



Australian Centre for Advanced Photovoltaics Australia-US Institute for Advanced Photovoltaics Annual Report 2013

Never Stand Still

Faculty of Engineering

School of Photovoltaic and Renewable Energy Engineering



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AUSIAPV
ACAP
2013
ANNUAL
REPORT

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1. DIRECTOR'S REPORT

Photovoltaics involves the direct conversion of light, normally sunlight, into electricity when falling 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 under active investigation.

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

AUSIAPV aims to significantly accelerate photovoltaic development beyond that achievable by Australia or the US individually. This goal is achievable through leveraging the development of "over the horizon" photovoltaic technology, 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 the goal of consolidating 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 earlier signing of a Head Agreement between University of New South Wales (UNSW) and ARENA. During 2013, related Collaboration Agreements were signed between UNSW and the other ACAP nodes,

Australian National University (ANU), University of Melbourne (UoM), Monash University, University of Queensland (UQ) and CSIRO (Materials Science and Engineering, Melbourne) and additionally with ACAP industrial partners, Suntech Research and Development, Australia (SRDA), Trina Solar Co. Ltd., Bluescope Steel and BT Imaging. Letters confirming participation under the terms of the Head Agreement have been received from our major international partners, the NSF-DOE Engineering Research Center for Quantum Energy and Sustainable Solar Technologies (QESST) based at Arizona State University and the US National Renewable Energy Laboratory (NREL), as well as 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.

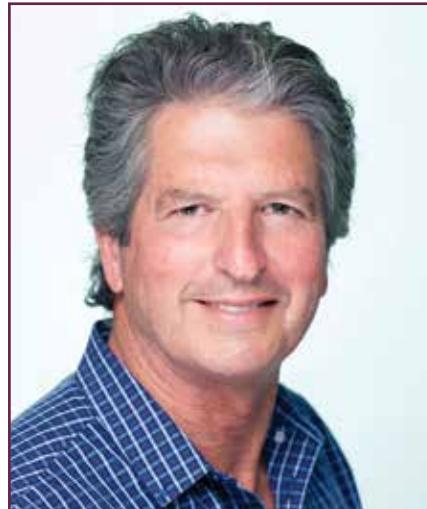
This report covers the period from 1 February to 31 December, 2013. As well as the administrative progress noted above, both AUSIAPV and ACAP have moved very quickly to establish a high profile within the international research community, with this profile consolidated by the high quality of the research being undertaken. At the first major international conference where ACAP was represented (39th IEEE Photovoltaic Specialists Conference, Tampa, June 2013), UNSW students Brett Hallam and Jonathon Dore each received the award for the best student paper in their separate Topic Areas 4 ("Silicon Feedstock") and 5 ("Thin Film Silicon Based Solar Cells"). Later in the year, I had the honour of delivering an opening plenary talk at the major international conference of the year (28th European PVSEC, Paris, October 2013) on behalf of UNSW and its US-collaborators, NREL and Ohio State University, the first international presentation under the AUSIAPV banner. This paper was commended by the scientific committee as one of the most outstanding papers of the conference (Photon International, December 2013).

More is in the pipeline. During 2013, with ACAP support, ANU developed a world-record rear-junction silicon solar cell with a confirmed 24.4% energy conversion efficiency. ACAP industrial partner, Trina Solar, recently announced the company's intention to commercialise this new high-performance technology. These and several of the other highlights over the year are documented in the pages immediately following my report.

Other achievements outlined elsewhere in this Annual Report contributed to making 2013 an extremely successful year for the Institute. The Institute's commencement coincides with the return of the photovoltaic industry to profitability after several years of frugality, the result of an earlier overly aggressive industry-wide expansion of manufacturing capacity. This return to profitability has restored vitality to the industry and to its relentless search for improved technology, which ACAP is uniquely positioned to supply.

I would like to thank ARENA for their ongoing financial support and also for the 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 results reported in the following pages.

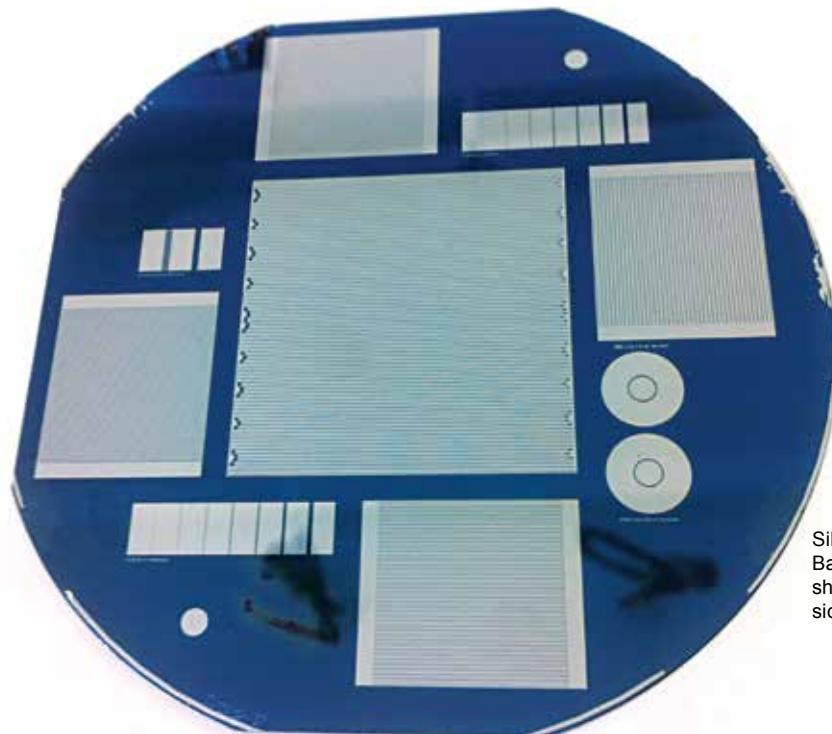
Finally, I am pleased to be able to report that AUSIAPV/ACAP has taken its first major step in attaining its significant long-term objectives by achieving all first year milestones, some by a very comfortable margin, on time and within budget. We look forward to similar results in 2014 and subsequent years.

A handwritten signature in black ink, appearing to read "M.A. Green".

2. HIGHLIGHTS

ANU 24.4% REAR JUNCTION CELL

Interdigitated back contact (IBC) silicon solar cells are under development at the Australian National University (ANU) with collaboration and support from PV Lighthouse, ACAP, Trina Solar and the Solar Energy Research Institute of Singapore. In IBC solar cells, both the positive and negative metal contacts are placed upon the rear surface rather than one polarity on each surface. This allows the surface facing the sun to be uniformly black, without any of the metal electrodes present on most solar cells. Recently, the efficiency of one of the IBC cells was measured at the Calibration Laboratory at the Fraunhofer Institute for Solar Energy Systems. The measured efficiency of 24.4% became the highest independently confirmed efficiency for a conventional IBC cell. Work continues with support from ARENA to increase laboratory IBC cell efficiency into the 25-26% efficiency range. A photograph of the rear surface of the IBC cell is shown below. It shows the positive and negative metallisation of five square solar cells and a range of characterisation features. The reverse side of the wafer (the sunward-facing side in normal operation) has very low reflection and is thus very dark.



Silicon wafer with Interdigitated Back Contact silicon solar cells shown from the rear (unilluminated) side.



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

BEST PAPER AWARDS

Two ACAP students, Brett Hallam and Jonathon Dore, supported by the UNSW node, were awarded "Best Student Presentation" for Topic Areas 4 ("Silicon Feedstock") and 5 ("Thin Film Silicon Based Solar Cells and Panels") respectively, at the 39th IEEE Photovoltaics Specialists Conference in Tampa, Florida in June 2013. A third UNSW student, Ibraheem Al Mansouri was selected as a finalist in Area 3 ("Single Junction III-V Cells") but was unable to present due to visa delays. The photograph above shows Jonathon and Brett in the centre, with Brett on the left. Later in the year at the 28th European

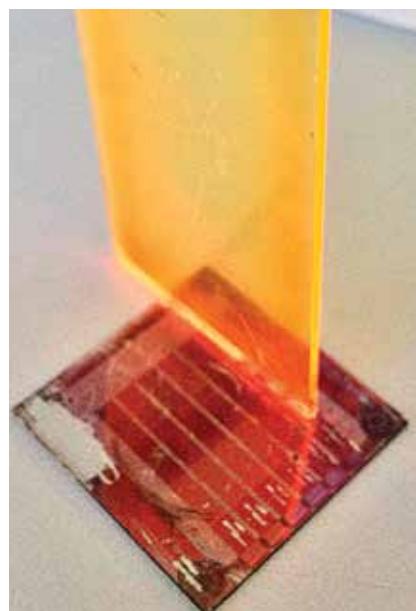
PVSEC, Prof. Green's opening plenary presentation was commended by the scientific committee as one of the most outstanding papers of the conference. This was a joint paper with NREL and Ohio State University, one of the first to be presented under the AUSIAPV logo. In November, Jonathon Dore followed up on his earlier success by also becoming the winner of the Australian Institute of Physics Postgraduate Presentation for 2013, for his talk on Laser Crystallised Silicon Films for Second Generation Solar Cells, also ACAP supported research.

RAISING THE BAR IN SOLAR CONCENTRATORS

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

A limitation of the current materials used for LSCs is that their luminescence, declines at the high concentrations necessary for efficient light absorption, due to aggregation of the dyes. Luminescence reabsorption restricts the light concentration factor that can be achieved. In a project being undertaken at the University of Melbourne ACAP node by PhD student, James Banal, supervised by Dr Wallace Wong and Prof. Ken Ghiggino, a number of luminescent dyes, that do not exhibit the aggregation and

reabsorption deficiencies of existing materials, have been synthesised and investigated. In testing, these materials have been shown to have, in unoptimised devices, optical quantum efficiencies among the very highest that have been reported for state-of-the-art LSCs. Currently research is being undertaken to explore the integration of these LSCs with high efficiency 'sliver solar cells' developed by ACAP partner collaborators at ANU. These present a much better match to the concentrator geometry than the solar cell shown in the photograph.



Luminescent Solar Concentrators (LSCs) with light emitted from dyes embedded in the planar sheet emitted at its edges (for use with a much narrower solar cell than the one shown). (Image courtesy of IEEE).

RESEARCHERS HONOURED

Announced in London just prior to the Annual Report going to press, Professor Stuart Wenham has been awarded the prestigious Institution of Engineering and Technology's (IET) AF Harvey Engineering Research Prize. The award recognises the discovery by Professor Wenham and his team of a mechanism to control the charge state of hydrogen atoms to correct deficiencies in silicon, the most costly part of a solar cell (see further details in Section PP1.1 of this report). "Our patented advanced hydrogenation technology will allow lower-quality silicon to outperform solar cells made from better quality materials, producing higher efficiencies at significantly lower cost," said Professor Wenham. "Our UNSW team is now working with the world's biggest solar manufacturers through collaborative agreements with NewSouth Innovations to commercialise this low-cost technology," said Professor Wenham, who acknowledged ARENA's funding support for the project. Professor Wenham will deliver a special IET lecture in London on 21 May 2014 to commemorate his award.

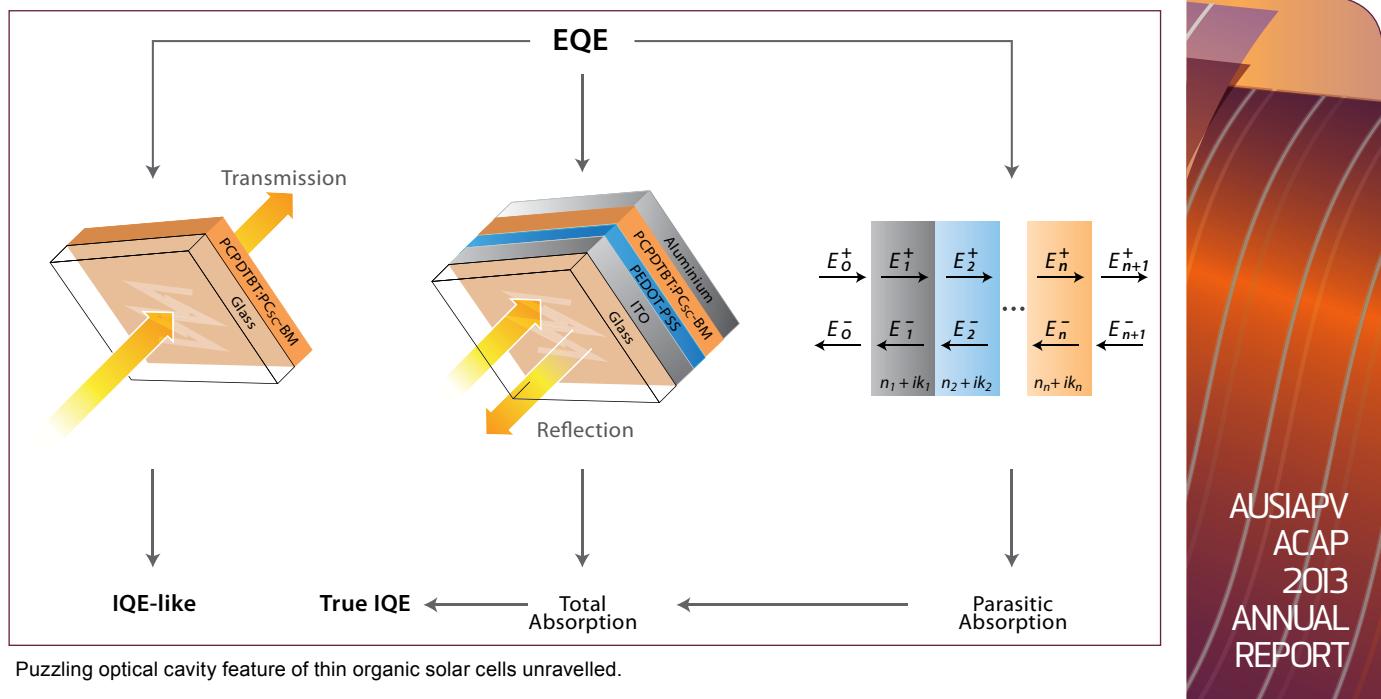
In July 2013, ACAP Director, Professor Martin Green, was one of 44 new fellows, from a pool of 700 nominations, elected to the Royal Society, the United Kingdom's venerable National Academy of Science. The Royal Society Fellowship is comprised of some 1,450 of the world's most distinguished scientists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

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



Professor Martin Green signing the Charter Book on election to the Royal Society, London in July 2013.

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



Puzzling optical cavity feature of thin organic solar cells unravelled.

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THIN ORGANIC SOLAR CELLS: HOT EXCITONS OR OPTICAL CAVITY EFFECTS?

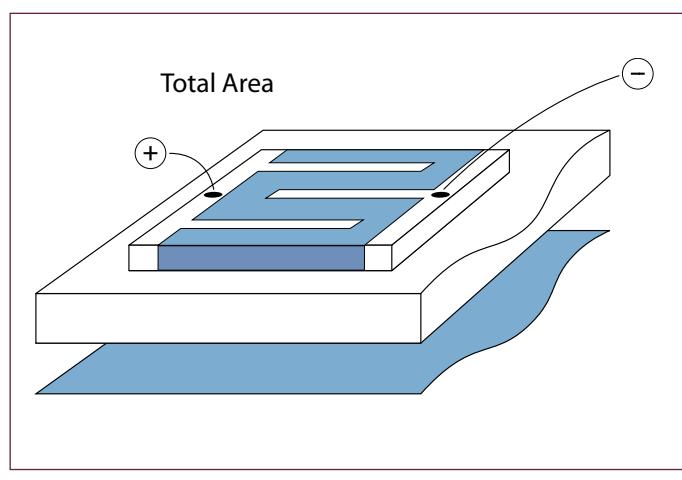
Researchers Ardalan Armin, Paul Burn and Paul Meredith from the University of Queensland ACAP node have deciphered a previously puzzling feature of thin-film organic solar cell operation. Since these cells are so thin, the internal optical field distribution is significantly affected by cavity effects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

IQE was recently used to justify an apparent observation of "hot excitons" in a solution processed organic solar cell (Grancini, G. et al., Nat. Mater. 12, 29, 2013).

