and an impressive Jₚ, which is reflected by lower redox potential of the material. However, an impressive efficiency of 1.2% is achieved with moderate Vₚ, a choice in tuning their electronic and optical properties. Highly reversible redox processes at varying scan rates in solution phase electrochemistry make this metal complex an ideal candidate for studying solid state electrical properties and its application as a solid-state hole conducting material.

![Figure 6.2.1: J-V curves showing the DSCs performance for the best devices made using solid-state hole conducting material](image)
6.3 Carrier selective contacts for boosting Si solar cell efficiency

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Funding Supporters:
ARENA, Department of Energy (USA)

UNSW has been partnering with a consortium of top US and international universities on next-generation silicon solar cells with targeted efficiencies of 29%, as part of the US Department of Energy SunShot Initiative (Foundational Program to Advance Cell Efficiency II (FPACE II)). This US$3.5 million grant is led by Arizona State University (ASU) with UNSW is listed as a collaborator, along with MIT, Caltech and the Swiss Federal Institute of Technology.

UNSW’s involvement is being coordinated through the Australia-US Institute for Advanced Photovoltaics (AUSIAP).

The aim of the program is to develop a novel device structure for ultra-thin crystalline silicon (c-Si) solar cells based on “carrier selective contacts,” (see Fig. 6.3.1a), with targeted efficiencies of 29%. UNSW contributes device modelling (e.g., using Sentaurus TCAD), materials deposition (e.g., via atomic layer deposition), characterisation and integration of selected wide band gap materials (e.g., GaP) as carrier selective contacts for the novel Si cell structure as part of a collaborative effort.

The motivation of using carrier selective contacts (CSCs) via deposited semiconductor layers that can induce strong inversion in the underlying silicon, (see Fig. 6.3.1b), while allowing...
efficient carrier transport, is to avoid non-idealities associated with diffused junctions. The very low surface recombination velocities that can be achieved using these hetero-structures allow much higher open circuit voltages, especially on ultra thin silicon with appropriate light trapping schemes.

One of UNSW’s tasks is to develop a predictive model for CSC solar cells. This is being achieved using Sentaurus TCAD (see Fig. 6.3.2a for the methodology). The general concept of the cell structure for the model is shown in Fig. 6.3.2b and it incorporates the latest Auger and radiative recombination parameters for silicon, (Limpert 2014).

A working model for a thin silicon device with a front GaP/Si electron CSC has been produced to allow the influence of design parameters to be determined. The effect of GaP-i/Si interface recombination velocities (IRV) on cell efficiency has been investigated and determined, with some key results displayed in Fig. 6.3.3. $V_{oc}$ and FF as a function of interface recombination velocity (IRV) show that while it is clear the IRV should be kept below 100 cm/s to maintain close to ideal $V_{oc}$ and FF, record performance is achievable even for a relatively high IRV of 1000 cm/s, due to a lack of minority carriers in the GaP and at the GaP/Si interface.

Candidate CSC materials ZnS and SiC have been trialled with results for ZnS on Si, deposited by sputtering summarised in Figure 6.3.4. The results show that a deposition temperature of 500°C gives the best outcome, firstly in terms of crystallinity of the ZnS layer as indicated by the X-ray diffraction results in a) and b) for 500°C and 700°C respectively. This also delivers the best outcome in terms of interface recombination, as shown by photoluminescence images in c) and d) for 500°C and 700°C deposition temperature, respectively. Work is ongoing to develop models for these materials and to assess their suitability for use in CSC devices.

References

6.4 Solar Cell Performance Documentation

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NREL Team
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Funding Support
AUSIAPV, UNSW, NREL

A long-standing research collaboration between UNSW and NREL, now being conducted as an AUSIAPV collaborative project, involves the reliable documentation of the current status of the whole range of photovoltaic technologies worldwide. This takes the form of 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, this not only provides an authoritative summary of the current state of the art but also ensures 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.

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. Figure 6.4.1 shows spectral response information published for such cells in the most recent version of these tables.

The Tables are widely used by the photovoltaic research community. According to the ISI Web of Knowledge, the four versions prepared in 2013 and 2014 have all been amongst the most cited papers published since 2010 in the engineering discipline worldwide, already holding first, third and fifth positions.

6.5 PV Factory

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Funding Support
ACAP, UNSW, PV Lighthouse

Aim

Many students come to UNSW wanting to learn how solar cells are manufactured. However silicon solar cell manufacturing involves a diverse range of processing, ranging from chemical etching, plasma physics, and metal alloying to screen printing. Understanding all of these processes, and how they interact in a production line, is challenging, to say the least, especially when it is not possible to take students to see a cell production line. Combined with the need for students to learn how to optimize a process with so many interrelated steps, a major educational challenge arises. To address this challenge, in 2001 - 2002 Professor Stuart Wenham and Dr Anna Bruce from the School of Photovoltaic and Renewable Energy Engineering at UNSW developed a simulation of the production of screen-printed silicon solar cells, called the Virtual Production Line (VPL).