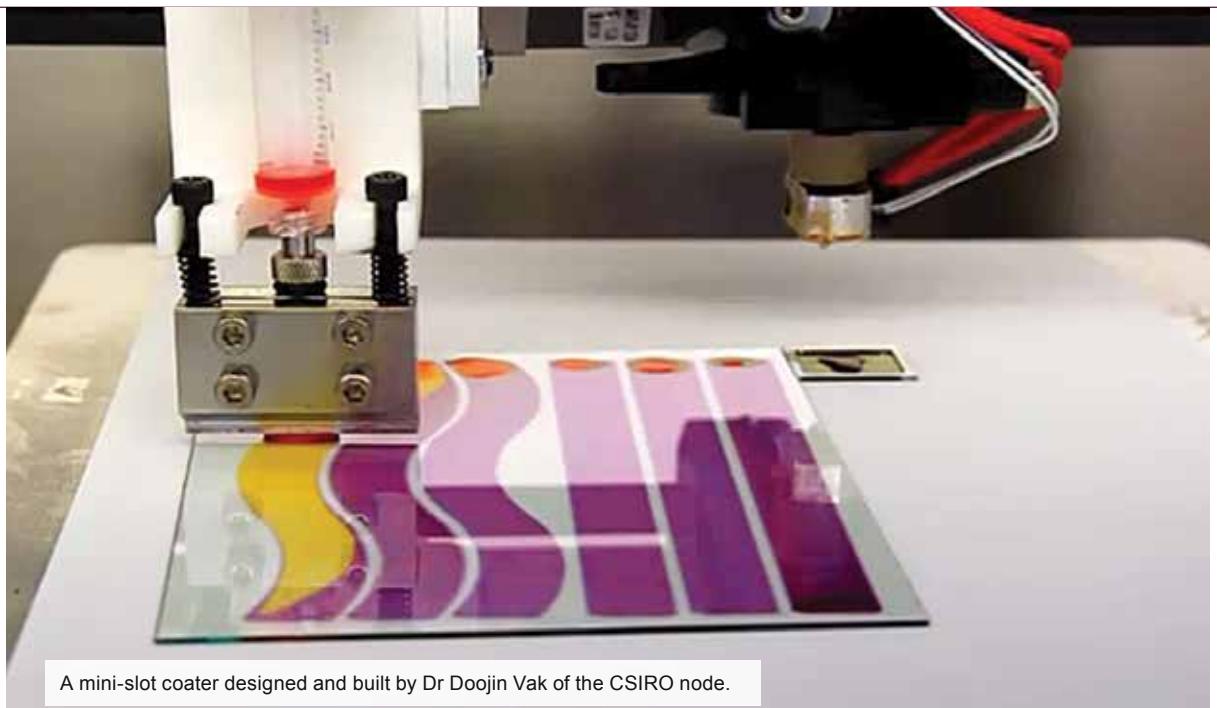
To accurately calculate the IQE from the measured EQE one must determine the number of photons absorbed by the junction as a function of wavelength. This in turn requires measurements and simulations of the junction and the whole device as a low finesse multi-layer structure. In this work these optical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

AUSIAPV "HOT PAPERS"

Two papers, which were prepared under the AUSIAPV banner during 2013, have been identified by the ISI Web of Knowledge as "hot papers", based on their impact, as calculated from rates of citation by other researchers. These papers were co-ordinated by Martin Green at the UNSW ACAP node and Keith Emery at AUSIAPV partner NREL. The papers, "Solar Cell Efficiency Tables", published by the Wiley Journal, Progress in Photovoltaics, document progress in independently confirmed solar cell conversion efficiencies, measured at a group of designated international test centres. Not only are key features of enhanced performance cells described but guidelines are also established for standardised measurement procedures, such as for defining cell area. Of the 80 papers published



Setting standards: defining total cell area (larger blue area)



A mini-slot coater designed and built by Dr Doojin Vak of the CSIRO node.

worldwide in 2013 and designated as “hot papers” in the engineering discipline, both AUSIAPV papers were ranked near the top, with one earning the distinction of being the most cited in this discipline.

A third paper resulting from collaboration between the group of Professors Udo Bach and Leone Spiccia at the ACAP Monash node and Jeff Long and Chris Chang at the University of California, Berkeley, on dye-sensitised cells based on cobalt mediators, was also selected as the editor’s choice for hot paper designation (M. K. Kashif, M. Nippe, C. M.

Forsyth, C. J. Chang, J. R. Long, L. Spiccia and U. Bach, *Angew Chem. Int. Ed.*, 52, 5527, 2013).

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

FROM BENCHTOP TO ROOFTOP: SCALING UP

The primary aim of a project at the CSIRO, Melbourne ACAP node is to develop the tools and processes required to translate small, laboratory-based devices to large area, mass-produced modules. Small scale, laboratory devices are currently produced using spin-coating techniques. This is a robust and reproducible method for depositing very thin, uniform layers, whereby the film thickness and morphology are controlled by adjusting the solution concentration, the boiling point of the solvent and the spin speed. While this is an excellent way to optimize the device architecture, the method is unfortunately not scalable. A further complication arises in that spray deposition and roll-to-roll printing consume a significant amount of ink (active material). The aim of the present project is to develop techniques that closely emulate manufacturing processes (spray, print) on a small, but scalable, format. In the course of this project, a member of the research staff, Dr Doojin Vak, has designed and built a mini-slot die coater (see figure above). The modular construction can incorporate a heating stage and air drier and requires microlitres of ink only. Different heads can be fitted to produce different coating widths. With this

set-up a wide range of different printing configurations can be tested. Preliminary solar cell power conversion efficiencies of >10% have been achieved with a variety of materials. The team has also further optimised the dual-feed spray deposition equipment to enable rapid assay of blend ratio and thickness in evaluating materials for solution processed solar cells.



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3. ORGANISATIONAL STRUCTURE AND RESEARCH OVERVIEW

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 Suntech R&D Australia, Trina Solar, 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 will target 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 the ACAP National Steering Committee, 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 organic solar cells (OPV), organic/inorganic hybrid cells, "earth abundant" thin-film materials, including Si and CZTS, as well as more futuristic "third generation" approaches, with the

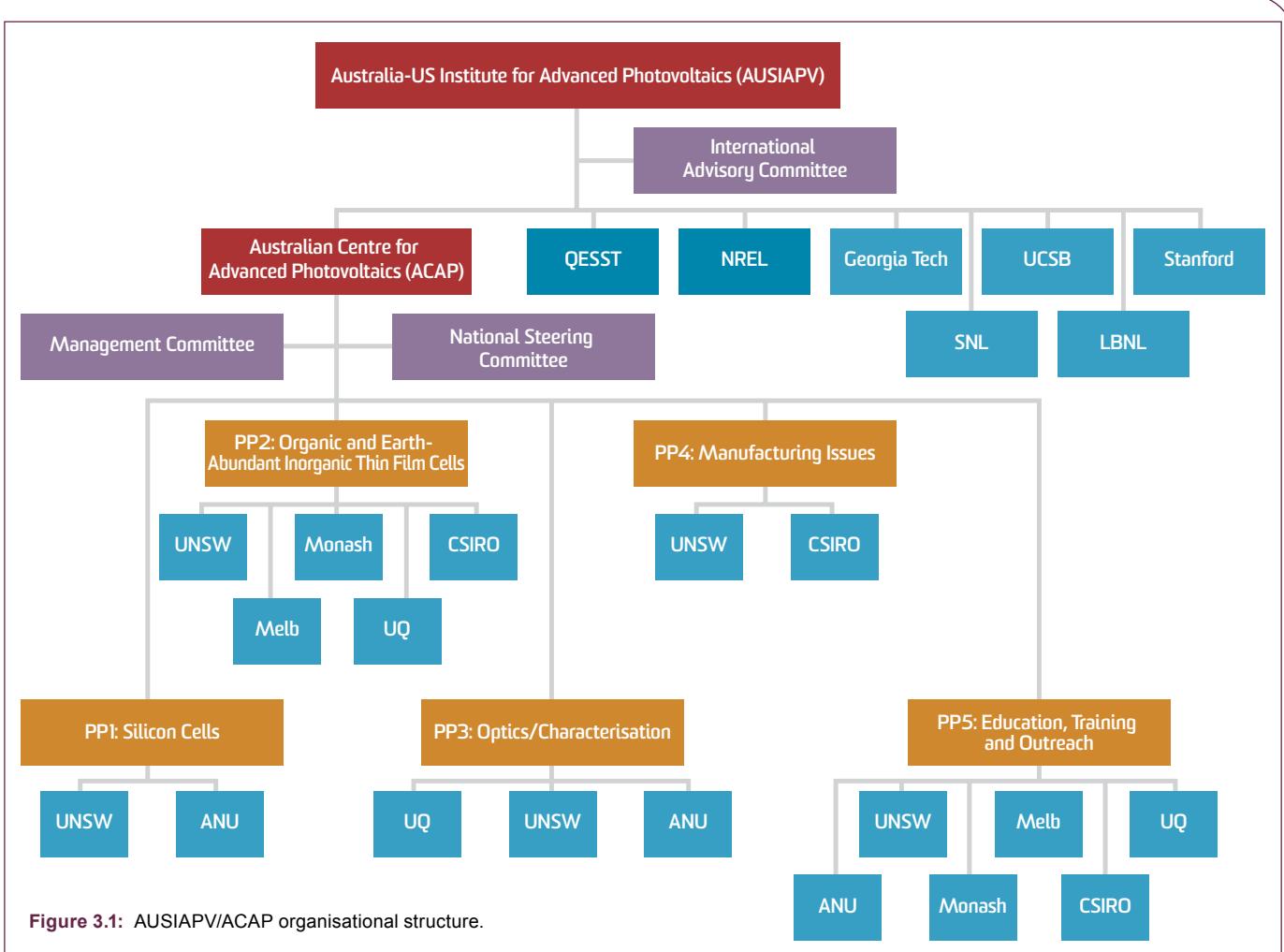


Figure 3.1: AUSIAPV/ACAP organisational structure.

overall goal of demonstrating efficiency above 15% during the program for cells of above 1cm² 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 exceed 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.

4. AFFILIATED STAFF AND STUDENTS

University of New South Wales

Academic Staff and Senior Researchers

Green, Martin (Node Leader and Centre Director)

Corkish, Richard (ACAP Chief Operating Officer)

Bagnall, Darren (since Dec 13)

Barnett, Allen

Bremner, Stephen

Campbell, Patrick

Conibeer, Gavin

Edwards, Matthew

Ho-Baillie, Anita

Huang, Jialiang

Huang, Shujuan

Keevers, Mark

König, Dirk

Lennon, Alison

Mehrvarz, Hamid

Mitchell, Emily

Perez-Wurfl, Ivan

Shrestha, Santosh

Sproul, Alistair

Teal, Anthony

Trupke, Thorsten

Uddin, Ashraf

Varlamov, Sergey

Watt, Muriel

Wen, Xiaoming

Wenham, Stuart

ECR and Postdoctoral Fellows

Cui, Hongtao

Edwards, Matthew

Hao, Xiaojing

Ishwara, Thilini

Johnson, Craig

Kampwerth, Henner

Karuturi, Siva

Lee, Sammy

Liu, Fangyang

Mai, Ly

Mitchell, Bernhard (since Jul 13)

Ouyang, Zi

Patterson, Robert

Pillai, Supriya

Puthen-Veettil, Binesh

Rao, Jing

Tayebjee, Murad

Wang, Xi

Yang, Yang

PhD Students

Ahn, Chaho

Al Masouri, Ibraheem

Allen, Vincent

An, Xin

Augarten, Yael (until Jun 13)

Borojevic, Nino

Cao, Wenkai

Chan, Catherine

Chan, Kah

Chen, Ran

Chung, Simon

Conrad, Brianna

Cui, Jie

Di, Dawei (until Jun 13)

Diaz, Martin

Disney, Claire

Dore, Jonathon

Evans, Rhett (since Jul 13)

Feng, Yu (until Jun 13)

Guangqi, Xu

Gupta, Neeti

Hallam, Brett

Han, Jianshu

Hsiao, Pei-Chieh

Hsieh, Andy

Jia, Xuguang

Jiang, Yajie

Juhl, Mattias

Jung, Do

Jung, Miga

Kim, Kyung

Lan, Dongchen

Li, Dun



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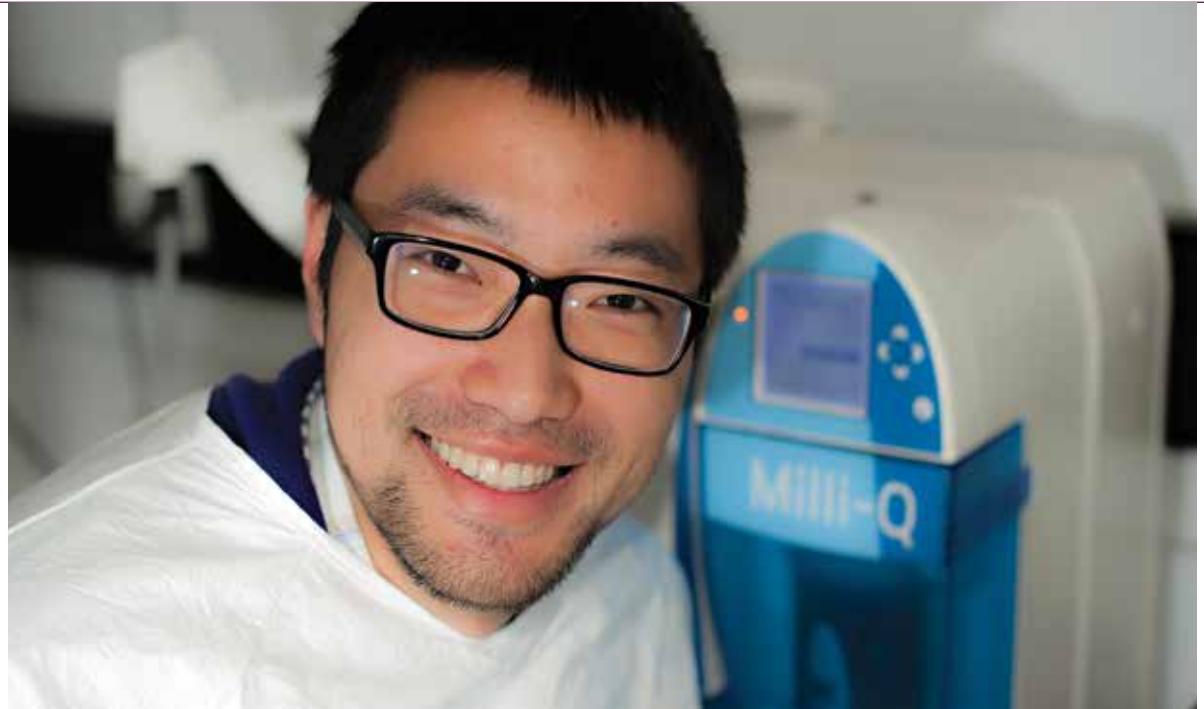
		<i>Masters students</i>
Li, Hongzhao	Teng, Peinan	
Li, Hua (until Jun 13)	To, Alexander	Ahn, Chaho
Li, Wei (until Jun 13)	Wang, Kai	Fogarty, Mark
Li, Yang	Wang, Li	Griffin, Mark (until Jun 13)
Li, Zhongtian	Wang, Lu	Jung, Do Soon
Liao, Yuanxun	Wang, Pei	Kim, Kyung Hun
Limpert, Steven	Wang, Qian	Wang, Li
Lin, Dong	Wang, Sisi	<i>Honours students</i>
Lin, Rui	Wenham, Alison	Chen, Kuan
Lin, Shu	Western, Ned	Chen, Sheng
Lin, Ziyun	Woo, Sanghun	Chen, Yi Fei
Liu, Xiaolei	Wright, Matthew	Chu, Yuan
Lu, Pei	Wu, Lingfeng	Colwell, Jack Killian
Lu, Zhong	Wu, Qiyuan	Feng, Yao
Mahboubi Soufiani, Arman	Xia, Hongze	Fu, Xiao
Mitchell, Bernhard (until Jun 13)	Xiao, Bo (until Jun 13)	Grisold, Joseph Robert
Nampalli, Nitin	Xu, Guangqi (until Jun 13)	Hee, Kenneth
Pakhruruddin, Mohd	Xue, Chaowei	Jiang, Yu
Qi, Fang	Yan, Chang	Kang, Chris Nam Hoon
Rodriguez, John	Yang, Chien-Jen	Kim, Hee Chul
Shen, Chao	Yang, Xiaohan (until Jun 13)	Li, Bing
Sheng, Rui	Yao, Yao	Lin, Simao
Shi, Lei	Yun, Jae Sung	Lin, Yu
Smyth, Suntrana	Zhang Tian	Liu, Tongxin
Soeriyadi, Anastasia	Zhang, Haizhang	Miwa, Masahiro
Song, Lihui	Zhang, Pengfei	Moore, Jeremy
Song, Ning	Zhang, Qiuyang	Pu, Aobo
Teal, Anthony (until Jun 13)	Zhang, Yi	Ross-Smith, James



Tam, Nathan	Bi, Qunyu	Bullock, James
Tian, William Ye	Blackmore, Kim	Cong, Jin Jin
Tong, Jingnan	Catchpole, Kylie	Lim, Siew Yee
Wang, Bo	Chern Fong, Kean	Liu, Anyao
Wang, Tao	Chowdury, Dibakar (since Sep 13)	McKinley, Arnold
Wang, Tian	Cuevas, Andres	Nguyen, Hieu
Willard, Samuel Scott	Everett, Vernie	Osorio Mayon, Yahuitl
Wu, Heng	Fell, Andreas	Phang, Pheng
Wu, Yandi	Franklin, Evan	Phang, Sieu
Xing, Hang	Kho, Teng Choon	Qiaoke
Xue, Dean Ling	Lal, Niraj	Ratcliff, Thomas
Xue, Yan	Macdonald, Daniel	Sio, Hang Cheong
Yang, Wenjie	McIntosh, Keith	Sun, Chang (since Jul 13)
Yang, Zhizhi	Rougieux, Fiacre	Wang, Da
Yi, Chuqi	Samundsett, Christian	Zhang, Xinyu
Yu, Jinyang	Stocks, Matthew	Zheng, Peiting
Zeng, Xianghuang	Thomsen, Elizabeth	
Zhang, Muye	Weber, Klaus	
Zhang, Yahui	White, Tom	
Zhang, Yao	Zin, Soe	CSIRO (Materials Science and Engineering, Melbourne)
Zhao, Siyuan	<i>ECR and Postdoctoral Fellows</i>	
Zhou, Zi Bo	Baker-Finch, Simeon	Academic Staff and Senior Researchers
Zhu, Li Qun	Ernst, Marco	Wilson, Gerry (Node Leader)
Zhu, Yiwen	Grant, Nick	Chantler, Regine (since Sep 13)
Australian National University		
<i>Academic Staff and Senior Researchers</i>		
Blakers, Andrew (Node Leader)	Hargreaves, Stuart	Faulks, Andrew
	Yang, Xinbo	Fell, Chris
	PhD Students	Scholes, Fiona
	Allen, Thomas Gerald	
	Barugkin, Chog	



Vak, Doojin	Farley, Sam	ECR and Postdoctoral Fellows
Watkins, Scott	Van As, Dean	Clulow, Andrew
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Graeser, Anna (since Jul 13)		Shaw, Paul
Hwang, Kyeongil (since Sep 13)		PhD Student
Jung, Yen-Sook (since Sep 13)		Armin, Ardalan
University of Melbourne		
Academic Staff and Senior Researchers	Academic Staff and Senior Researchers	Chandrasekharan, Ajeesh
Holmes, Andrew (Node Leader)	Cheng, Yi-Bing (Node Leader)	Hamsch, Mike
Ghiggino, Ken	Arachchige, Ishanie	Jiang, Wei (Larry)
Jones, David	Bach, Udo	Kim, Il Ku (Benjamin)
Wong, Wallace	Han, Yu	Stolterfoht, Martin
ECR and Postdoctoral Fellows	He, Jiangjing	Honours student
Kumar, John (since Oct 13)	Huang, Fuzu (since Oct 13)	Sarah McGregor
Lai, Yuying (since Dec 13)	Kashif, Kalim (since Sept 13)	Arizona State University (QESST)
Lu, Shirong (since Dec 13)	Meyer, Steffen (since Oct 13)	Honsberg, Christiana
Subbiah, Jegadesian (since Oct 13)	Pasco, Alex	Bowden, Stuart
PhD Students	Sepalage, Anuradha	Cotter, Jeff
Banal, James	Spiccia, Leone	Mitchell, John
Mitchell, Valerie (since Aug 13)	Xiao, Manda	Fraser, Matthew
Schwartz, Kyra (since Apr 13)		
Song, Aaron (until Nov 13)		
Masters Students		University of Delaware (QESST)
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		National Renewable Energy Laboratory
		Friedman, Dan



Kazmerski, Larry (until Oct 13)

Kopidakis, Nikos

Teeter, Glenn

Wilson, Gregory

Young, Mathew

Suntech Research and Development, Australia

Egan, Renate

BT Imaging

Bardos, Robert

Maxwell, Ian

Trupke, Thorsten

Sandia National Laboratories

Nielson, Gregory

Trina Solar

Verlinden, Pierre

Molecular Foundry

Neaton, Jeffrey

Milliron, Delia

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McGehee, Mike

Georgia Technology Institute

Kippelen, Bernard

Marder, Seth

University of California, Santa Barbara

Bazan, Gui

Nguyen, Quyen

5. RESEARCH REPORTS

PROGRAM PACKAGE 1: SILICON CELLS

Overview

Program Package 1 (PP1) deals with silicon wafer-based cells, by far the dominant photovoltaic technology commercially and likely to remain so far at least the next 10 years. Here the challenge is to continue to reduce manufacturing cost while maintaining or preferably, improving, energy conversion efficiency. The ACAP program focusses on three main areas: cells made from solar grade silicon, rear contact cells and silicon-based tandem cells, both monolithic and mechanically stacked.

The work on solar grade silicon (PP1.1) encompasses a complementary effort by ANU and UNSW. This work targets identification and elimination of the impact of the defects that limit the electronic quality of inexpensive solar-grade wafers. Good progress was made during 2013 with the 18% efficiency milestone for this package comfortably exceeded. The ultimate aim is to produce cells made from low cost material without performance penalty.

Rear contact cells (PP1.2) offer the most promising route to exceeding the 25% efficiency record for a conventional cell with contacts on both front and rear surfaces. Good progress was made during 2013 with a team from ANU, supported by industry partners

PV Lighthouse and Trina Solar, achieving an independently confirmed record 24.4% efficiency for this approach during the year. Trina Solar recently announced the company's intent to commercialise this technology.

The final area (PP1.3) 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, each with its own particular strengths. Three involve finding approaches for stacking Group III-V cells upon silicon, each involving a distinct approach for matching the larger atomic spacing of these materials to that of silicon, while preserving silicon's good crystallographic quality. The final two technologies involve materials that are either already lattice-matched to silicon or do not require good crystal quality for high performance. Again, good progress was made in 2013 with the 18% milestone exceeded by a monolithic cell stack. Ultimately, an efficiency of 32% is targeted for at least one of the approaches being studied, significantly higher than feasible with a single junction cell.

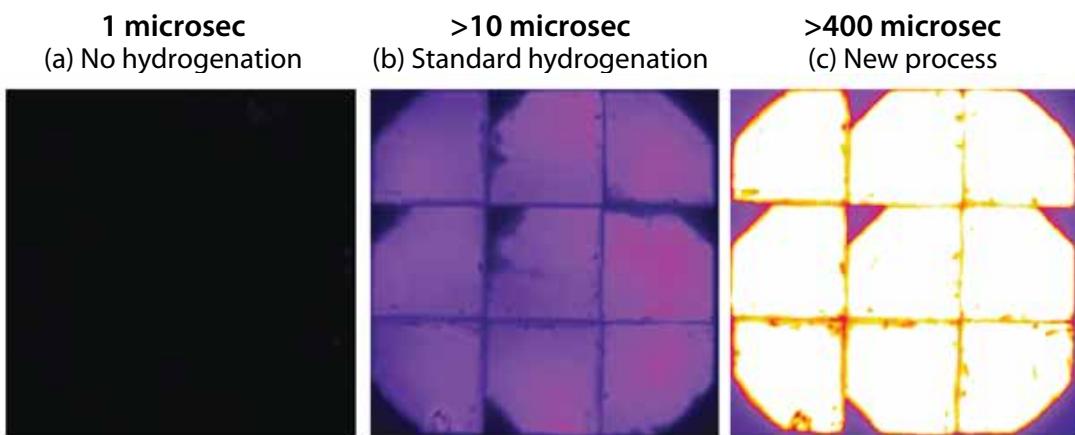


Figure PP1.1.1: Photoluminescent (PL) images for three identical UMG p-type CZ wafers from Apollon Solar showing large variations in carrier lifetimes as a function of the application of passivation technology. All three wafers are coated on both surfaces with identical SiN_x layers to provide both surface passivation and a source of hydrogen. The use of hydrogen charge state control on the wafer segments to the right facilitated the achievement of greatly improved carrier lifetimes and corresponding $i\text{Voc}$ values in the vicinity of 700mV.

PP1.1 Solar Silicon Lead Institutions: ANU/UNSW

Research Team

Academic/ Post-Doctoral

ANU	Assoc Prof Daniel Macdonald Dr Fiacre Rougieux Dr Nick Grant
UNSW	Assoc Prof Chee Mun Chong Dr Malcolm Abbott Dr Matt Edwards Dr Adeline Sugianto

Research Students

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UNSW Brett Hallam, Sisi Wang, Catherine Chan, Phil Hamer, Alison Wenham

Academic Partners

ISFH (Germany), Fh-ISE (Germany)

Industry Partners

Apollon Solar

Funding Support

ACAP, ARENA, ARC, ANU, UNSW

Background

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 when standard silicon wafers are used. Prior to the establishment of ACAP, both ANU and UNSW had active programs targeted at identifying and understanding the defects and impurities that limit the electronic quality of solar-grade wafers. They aimed to develop techniques that eliminate the impact of such

defects, either at the crystal growth stage, or by developing optimal cell fabrication processes that are tailored to these materials. ANU has had considerable success, particularly with the latter, while the focus of UNSW initiatives has been to develop innovative approaches to passivating crystallographic and impurity related defects, which transform the solar grade silicon electronic quality into the equivalent of expensive semiconductor grade silicon. ACAP provides the opportunity for these apparently complementary technologies from ANU and UNSW to be evaluated for compatibility and integrated, in order to provide outcomes superior to those achievable by either institution independently.

Material properties

The solar-grade silicon wafers for both the ANU and UNSW programs were provided by collaborators at Apollon Solar in France. These wafers were sliced from both p-type and n-type Czochralski-grown ingots, in which the silicon feedstock was 100% solar-grade silicon. In this case the feedstock was so-called Up-graded Metallurgical Grade silicon (UMG silicon). Carrier lifetime measurements at ANU have shown that the p-type material is relatively poor, with initial lifetimes around 25 microseconds. These improved to around 100 microseconds after phosphorus diffusion gettering, a process which removes certain mobile impurities such as iron and chromium. P-type wafers of even lower quality and lower cost, with initial lifetimes of around only 1 microsecond, were

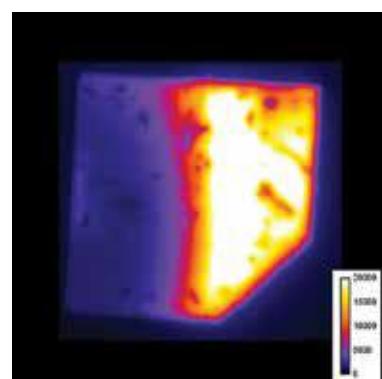


Figure PP1.1.2: PL image of a UMG p-type CZ wafer from Apollon Solar with hydrogen charge state control applied only to the right hand side of the wafer during heating and cooling.

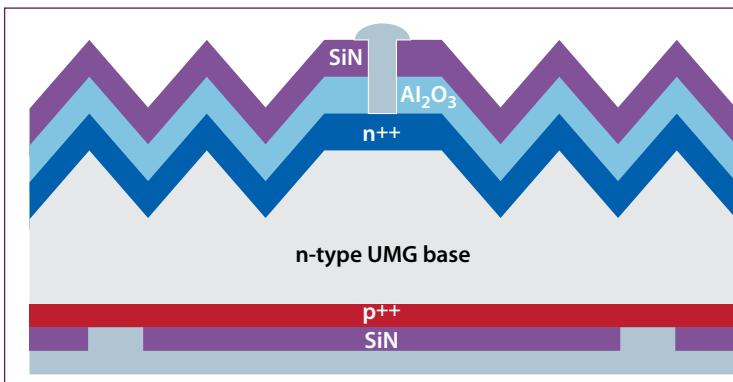


Figure PP1.1.3: Schematic diagram of the device structure used for n-type solar-grade silicon cells fabricated at ANU.

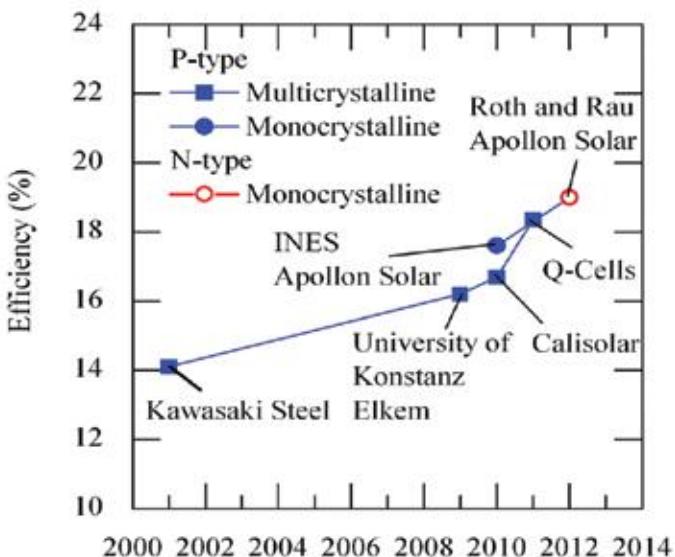


Figure PP1.1.4: Historical development of record efficiencies for solar cells made from 100% solar-grade silicon wafers.

supplied to UNSW for application of the new UNSW passivation technology, which is based on controlling the charge state of the hydrogen atoms within the silicon in order to enhance both their mobility and reactivity. As shown in Figure PP1.1.1, this process has facilitated significant improvement in the wafer quality with minority carrier lifetimes increasing from about 1 microsecond to over 400 microseconds, similar to that expected for p-type CZ wafers formed using the highest possible quality of silicon feedstock. The “new process” referred to in Figure PP1.1.1 and used to achieve this passivation quality, involves controlling the charge state of the hydrogen during both the passivation process and the subsequent cooling process. This can also be applied on a localized basis to areas as small as 100 microns in diameter. Figure PP1.1.2 demonstrates the application of the passivation process to only half of the solar grade wafer with a corresponding increase in implied open circuit voltage (iV_{oc}), for the treated half, of approaching 100mV to approximately 700mV.