The VPL simulation was used for 11 years to teach undergraduate and postgraduate engineering students at UNSW how solar cells are manufactured as part of the Photovoltaic Technology and Manufacturing course (SOLA3020, SOLA9060). Students would access the simulation from UNSW computers, or download it to their laptops, and participate in a number of tutorials that teach them how to optimise individual steps. However, since the simulation was first developed there have been many changes in the PV manufacturing process and, although the teaching staff at UNSW tried to maintain the currency of the simulation over the years, major changes in both the simulation and how it is accessed/used by students became desirable.

Cloud computing has provided a new connectivity that enables people to interact on-line and engage in new activities where learning can occur as part of a game. This trend is often referred to as “gamification”. In 2014, ACAP supported a project to modernise and re-deploy VPL as a cloud-based simulation, now known as the PV Factory.

The PV Factory project involved the engagement of the Australian company PV Lighthouse to develop a cloud-based platform in which the UNSW VPL simulation could operate. PV Lighthouse hosts a website to assist PV researchers by providing simulation programs and experimental data. The website now receives 10,000 visits per month and is widely used.
used throughout the PV industry. The software is hosted in the cloud, making it fast, readily accessible, and easy to expand. With a suite of state-of-the-art algorithms for solar cell operation, an established framework for delivering cloud software, and a large user base, PV Lighthouse was ideally placed to take the UNSW simulation to the next level.

**Progress**

During 2014, UNSW researchers worked closely with PV Lighthouse to the PV Factory, which now hosts the UNSW simulation of the manufacture of screen-printed solar cells. During the second half of the year, PV Factory underwent beta testing as part of running the UNSW PV Technology and Manufacturing course. New tutorials, which used PV Factory, were developed. During the 2014 course, the 52 students and tutors fabricated 571,145 virtual screen-printed solar cells.

Hosting of the simulation in the cloud has made it simpler for students to use the simulation, with the software being hosted on the cloud there is no limitation regarding downloads nor version control. An additional benefit for course co-ordination and teaching the availability of statistics on student use of the simulation for course planning and development. For example, although an assignment requiring the use of PV Factory was released before the mid-semester break, data showed that students really only got engaged in the project in the two weeks preceding submission date. Furthermore, by relating the number of solar cells produced to final average cell efficiency it is possible to gauge the amount of work required to achieve a specified solar cell performance. A paper describing PV Factory and the lessons from the beta testing was submitted to the IEEE PVSC, to be held in June 2015.

PV Factory is now publicly available and can be accessed from: https://factory.pvlighthouse.com.au.

PV Factory is being used by people from all corners of the globe with the number of new users increasing steadily. As was reported in the first Annual Report, the Virtual Production Line supported, in March 2014, delivery of a course, EEE498 Fabrication Science of Solar Cells, at Arizona State University. 24 students took the course, which is similar to the one that is run as part of the Photovoltaic and Solar Energy program at UNSW. In March 2015 PV Factory will be used there to teach the course to 72 students. A number of other institutions are also reviewing the resource with a view to adopting it for their educational programs. The project was completed 16 Dec 2014.

**Highlights**

- Successful completion of the beta testing performed during the teaching of the UNSW PV Technology and Manufacturing course in 2014.

**Future work**

PV Lighthouse will continue to evolve the PV Factory application. At UNSW, student projects will be used to enhance the algorithms in the UNSW simulation so that it can remain technologically current and relevant.
7. Financial Summary

In December 2012, a grant of $33.1 million from the Australian Government through ARENA was announced to support the 8-year program of the Australia-US Institute for Advanced Photovoltaics (AUSIAPV). This support leveraged an additional $55.4 million cash and in-kind commitment from AUSIAPV participants taking the total value of the project to $88.5 million.

AUSIAPV 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. This was somewhat later than originally expected due to the complexity of the multiple-party legal negotiations involved.

The Milestone 3 payment from ARENA to UNSW was paid in two parts, on 2 July 2014 and 4 September 2014. Disbursements were made to each node following confirmation of institutional cash contributions. Despite the slower than anticipated start in 2013, good progress was made in 2014 towards regaining the original project timelines, both in terms of technical progress and budgetary expenditure. All technical milestones for 2014 were achieved. The breakdown by institution of the $10.4 million total cash and in-kind budget for 2014 is shown in Figure 7.1(a). The total cash and in-kind expenditure as at 31 December 2013 was $12.5 million as shown in Figure 7.1(b), with additional inevitable cash commitments carried into 2015.

By carrying over some of the originally planned 2014 expenditure into 2015, it is anticipated that the established favourable technical trajectory can be retained while bringing the project onto its original budgetary timeline by 2016.

Figure 7.1: (a) Total AUSIAPV/ACAP cash and in-kind budget for 2014 broken down by institution; (b) Actual cash and in-kind expenditure breakdown for 2014.
8. Publications

8.1 Books


8.2 Book Chapters


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8.7 Report


8.8 Research Training Tool