By contrast, the n-type wafers had much higher lifetimes, around 300 microseconds before gettering, and close to 1 millisecond after gettering. However, these lifetimes were found to degrade again during the boron diffusion step required for fabrication of standard n-type cells. As a result, the boron diffusion step has been modified to minimize the degree of thermal degradation, and the optimization of the process continues.

Cell results

Small area solar cells (2×2 cm) have been fabricated at ANU on the n-type UMG-Si wafers from Apollon Solar. Figure PP1.1.3 above gives a schematic diagram of the cell structure. These cells have a boron-diffused, random-pyramid textured front surface, passivated by a stack of aluminium oxide and silicon nitride. The rear side is phosphorus diffused with a passivating layer of silicon nitride, with local contact openings. The best of these cells (#153a) had an efficiency of 19.8%, which, to our knowledge, is the most efficient silicon solar cell made from 100% solar-grade silicon, as shown in Figure PP1.1.4 above, where the improvement in reported efficiencies of solar-grade silicon cells are set out. This is an in-house efficiency measurement, and has not yet been certified. The measurement uncertainty is estimated to be 0.5% absolute. The champion cell had an open-circuit voltage of 637 mV, a short-circuit current density of 38.3 mA/cm², and a fill factor of 0.811. Eight cells were made in this batch, with average parameters as follows: efficiency 18.9%, open-circuit voltage 633 mV, short-circuit current density 38.1 mA/cm² and fill factor 0.780. Control cells using comparable electronic-grade n-type silicon wafers reached efficiencies above 21%, with cell parameters of 653 mV, 39.9 mA/cm², and 0.809. This indicates potential for further increases in the UMG cell efficiency above 20% in the near term, with further optimization of the cell process to maintain high carrier lifetimes.

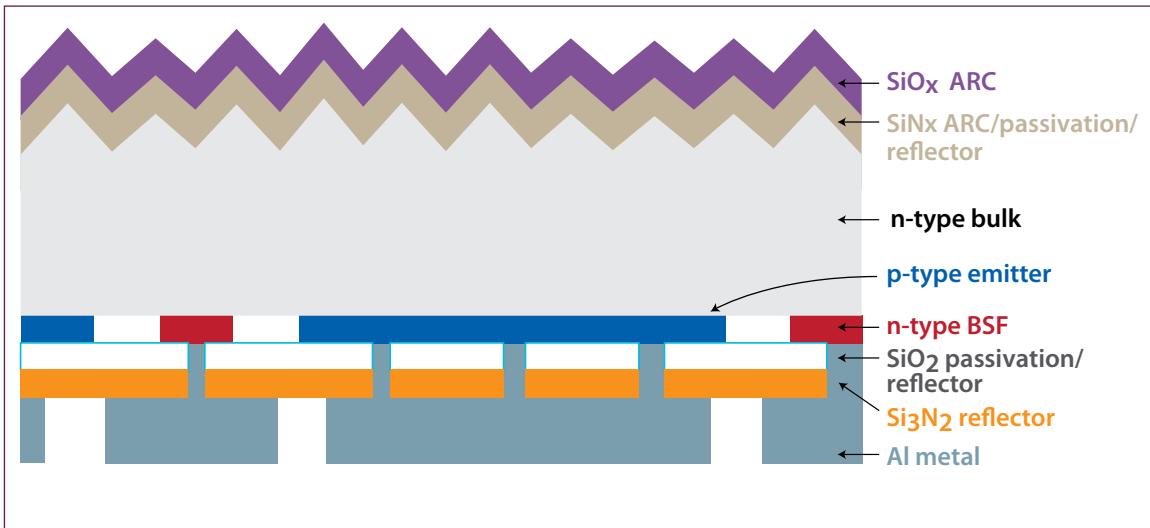


Figure PP1.2.1: Two-dimensional, cross-section representation of IBC cell fabricated at ANU.

Further work

The next 12 months will focus on clearly identifying the limiting defects in both the p- and n-type UMG wafers. In both cases it is clear that the well-known BO defect plays a significant role (even the n-type wafers have relatively large boron concentrations compared to standard material). Other defects related to stacking faults and metal impurities may also be important. Once

these are identified, and their impact quantified, strategies for mitigating them more effectively, such as the use of UNSW's new passivation approaches, will be incorporated into the ANU cell fabrication process, with the aim of reaching 21% efficiency by the end of 2014. Impurity and defect results will also be fed back to colleagues at Apollon Solar, with whom collaboration will continue to develop methods for reducing the presence of such impurities in the ingots during the crystal growth stage.

PPI.2 Rear Contact Silicon Cells Lead Institutions: ANU/UNSW

Research Team

Academic/ Post-Doctoral/Professional:

ANU: Dr Evan Franklin, Prof Andrew Blakers, Dr Andreas Fell, Dr Kean Chern Fong, Dr Nicholas Grant, Dr Keith McIntosh, Dr Matt Stocks, Mr Kho Teng, Dr Yimao Wan, Mr Er-Chiang Wang, Dr Soe Zin

Research Students:

ANU: Mr Da Wang

Industry Partners:

Trina, PV Lighthouse

Funding Support:

ACAP, ARENA, ANU

Background

Inter-digited Back Contact (IBC) cells are widely regarded, along with the so-called HIT cell concept, as the most likely cell type to surpass the long-held 25.0% efficiency record for conventional bifacially-contacted silicon single junction solar cells, currently belonging to the well-known PERL cell design. Following SunPower's lead, IBC cells also provide a promising route for industry to follow, in order to continue the ongoing trend of increasing commercial cell efficiencies.

Hence the considerable attention that is being paid to the technology by a number of research institutes and companies. The development of IBC cells at ANU is targeted firstly at realising the highest lab-scale cell efficiency practically possible, and secondly at using the knowledge gained to subsequently incorporate fabrication simplifications and industrially applicable processes to achieve high efficiency industrial IBC cells.

Cell design

A two-dimensional representation of an IBC cell design, as fabricated in ANU's laboratories, is shown in Figure PP1.2.1. This is in fact one particular variant of IBC cell design, where there is no front diffusion (hence no Front Surface Field (FSF)), where n⁺ base contacts and diffusions are both localised, but where p⁺ emitter coverage is relatively large with, in turn, a small fraction of p⁺ contact points. Both the n and p contacts are removed to the rear surface, hence eliminating shading of the front surface by metal gridlines. Substantial reductions in resistive losses are possible because the n and p contact metallisation can cover much of the rear surface, even when overlapping, provided that an interposed pinhole-free insulating layer is used. For high efficiencies, outstanding front surface passivation is needed, since all carriers must be transported to the rear surface for collection without excessive front surface

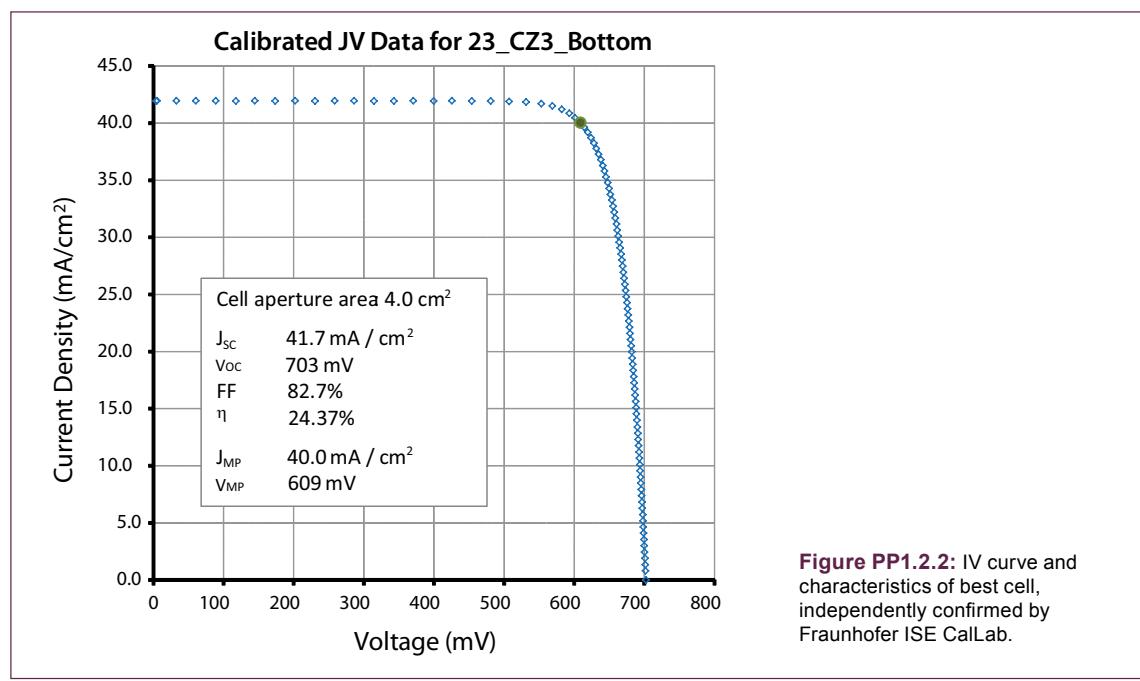


Figure PP1.2.2: IV curve and characteristics of best cell, independently confirmed by Fraunhofer ISE CalLab.

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. Front surface optics should of course be optimised for minimum reflectance and maximum internal path-length.

Results

Based upon a rear cell architecture consisting of localized n⁺ diffusions and sheet p⁺ diffusions, fabricated on a 500 μm pitch and using patterned 3.5μm thick evaporated aluminium fingers having width of 130μm

and 290μm respectively for n⁺ and p⁺ fingers, passivated with thermal oxide and LPCVD SiN, with outstanding front side PECVD SiN_x passivation and PECVD SiO₂ DLARC, cells were successfully fabricated on both CZ and FZ n-type material. The best cells had an independently confirmed aperture-area (4 cm²) efficiency of 24.4%, measured at Fraunhofer CalLab.

Further work

Systematic improvements in optical design, along with suppression of recombination and minimization of resistive losses will be pursued during 2014 with the ultimate aim of reaching 25-26% efficiency.

PP1.3a Silicon Tandem Cells (monolithic) Lead Institution: UNSW

Research Team

Academic/ Post-Doctoral:

UNSW: Prof. Allen Barnett, Dr Stephen Bremner, Prof. Gavin Conibeer, Prof. Martin Green, Dr Xiaojing Hao, Dr Anita Ho-Baillie, Dr Shujuan Huang, Dr Henner Kampwerth, Dr Mark Keevers, Dr Ivan Perez-Wurfl

Monash: Prof. Udo Bach, Prof. YiBing Cheng, Prof. Leone Spiccia

Research Students:

UNSW: Ibraheem Al-Mansouri, Brianna Conrad, Martin Diaz, Dun Li, Fangyang Liu, Ziheng Liu, Rui Sheng, Anastasia Soeriyadi, Ning Song, Li Wang, Sanghun Woo, Xin Zhao

Monash: Fuzu Huang, Mando Xiao

Academic Partners:

NREL (USA), Ohio State University (USA), U. of Delaware, Yale University, Arizona State University

Industry Partners:

Epistar Corporation, Shin Shin National Gas Col, Ltd., Veeco, AmberWave

Funding Support:

ACAP, ARENA, ARC, Epistar, Shin Shin, UNSW, Monash

Background

The limiting efficiency for silicon wafer cells alone is 29%, with commercial silicon cells expected to approach the world best laboratory value of 25% (a UNSW result) by 2020. Unavoidable Auger recombination in silicon is the main reason why silicon's limiting value is less than the unconstrained limit of 33% for a single device (Figure. PP1.3.1). Stacking cells on silicon brings the limiting performance even closer to that of the unconstrained limit, due both to silicon's near ideal bandgap in a stacked cell role and to a reduction in the significance of Auger effects as generation is split between multiple

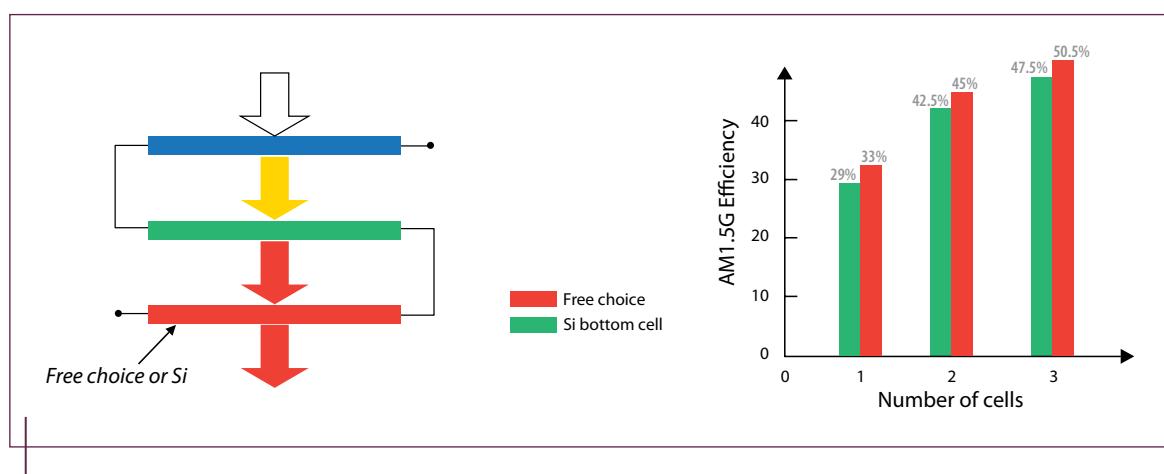


Figure PP1.3.1: Tandem cell stack (left) and limiting energy conversion efficiency (right), with (green) and without (red) the bottom cell constrained to be silicon.

devices. For three cells stacked on silicon, the limiting efficiency exceeds 50% (Figure. PP1.3.1).

The large and vigorous photovoltaic manufacturing industry will continue to perfect the production of low-cost, high quality wafers. Combined with the large potential efficiency gains indicated in Figure. PP1.3.1, this suggests that one possible evolutionary path for silicon wafer based cells would be to use a Si cell as a template for the deposition of thin, high performance, wide-bandgap crystalline cells on its top surface, much the same way as an antireflection coating layer or a heterojunction emitter structure is deposited in present commercial cell sequences (Figure. PP1.3.2).

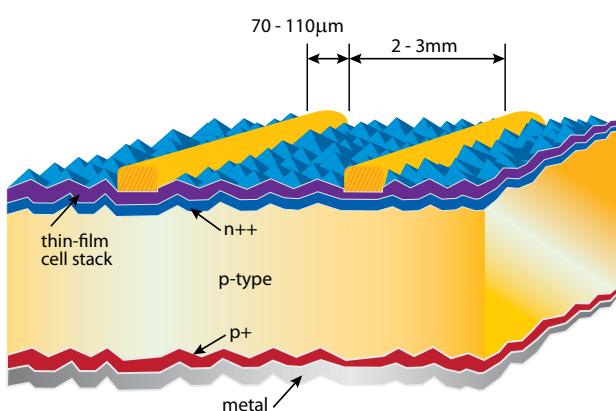
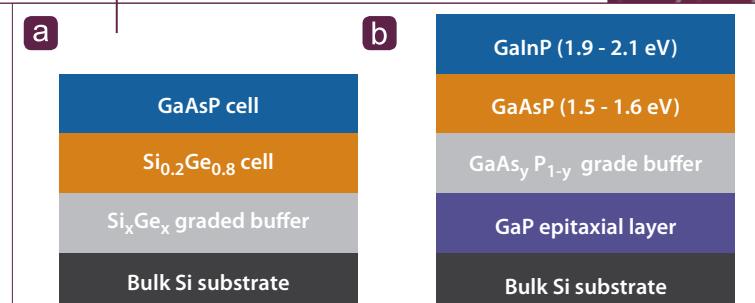


Figure PP1.3.2: Conceptual drawing of a standard silicon cell with one or more thin-film cells formed on the cell top surface.

For 2013, five strands of activity were pursued, targeting such a high-performance stacked cell as the ultimate objective. Four strands of Program Package PP1.3a are attempting, for the first time, to effectively mate the most successful photovoltaic technologies, Si, III-V and the chalcogenides. Of the III-Vs of interest, only GaP offers a lattice match to silicon, with the other III-Vs used in the best III-V cells having about 4% mismatch,

Figure PP1.3.3: (a) Double junction cell design using SiGe buffer layer to match III-V and Si lattice constants; (b) Triple junction cell design based on GaP epitaxy on silicon.



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 Si_xGe_{1-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-rich surface (Figure. PP1.3.3a). Operational tandem cell stacks using this approach with efficiency above 18% were demonstrated during 2013.

A parallel approach, PP1.3(a(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_xAs_{1-x} 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. Epitaxial GaP layers were grown on silicon substrates during 2013 and the bottom silicon cell designed and tested.

Working with US- and Australian-based collaborators, with additional project support leveraged beyond that of present funding, an efficiency of over 24% with one or more of these approaches is targeted for the first 4 years of ACAP 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%.

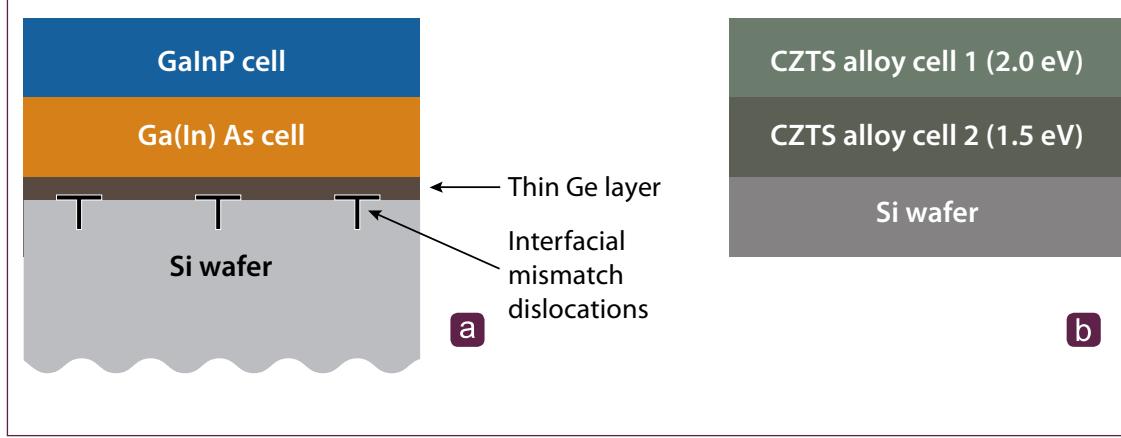


Figure PP1.3.4: (a) Possible triple or “out-of-sequence” quadruple junction cell on silicon using atomically abrupt transition from silicon to Ge atomic spacing; (b) Triple junction tandem cell based on epitaxial growth of CZTS alloy cells on silicon.

Two more adventurous approaches to building high quality tandem cells on silicon wafers are also being explored as part of Program Package PP1.3a. One approach, PP1.3a(iii), targets an atomically abrupt Si/Ge transition, where the lattice mismatch is taken up in a single atomic layer, thermodynamically feasible due to a low energy configuration (Figure. PP1.3.4a). UNSW has filed patent applications on approaches that have given promising results of this type. The aim is to make the Ge layer either very thin, creating negligible absorption loss, or thick enough to be used as an active cell in a novel “out-of-sequence-tandem”. Operational GaAs cells were fabricated on thin Ge layers deposited on silicon wafers during 2013. The aim in 2014 is to improve the performance of these GaAs cells to above 10% efficiency by better restricting mismatch defects to the Si/Ge interface.

The second of these more adventurous approaches, PP1.3a(iv), involves the investigation of silicon tandem cells using chalcogenides as the upper cells in the stack. Although the established chalcogenide cell materials (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 materials based on the $\text{Cu}_2\text{ZnSnS}_4$ (CZTS) system, which has already demonstrated energy conversion efficiency above 12%, despite the relatively small effort devoted to its development to this point. Moreover, the CZTS 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 Zn or Sn, for example, replaced by lighter elements such as Fe(ii) or Si, will increase the bandgap. This will make 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. In 2013, epitaxial CZTS films were grown on sapphire substrates but an intermediate oxide layer inhibited epitaxial growth on silicon by sputtering. The aim in 2014 is to demonstrate and characterize the growth of CZTS or associated alloys on silicon.

PP1.3a (i): III-V Cells on Silicon Using SiGe Buffer Layers

Key Resources

UNSW: Prof. Allen Barnett, Dr Ivan Perez-Wurfl, Brianna Conrad, Martin Diaz, Dun Li, Anastasia Soeriyadi, Li Wang, Xin Zhao

The difficulty with the SiGe lattice matching approach is due to the large lattice-mismatch between the silicon substrate and the III-V epitaxial layers, resulting in an increased threading dislocation density (TDD). A higher TDD significantly affects the minority carrier lifetime and reduces the open-circuit voltage (V_{oc}) of the device [1.3.1]. By lattice matching the top and bottom cells, the voltage loss due to threading dislocations can be minimized. The lattice-matched GaAsP/SiGe

tandem structure, from which this research stems, has been studied by Schmieder et al [1.3.2]. The key technology behind this structure is the metamorphic SiGe grade buffer, developed by AmberWave, which allows for this lattice matching and low dislocation interface between the silicon substrate and the device layers, resulting in high performance from the top cell.

Experimental

The growth of the tandem structures is completed using a two-step growth process of the epitaxial layers and fabrication is finalized with the aid of photolithography. The first growth step involves the

$\text{GaAs}_{0.84}\text{P}_{0.16}$	Contact	1.67eV	n+
$\text{In}_{0.35}\text{Al}_{0.65}\text{P}$	Window	2.4eV	n
$\text{GaAs}_{0.84}\text{P}_{0.16}$	Emitter	1.67eV	n
$\text{GaAs}_{0.84}\text{P}_{0.16}$	Base	1.67eV	p
$\text{Ga}_{0.59}\text{In}_{0.41}\text{P}$	BSF	2eV	p
$\text{GaAs}_{0.84}\text{P}_{0.16}$	Buffer	1.67eV	p
$\text{GaAs}_{0.84}\text{P}_{0.16}$	TJ	1.67eV	p+/n+
$\text{GaAs}_{0.84}\text{P}_{0.16}$	Buffer	1.67eV	n
$\text{Ga}_{0.59}\text{In}_{0.41}\text{P}$	Nucleation	2eV	n
$\text{Si}_{0.18}\text{Ge}_{0.82}$	SiGe	0.86eV	i
$\text{Si}_{0.18}\text{Ge}_{0.82}$	Emitter	0.86eV	n
$\text{Si}_{0.18}\text{Ge}_{0.82}$	Base	0.86eV	p
$\text{Si}_{0.18}\text{Ge}_{0.82}$	Graded Buffer	1.1-0.86eV	p
	Si Substrate		p

Figure PP1.3.5: Simplified GaAsP/SiGe on Si device structure.

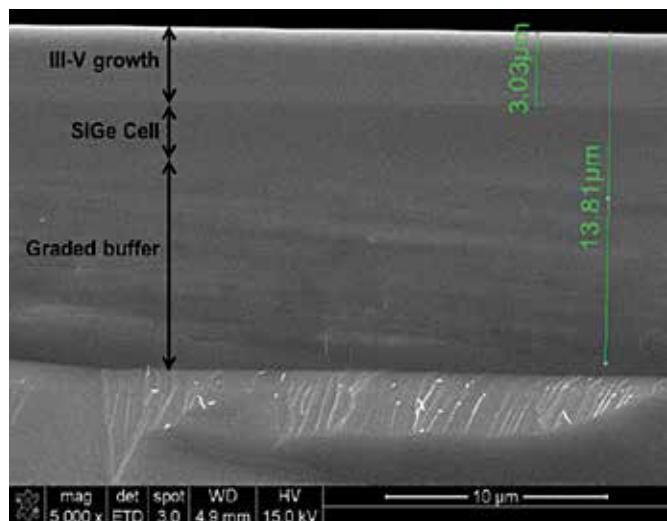


Figure PP1.3.6: III-V/SiGe on Si cross-section SEM.

growth of the SiGe layers, while the second growth step produces the III-V layers. Figure PP1.3.5 shows the simplified device structure details.

AmberWave uses reduced pressure chemical vapor deposition (RPCVD) to carry out the growth of SiGe on (100) 6° offcut CZ silicon. Threading dislocation densities (TDD) as low as $3 \times 10^5 \text{ cm}^{-2}$ have been realized with this growth process [1.3.3]. Ge concentrations of 82-86% for the SiGe bottom cell are achieved with the SiGe graded buffer.

Veeco then completes the lattice-matched III-V growth using metal organic chemical vapor deposition (MOCVD), while keeping the thickness to a minimum $< 3\mu\text{m}$. Contributing to the thickness of these layers is the tunnel junction for these n+/p structures, however it will be beneficial to have the SiGe material contain the tunnel junction in future tandem device structures. These III-V layers have exhibited a TDD of $6.2 \times 10^6 \text{ cm}^{-2}$ on SiGe [1.3.4]. Figure PP1.3.6 shows an SEM cross-section of the full growth structure.

The primary process used for fabrication in this research is photolithography, which provides all necessary processing requirements with few disadvantages. Figure PP1.3.7 shows a photo of a fabricated quick turnaround device for immediate results. Figure PP1.3.8 shows the two-terminal fabricated structure. This photolithography process allows for a variety of tests during the stages of fabrication and provides an adequate number of solar cell devices of varying sizes within a 3cm^2 area.

The rear Al metal and front Ni/AuGe metal is deposited using thermal evaporation. The contacts are then annealed using rapid thermal processing (RTP). Isolation of the devices is performed using a combination of wet and dry etching resulting in devices ranging from 0.01mm^2 to 1cm^2 in size as shown in Figure. PP1.3.7. The final step is application of the anti-reflection coating (ARC) deposited by plasma-enhanced chemical vapor deposition (PECVD).

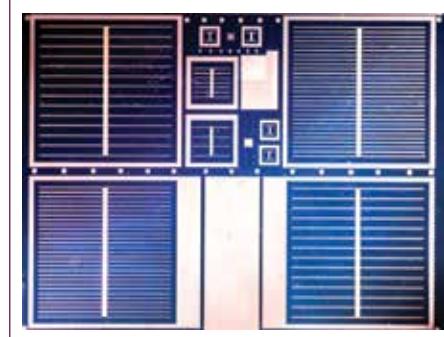


Figure PP1.3.7: Fabricated GaAsP/SiGe on Si devices.

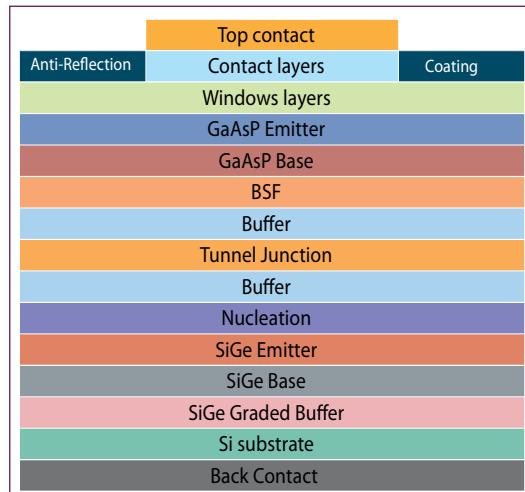


Figure PP1.3.8: GaAsP/SiGe on Si two-terminal structure.

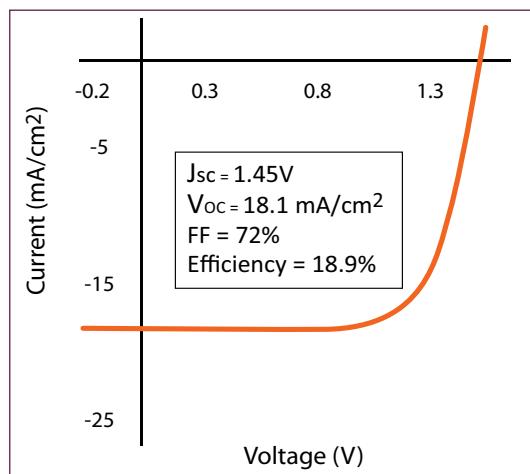


Figure PP1.3.9: IV performance for GaAsP/SiGe tandem solar cell with ARC.

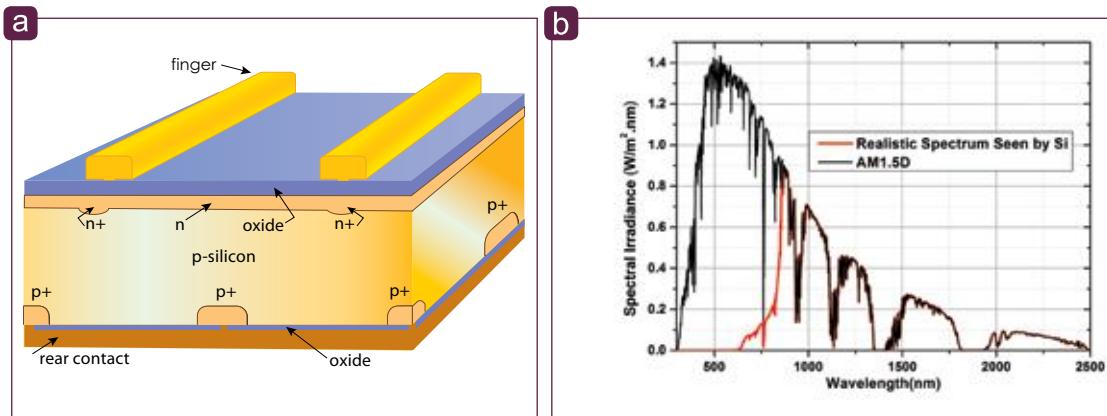


Figure PP1.3.10: (a) The planar PERL (Passivated Emitter Rear Locally-diffused) cell structure and (b): The AM1.5D solar spectrum and realistic spectrum seen by the Si bottom cell after it is filtered by an upper stack with bandgap of 1.5 eV.

Results

The completed tandem devices are tested indoors under a simulated AM1.5G spectrum. The devices presented here contain a SiN/SiO₂ double layer ARC (DLARC) and demonstrate a short-circuit current density of 18.1 mA/cm² and an efficiency of 18.9%. The I-V curve for the device with improved J_{sc} is provided in Figure. PP1.3.9.

Conclusions

This GaAsP/SiGe tandem structure continues to show promising results although the bottom SiGe cell remains the current limiting cell, as it is not fully optimized and the addition of a non-optimized DLARC shows an improvement of only 30% of what was expected. With further improvement to fill factor, current, such that it is matched at the highest top cell current measured, and voltage, such that the best voltage of each cell measured is combined into a single tandem device, the potential efficiency of this tandem structure approaches 25%.

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

Key Resources

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Ohio State University:

Prof. Steve Ringel, A/Prof. Tyler Grassman, Dr John Carlin

A parallel approach, PP1.3(a(ii), which demonstrated some success in 2013, is to take advantage of the similar miscibility of GaP and GaAs by growing a step graded of $\text{GaP}_x\text{As}_{1-x}$ buffer layer on Si with x again steadily decreasing, allowing a transition

from the Si lattice constant to that of GaAs [1.3.5]. 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. Epitaxial GaP layers were grown on silicon substrates during 2013 and the bottom silicon cell designed and tested [1.3.6].

Figure PP1.3.10(a) shows the planar PERL (Passivated Emitter Rear Locally-diffused) cells fabricated for this work which sees the spectrum shown in Figure PP1.3.10(b) after being filtered by an upper stack with a bandgap of 1.5eV. The effect of front surface recombination velocity, used in this case to simulate

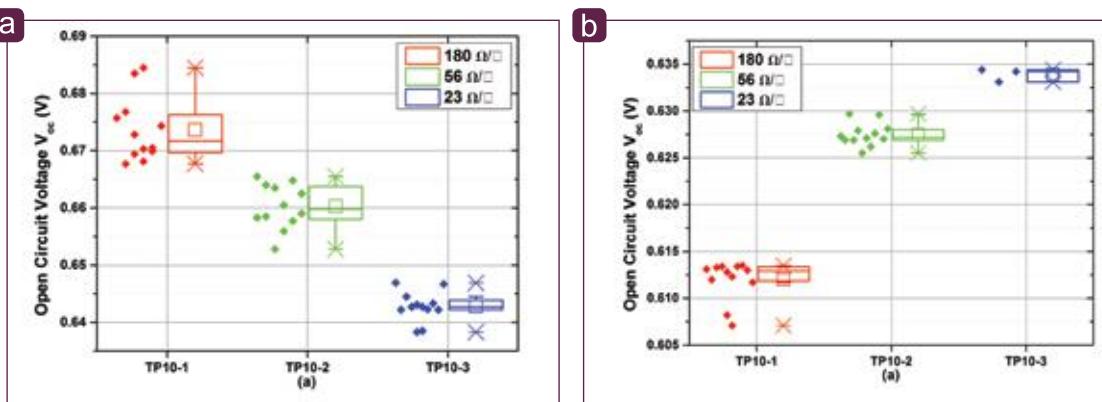


Figure PP1.3.11: Open circuit voltages of planar PERL cells with (a) low and (b) high interface recombination velocities. Note the sheet resistivities of the lightly doped, mid-doped and heavily doped front n-type emitters are 180, 56 and 23 ohm/sq. respectively.

the interface recombination between Si and the epitaxial GaP layer, on the cell performance is investigated and a strategy for front n-type emitter doping to achieve best performance for high and low interface recombinations are demonstrated, see Figure PP1.3.11. If light filtering by the upper stack is considered whereby light with energy $> 1.5\text{eV}$ is absorbed by the top cell while the rest gets absorbed by the Si bottom cell, then a J_{sc} of $7.8\text{-}8.5 \text{ mAcm}^{-2}$ is achieved depending on the front emitter doping levels when the interface recombination velocities are low. If interface recombination velocities approach infinity, then a J_{sc} of $7.4\text{-}8.1 \text{ mAcm}^{-2}$ could only be achieved under the truncated spectrum with the highest value achieved by heavy emitter doping. PC1D modelling suggests efficiency of at least 4.3% (this is in addition to the upper stack of III-V cells) under a truncated spectrum can be achieved by the bottom cell with a J_{sc} of 7.9 mAcm^{-2} and V_{oc} of 608 mV as long as a heavy doping of around 20 ohm/sq . is employed

for the emitter even when the interface recombination velocities approach infinity. The performance will be improved by employing anti-reflection coating since presented results here are without any coating.

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PP1.3a (iii): III-V Cells on Silicon Using Atomically Abrupt Si/Ge Transition

Key Resources

UNSW: Dr Xiaojing Hao, Prof. Gavin Conibeer, Prof. Martin Green, Ibraheem Al-Mansouri, Ziheng Liu, Dr. Anita Ho-Baillie

NREL: Dr. Dan Friedman

As previously mentioned, two more adventurous approaches to building high quality tandem cells on silicon wafers are also being explored as part of Program Package PP1.3a. One approach, PP1.3a(iii), is 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 (Figure PP1.3.4a). 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”. Operational GaAs cells were fabricated on thin Ge layers deposited on silicon wafers during 2013, see Figure PP1.3.12. The aim in 2014 is to improve the performance of

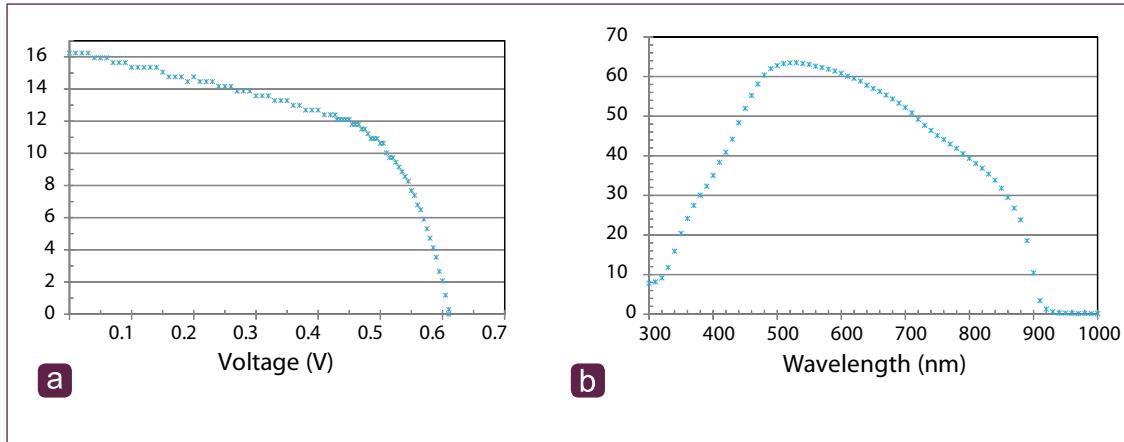


Figure PP1.3.12: (a) Light short circuit current density vs voltage characteristics and (b) external quantum efficiency of GaAs cell fabricated on thin Ge layer deposited on silicon wafer.

these GaAs cells to beyond 10% efficiency by better restricting mismatch defects to the Si/Ge interface.

PP1.3a (iv): Chalcogenide Cells on Silicon

Key Resources

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NREL: Dr Glenn Teeter, Dr Mathew Young

Epi-CZTS on Si substrate

CZTS thin films were prepared on single crystal Si substrates with different orientations (100), (100)4°, (111), (111)4°, (110) by sputtering from a single CZTS target. However, an intermediate oxide layer inhibited epitaxial growth of CZTS on silicon by this approach. Even with the intermediate oxide layer, the crystal structures, surface morphologies and microstructures of the CZTS films were found to change with the orientation of the Si substrate. CZTS on Si (100) was more (112) textured from XRD results and CZTS on Si (111) 4° showed better crystal quality from TEM images.

UNSW's collaborator NREL demonstrated the successful epitaxial growth of CZTS on Si by the MBE method as evidenced in Figure PP1.3.13. This shows that epitaxial growth of CZTS on Si is feasible. In our case, this appears to be inhibited by the intermediate oxide layer formed on Si wafer during the long-duration pumping down period due to the old-style sputter system used, without a load-lock. This motivated us to use alternative substrates for testing such epitaxial growth by sputtering while awaiting the commissioning of a new sputter (with a load-lock) dedicated for CZTS.

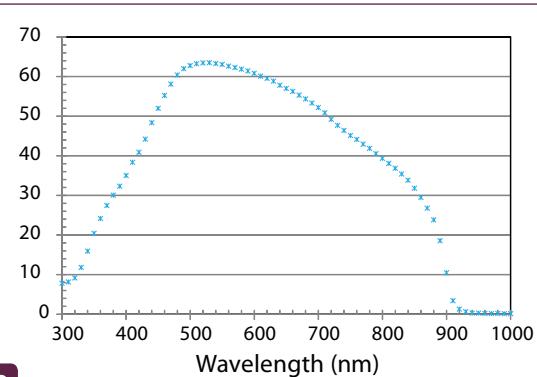
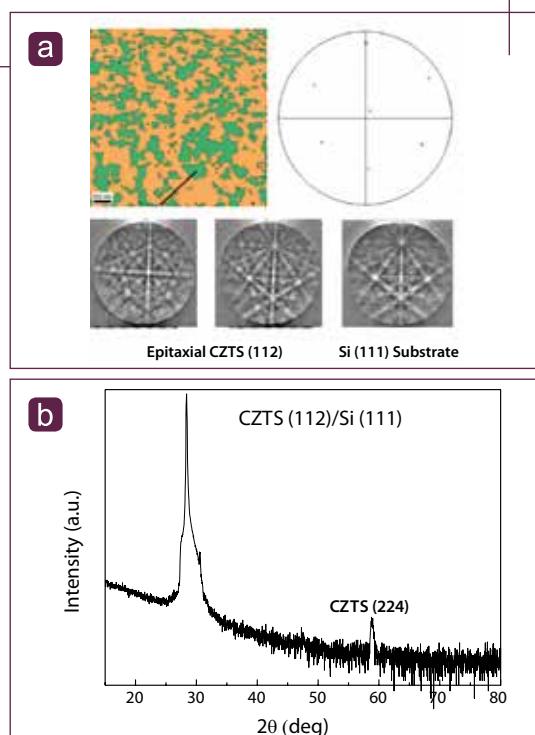


Figure PP1.3.13: (a) EBSD and (b) XRD patterns from an epi-CZTS film on a Si(111) (4° offcut) substrate (data from NREL).



Epi-CZTS on Sapphire substrate [I.3.7]

The hetero-epitaxy of tetragonal $\text{Cu}_2\text{ZnSnS}_4$ (CZTS) thin films on hexagonal sapphire (0001) single crystal substrates is successfully obtained by radio frequency (RF) magnetron sputtering. The sputtered CZTS film has a mirror-like smooth surface with a root mean square roughness of about 5.44 nm. X-ray θ-2θ scans as well as Raman spectrum shown in Figure PP1.3.14 confirm that the obtained CZTS film is (112)- oriented on sapphire with an out of plane arrangement of CZTS (112) || Sapphire (0001). X-ray Phi scan [See Figure PP1.3.15 (a)] further illustrates an in plane ordering of CZTS [201] || sapphire (0110). The high-resolution transmission electron microscopy (HRTEM) image of the interface region clearly shows that the CZTS thin film epitaxially grows on the sapphire (0001) substrate [See Figure PP1.3.15 (b)]. The band gap of the film is found to be approximately 1.51 eV by Tauc plot, well suitable for the middle cell in a 2-cell stack on silicon.

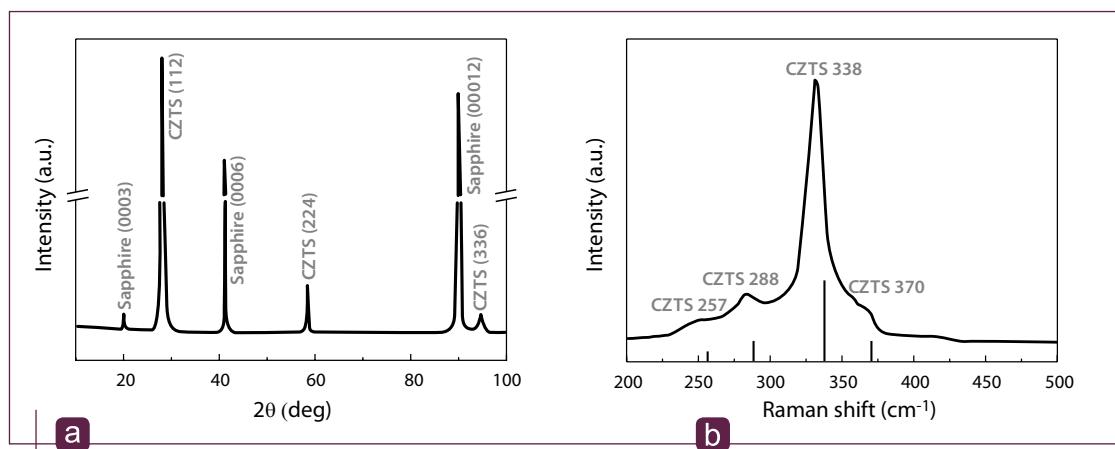


Figure PP1.3.14: (a) XRD pattern (b) Raman spectrum of sputtered CZTS film on sapphire (0001).

Epi-CZTS on ZnS substrate

Heteroepitaxial growth of $\text{Cu}_2\text{ZnSnS}_4$ (CZTS) thin films on cubic ZnS (100) single crystal substrates was also achieved by Radio Frequency (RF) magnetron sputtering from a single target at a substrate temperature of 470 °C. The growth of the CZTS was conformed to be along the a-axis. The as-sputtered film has a mirror like surface

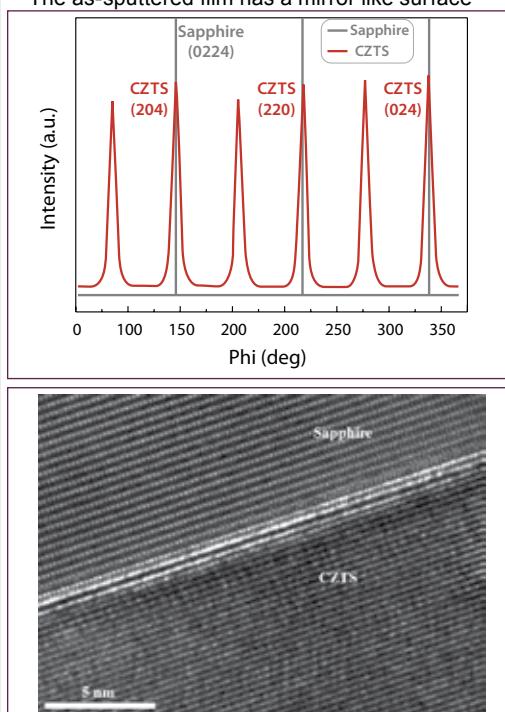


Figure PP1.3.16: (a) and (b) are the dark field and bright field Scanning TEM images of the CZTS film on ZnS substrate obtained at 470 °C, respectively. (c) and (d) are the SAED patterns of the circled area in the ZnS substrate and CZTS layer in (a), respectively. (e) and (f) are the elemental profiles determined by EDS scan of the arrow L1 and L2 in (b), respectively.

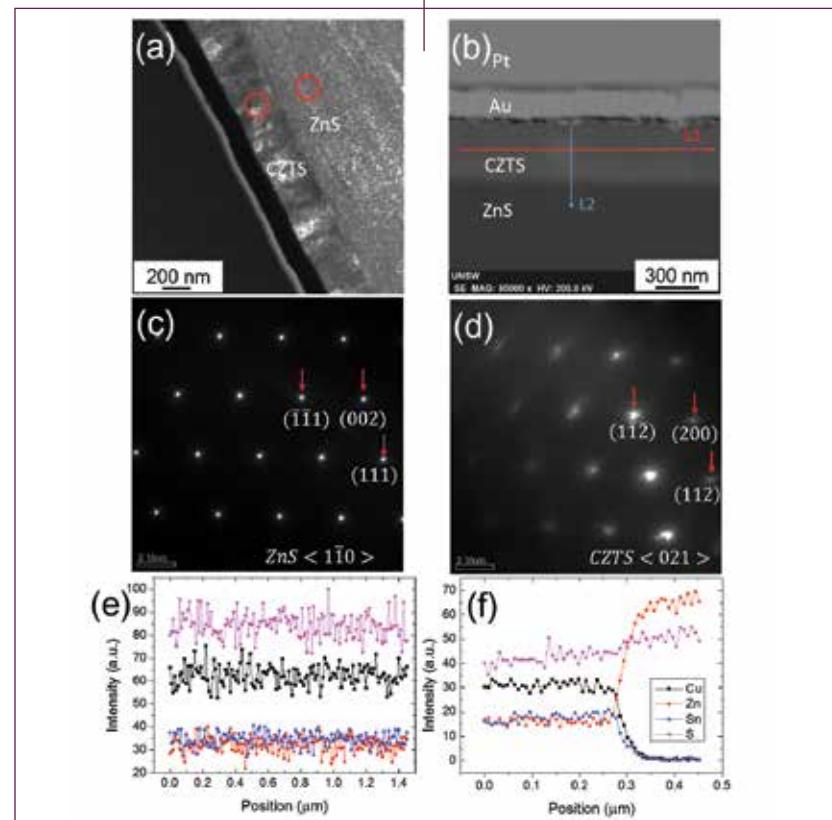


Figure PP1.3.15: (a) In-plane Phi scan of CZTS film recorded at {204}/{220} and sapphire substrate recorded at {024}; (b) Cross-sectional HRTEM image recorded at the interface of CZTS/sapphire.

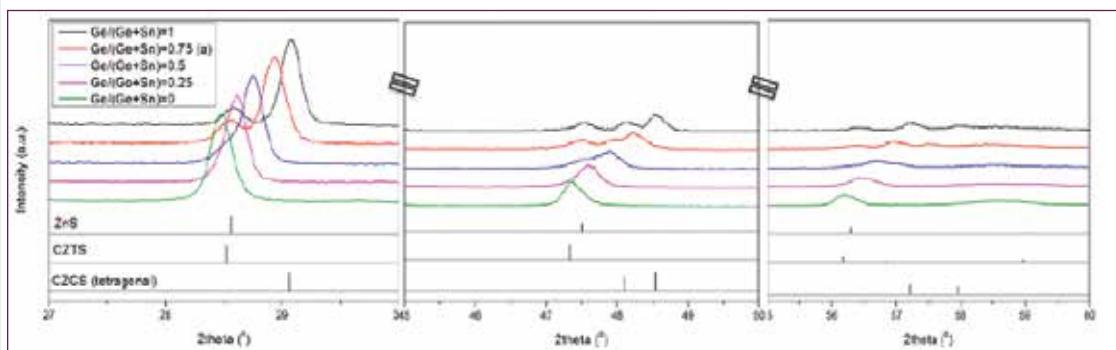


Figure PP1.3.17: XRD patterns of CZTS alloying with various content of Ge.

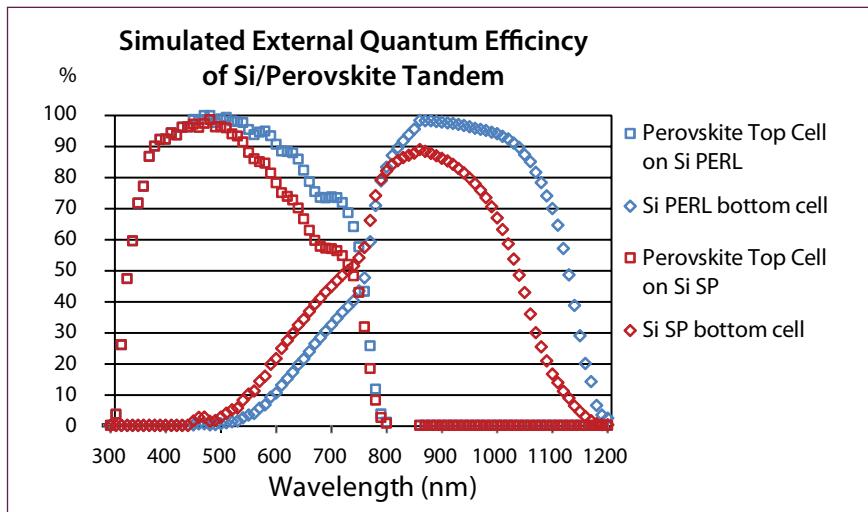


Figure PP1.3.18: External quantum efficiency of perovskite cells when monolithically stacked on top of a UNSW record Si PERL cell and a commercial SP cell.

with elements uniformly distributed throughout the whole film. The a-axis oriented epitaxial growth of CZTS was confirmed by XRD and SADPs, as shown in Figure PP1.3.16 (b) compared to those from the ZnS substrate.

Bandgap engineering of CZTS by alloying with Ge:

The reported bandgaps of CZGS ($\text{Cu}_2\text{ZnGeS}_4$) and CZTS ($\text{Cu}_2\text{ZnSnS}_4$) are 2.1eV and 1.5eV, respectively, indicating that 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 Si can be realized when slightly tuning the atomic ratio of Sn/Ge in CZTGS ($\text{Cu}_2\text{ZnSn}_x\text{Ge}_{1-x}\text{S}_4$) system.

With similar methods used for the fabrication of CZTS, $\text{Cu}_2\text{ZnSn}_x\text{Ge}_{1-x}\text{S}$ (CZTGS) compound series was obtained with varying Ge content. This is demonstrated by the diffraction peak shift as shown in Figure. PP1.3.17. Further studies on the optical and electrical properties of CZTGS system are currently under way.

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

Key Resources

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Monash: Prof. Udo Bach, Prof. YiBing Cheng, Prof. Leone Spiccia, Mando Xiao, Fuzu Huang

The final strand of activity, PP1.3a(v), will involve investigation of material systems that do not require lattice matching to silicon. Work in 2013 has been largely restricted to Si quantum dot cells, with the crystalline quantum dots dispersed in an amorphous matrix. Organic-Inorganic lead halide perovskites have the potential to increase the best quality PERL

c-Si cell record efficiency of 25% to above 27% with a deposition of a single 14% efficient perovskite cell on top. The relative improvements become larger as the c-Si cell quality becomes lower. Figure PP1.3.18 shows the spectral composition of the shared current for current-matched cells on a PERL cell and a low quality (16.5%) screen-printed multicrystalline cell.

For example, efficiencies above 22% and 20% appear feasible, if a 14% efficient perovskite cell is stacked on a normal multicrystalline screen-printed cell and a low grade multicrystalline or upgraded metallurgical grade Si cell respectively. Perovskites based on methylammonium lead bromide or their mixed halide will be good candidates for three or more cell stacks.

PP1.3b: Silicon Tandem Cells (4-terminal) Lead Institution: ANU

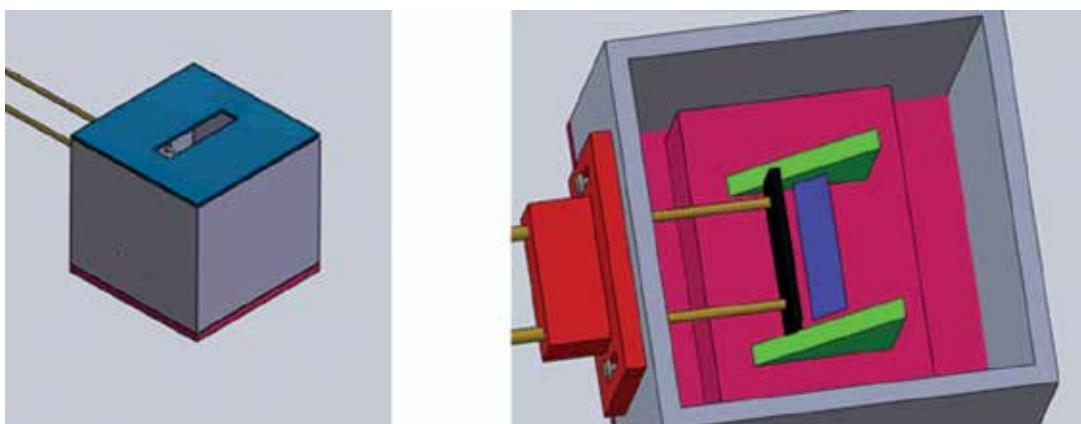


Figure PP1.3.19: System for measuring tandem cell performance. The high bandgap cell is mounted at 45 degrees to reflect incident light onto the low bandgap cell.

Research Team

Academic/ Post-Doctoral/Professional:

ANU: Dr Matt Stocks, Prof. Andrew Blakers,
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Elizabeth Thomsen, Dr Klaus Weber

Funding Support:

ACAP, ARENA, ANU

Background

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 some time. While large area cells with efficiency greater than 24% have recently been demonstrated, for photovoltaic performance to exceed 30% under non-concentrated light the silicon device needs to be combined with another, ideally higher bandgap cell, as discussed in previous sections.

This work focuses on four terminal tandem devices with silicon as the low bandgap device. White et al. [1.3.8] recently reported modelling that showed 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.

Most tandem cells to date have been based on the two terminal approach, with similar-area cells connected in series. This arrangement significantly constrains the bandgap of the top cell to approximately 1.7eV to avoid current mismatch losses with silicon devices. Additionally, matching of lattice constants and thermal expansion coefficient is required. The four terminal

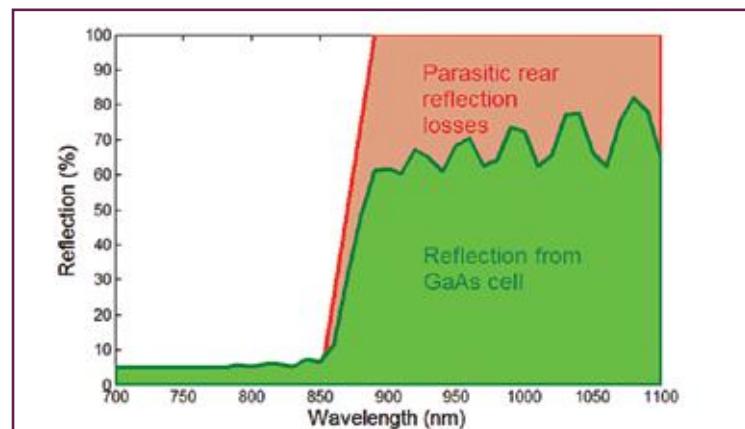


Figure PP1.3.20: Reflection from GaAs solar cell.
Reflection averaged ~70% for sub-bandgap photons and ~5% for photons above the bandgap.

approach provides freedom to choose the bandgap and other parameters (CTE, area, shape, thickness etc) for best system performance, albeit requiring a modest increase in interconnection cost.

A variety of approaches has been proposed for combining independent solar cells in a tandem configuration. A good summary of these can be found in the presentation by Honsberg from Arizona State University (<http://pv.asu.edu/files/EEE598/08-Tandem%20solar%20cells.pdf>). A significant challenge for the practical realisation of many of these approaches is the need for an expensive optical element (e.g. spectral beam splitter or hologram) to efficiently divide the spectrum into the components for which the individual cells are most efficient.

Approach

A quite different approach has been taken in this work. Instead of introducing an optical element to split the light, the high bandgap solar cell is used as a reflector, eliminating the need for an additional optical element. Photons with energy greater than the bandgap are absorbed by the high bandgap cell, while sub-bandgap photons are reflected by the rear metallisation towards the low bandgap cell.

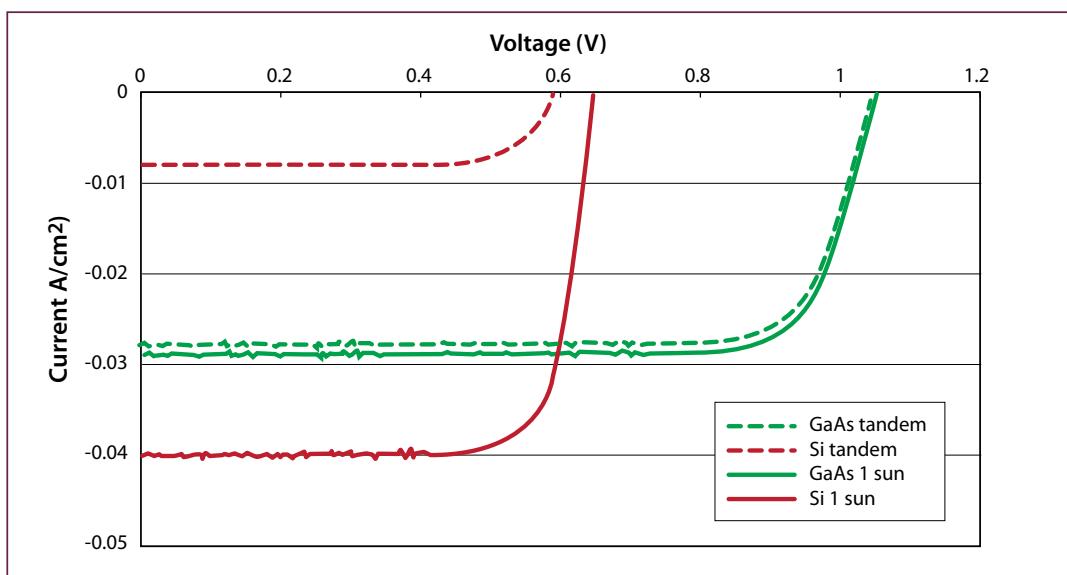


Figure PP1.3.21: Current voltage curves for the GaAs and Si cells at one sun and in the tandem system.

The cells are mounted in the configuration shown above in Figure PP1.3.19. The image on the left is the complete system with the defined aperture on the top of the box. This aperture is aligned to the high bandgap cell (purple in right image) which is mounted at 45 degrees to the incident light. Light is reflected from this cell to the low bandgap cell (shown black in right image). The total efficiency of the system is the sum of the electrical powers of the two cells mounted within the system divided by the quantity of light entering the aperture (light power x area).

Initial trials of this system were undertaken with a gallium arsenide (GaAs) and silicon (Si) tandem arrangement. The reflection from the GaAs cell was measured at an angle of 45 degrees (Figure PP1.3.20).

Although the GaAs cell was not specifically designed for this application, approximately two thirds of the photons with energy less than the bandgap are reflected from the GaAs cell. The sine wave appearance of the reflection above 900nm is due to interference effects from the thin GaAs layer. Rear reflection losses are due to absorption at the interface between the GaAs and the rear metallisation. These losses could be reduced with improved choice of rear metal and/or the introduction of an intermediate dielectric over most of the rear. The reflection losses could also be reduced with a suitable spectral reflector in front of the cell, but at higher cost.

Prior to placement in the system, the GaAs cell and the Si cell were measured at efficiencies of 24.6% and 20.3% at the equivalent of 1 sun on a solar simulator. The cells were then mounted in the system shown in Figure PP1.3.19 and the aperture and the silicon cell were positioned to maximise the performance of the GaAs and the silicon cells respectively.

Results

The resulting efficiency of the combined system was 27.8%, exceeding the performance of either of the individual cells. The IV curves for the cells can be seen in Figure PP1.3.21. As expected, the efficiency of the GaAs cell remains high at 24% given that it receives the full one-sun illumination. The slight drop in efficiency was due to a decrease in the short circuit current density from 29.2mAcm^{-2} to 28.1mAcm^{-2} offset by a slight increase in FF from 80.0% to 82.0%. The drop in current can be attributed to a combination of the increased reflection at 45 degrees and light falling outside the cell due to separation of the aperture from the cell. The performance of the silicon cell is reduced to 3.75%, due to a large drop in current from 40.2 mAcm^{-2} to 8.3 mAcm^{-2} . This is due to the higher energy photons being absorbed in the GaAs (as desired) and the parasitic losses in the rear reflector of the GaAs cell. Combined current across the system is 36.4 mAcm^{-2} which is 10% less than for the Si cell. The reduced cell current also led to a 10% decrease in the open circuit voltage of the silicon cell.

Targeting >30%

The improvement required in the GaAs cell performance is largely equivalent to improving its one sun performance. The high bandgap cell receives near full illumination (70% due to 45° inclination). Introduction of the best available one sun GaAs cell (29.1% Alta Devices) would increase performance by about 4.5% (absolute) to over 32%.

The scope for improving the relative performance of the silicon cell is far greater. Improving the sub-bandgap reflectance of the GaAs cell could dramatically increase the Si cell current. Simulation of significantly improved Si cell current is shown in Figure PP1.3.22. Including realistic external quantum

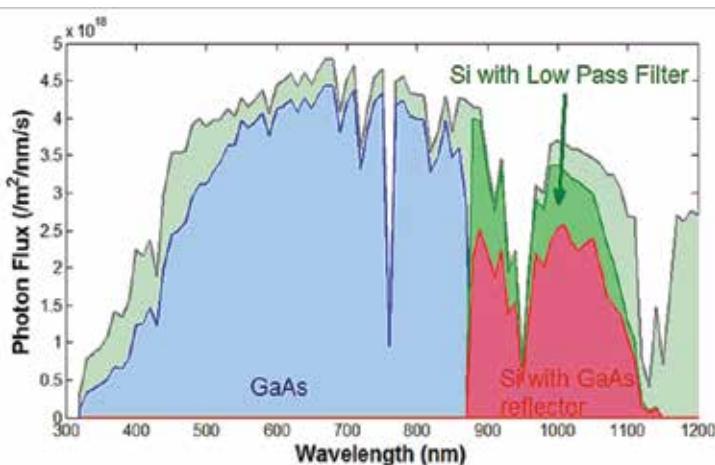


Figure PP1.3.22: Comparison of photon collection efficiencies for cells with and without a low pass filter in front of the GaAs cell (equivalent to an 860nm hot filter)

efficiencies, it is expected that the current of the Si cell could increase by up to 40%. This would result in a further increase in efficiency of 1.5% absolute.

Replacing the existing cell with a higher performance cell would also increase performance. High voltage is critical to maximise the value of the silicon cell in the system. The cells in this application were cut down from larger cells. This resulted in excessive edge recombination which limited open circuit voltage and fill factor. ANU has recently manufactured 4cm² IBC cells with efficiency of 24.4% (independently confirmed) with similar dimensions to the current system (6cm² aperture). The increase in voltage and fill factor by using these cells at approximately 1/4 current should boost the efficiency of the silicon cell in the system to about 5.5% to produce a potential system efficiency of greater than 34%.

The proposed system would lead to a more complex module build than a conventional module. One approach would be to have a 45 degree saw tooth superstrate on which the GaAs cells are placed. Bifacial silicon cells, such as SLIVER cells, would then be mounted in slots formed at the tops of the saw teeth. Light reflected from the GaAs cells would then strike the silicon devices as per the arrangement in these measurements. Opportunities exist for lower cost options than the GaAs cell provided performance exceeds the thresholds shown by *White et al.* [PP1.3.8].

Reference

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5. RESEARCH REPORTS

PROGRAM PACKAGE 2. Thin-Film, Third Generation and Hybrid Devices

Overview

Program Package 2 (PP2) involves collaborative research into a range of organic solar cells (OPV), organic/inorganic hybrid cells, “earth abundant” thin-film materials, including Si and CZTS, as well as more futuristic “third generation” approaches, with the overall goals of demonstrating efficiency above 15% during the program for cells of above 1cm² area and of demonstrating the feasibility of costs below the US Department of Energy’s SunShot targets.

The work on thin-film organic photovoltaics (PP2.1) represents one of ACAP’s largest sub-programs, involving almost all ACAP nodes and addressing roadblocks preventing economic mass manufacture of modules. The work involves investigation of different device structures, new materials and manufacturing processes as described in greater detail in the following pages. Ultimately, lower costs are targeted than with conventional cells or applications such as flexible or partly transparent cells, for which conventional cells are not well suited.

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 (CZTS) forms the focus of PP2.2, with the first operational devices produced during 2013 and 4.5% efficiency demonstrated by year-end. Good progress was also made with silicon thin-film devices under PP2.3, with laser processing proving the key to attaining record voltage output of 585 mV. As with PP2.1, lower costs than possible with conventional cells are targeted, or integration of these thin-film strands to form thin-film tandem cell stacks.

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. Silicon based nanodots and their potential application to photovoltaics forms a second key area of activity. These third generation approaches offer alternative approaches to attaining higher efficiencies than possible from tandem cell stacks.

PP2.1 Organic Photovoltaic Devices

Lead Institutions: UoM/Monash/CSIRO/UQ/UNSW

Background

(Organic Photovoltaics Priorities):

The current roadblocks preventing full module mass manufacturing of OPV include:

- a. Reduction of the transparent conducting electrode (TCE) sheet resistance will allow larger monolithic active areas – this will reduce manufacturing complexity versus the current serially connected thin strip architectures, allow greater current-voltage module flexibility, reduce the amount of interconnection metal, and improve yield because processes such as laser scribing will not be required. Ideally, indium tin oxide should be eliminated from organic photovoltaics for technical and cost reasons. Alternative, low cost, high transparency, low sheet resistance (< 5 ohm / sq) TCEs are a major focus in organic optoelectronics more broadly.
- b. Decrease the defect density in larger area organic solar cell sub-module architectures – Organic solar

cells are thin film structures with the junction often < 200 nm. For solution processing, this is a major issue causing an exponential scaling of defect density with area and a loss of fill factor because of shorting. This is also true to a somewhat lesser extent for vacuum evaporated systems. New junction materials with better electrical properties (higher mobilities and lower bimolecular recombination coefficients) will allow thicker junctions to be created whilst maintaining fill factor. Hence, larger monolithic active areas can be manufactured with dramatically lower defect densities. For solution-processed devices, junction thicknesses of 400 – 500 nm would be ideal and not dramatically impact cost.

- c. Improved light harvesting – multiple junctions extend the absorption range of a solar cell for more efficient light harvesting. However, multiple junctions are more complex and expensive to manufacture and an alternative strategy would be to extend the range of single junctions using concepts such as complementary absorbing acceptor-donor pairs.

PP 2.1a Organic Bulk Heterojunction Solar Cells

Research Team

Academic/ Post-Doctoral:

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Dr Thilini Ishwara, Dr Supriya Pillai

Research Students:

UNSW: Matthew Wright, Kah Chan, Rui Lin, Rui Sheng

Funding Support:

ACAP, ARENA, ARC, UNSW

Background

The primary goal is to fabricate the high efficiency organic bulk heterojunction solar cells in the OPV lab at UNSW. Although OPV conversion efficiency has improved significantly in recent years, progress in donor/acceptor morphology optimization still occurs largely by trial and error, in part because 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. If the morphology could be controlled on a molecular scale, the efficiency of charge separation and transport could be expected to be substantially higher. Work is now underway on fundamental issues of morphology optimization for organic films for OPV devices such as control of electronic structure at film interfaces, exciton dissociation and carrier transport for photovoltaic operation. *Ab-initio* (density functional theory – DFT) methods are a valuable tool to obtain insight into the charge separation (exciton dissociation) and transport process as well as the photochemical stability of organic molecules – a major challenge for organic PV. This helps

to find robust and electronically suitable molecules which determine the morphology of OPV devices. Furthermore, we have investigated the plasmonic enhancement of 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. Consequently, enhancements of external quantum efficiency at red wavelengths are observed. This plasmonic enhancement needs to be optimized to further improve the photo conversion efficiency of OPV cells.

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

The organic active layer in organic solar cell is composed of donor and acceptor blended materials. The concentration of donor and acceptor materials is an important parameter for the cell operation. We have systematically investigated the effects of solvent additive on inverted structure PCPDTBT:PC71BM bulk heterojunction organic solar cells. By incorporating 1,8-ODT into the polymer solution, an approximately 40 nm red-shift of absorption peak at long wavelengths was observed. The addition of 1 vol% 1,8-ODT greatly enhanced the overall optical absorption of

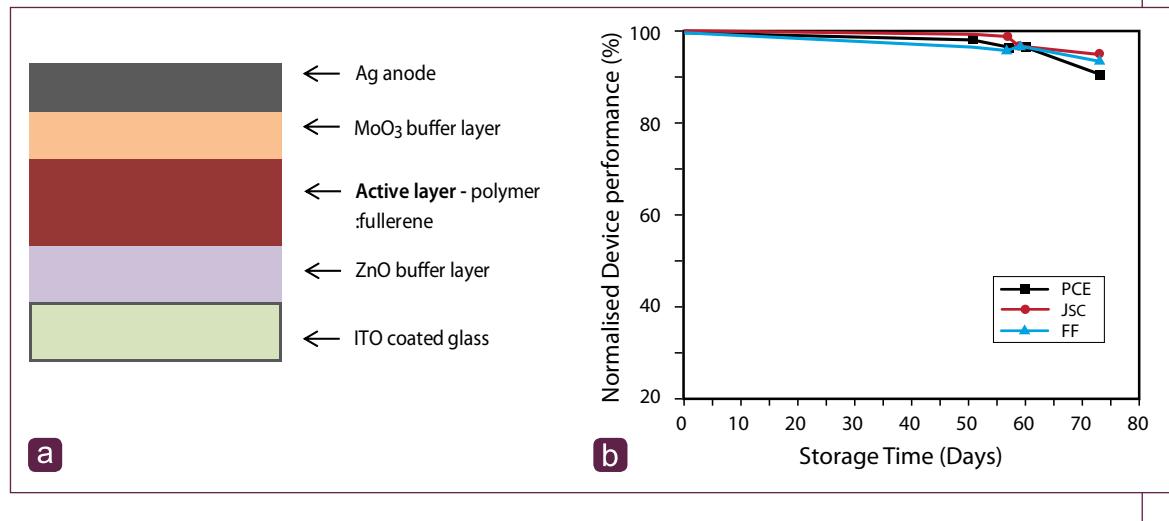


Figure PP2.1a.1: (a) Inverted structure of bulk hetero-junction OPV device;
(b) Average lifetime of inverted structure OPV devices without encapsulation.

PCPDTBT:PC71BM blend films and EQE spectra of the device. The J_{sc} was increased from 9.89 mA/cm² to 12.14 mA/cm² for the 1 vol% 1,8-ODT concentration. A reduction in device performance, caused by the residual 1,8-ODT, was observed as the additive concentration was increased. 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 a J-V characteristics is shown in Figure PP2.1a.2. The average improvements of device performance by the solvent additive for different concentration are summarised in Table PP2.1a.1.

(2-ethylhexyl)-4H-cyclopenta[2,1-b:3,4-b']dithiophene-silole 2,6-diyl]] (Si-PCPDTBT) is a low band gap donor material. It was reported that Si-PCPDTBT has higher mobility, better crystallinity and larger phase separation than other candidates. Si-PCPDTBT contains Si atoms which can be identified throughout the film to allow understanding of the vertical phase composition. These low bandgap polymers exhibit an absorption maximum in the 650 – 800 nm range, however, they have low absorption at 500 nm. This limits the maximum obtainable photocurrent. 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 causing poor device performance. We demonstrated ternary bulk heterojunction organic solar cells by incorporating P3HT into a Si-PCPDTBT:PC71BM 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 PCE by adding 1 wt% P3HT to the active layer blend. We have proposed that P3HT may act as recombination centres, which caused a reduction in device performance at higher P3HT concentrations. Through careful optimisation, we conclude that ternary blend photovoltaics can be a simple and effective way to achieve efficient organic solar cells. As an example the J-V characteristics of OPV devices are shown in Figure PP2.1a.3 for different concentrations of P3HT. The average improvements of device performance by adding P3HT for different concentrations are summarised in Table PP2.1a.2.

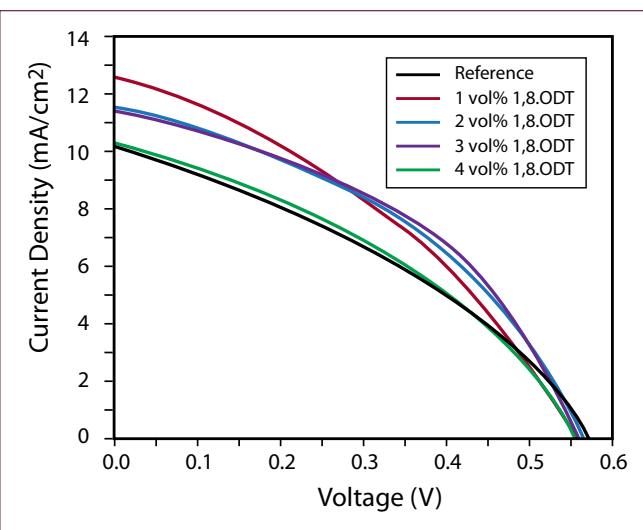


Figure PP2.1a.2: Current density (J) – voltage (V) curves of the reference device and the device with 1, 2, 3 and 4 vol% 1,8-ODT concentration.

We have also investigated the effect of P3HT as a sensitizer in Si-PCPDTBT:PC71BM active layer of OPV devices. Poly[2,1,3-benzothiadiazole-4,7-diyl][4,4-bis

	Average Jsc (mA/cm ²)	Average Voc (mV)	Average FF (%)	Average Efficiency (%)	Best Efficiency (%)
Reference	9.89	550.4	37.7	2.05	2.09
1,8-ODT 1 vol%	12.14	527.8	38.5	2.46	2.57
1,8-ODT 2 vol%	11.16	560.6	40.2	2.51	2.63
1,8-ODT 3 vol%	10.61	562.8	43.6	2.59	2.72
1,8-ODT 4 vol%	9.95	559.4	41.0	2.28	2.49
1,8-ODT 2 vol% after drying	11.61	540.3	40.3	2.53	2.64
1,8-ODT 3 vol% after drying	10.38	552.9	47.2	2.71	2.77
1,8-ODT 4 vol% after drying	11.32	563.2	44.8	2.85	3.00

Table PP2.1a.1: The average device performance of the reference device and the device with 1 vol%, 2 vol%, 3 vol% and 4 vol% 1,8-ODT concentration and the device with 3 vol% and 4 vol% 1,8-ODT after drying in vacuum overnight.

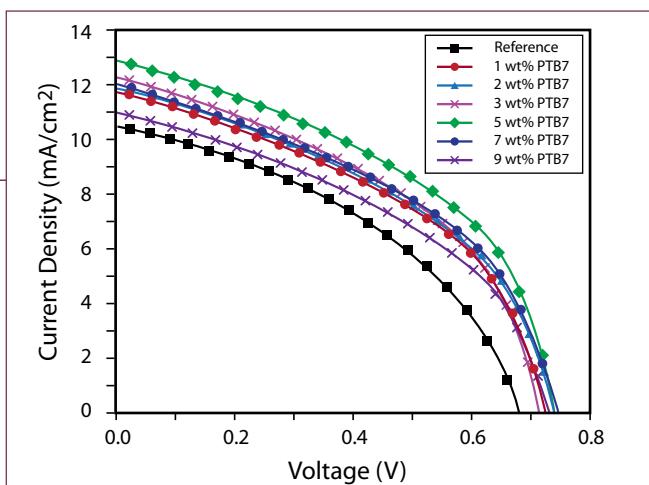


Figure PP2.1a.3: Current density-voltage curves of reference PCPDTBT:PC₇₁BM solar cell and PCPDTBT:PC₇₁BM solar cells with varying concentration of PTB7 from 1 to 9 wt%. The best improvement is coming for the 5 wt% of PTB7.

	Voc (mV)	Jsc (mAcm ²)	FF (%)	Rs ($\Omega \cdot \text{cm}^2$)	Average PCE (%)	Highest PCE (%)
Reference	626.9	11.1	42.2	13.6	2.93	3.21
1 wt% PTB7	667.1	12.7	43.4	10.3	3.68	3.68
2 wt% PTB7	663.6	13.2	42.5	10.1	3.72	3.82
3 wt% PTB7	657.3	13.3	44.5	9.2	3.89	3.91
5 wt% PTB7	675.4	13.4	45.0	9.1	4.07	4.28
7 wt% PTB7	676.2	12.2	42.4	11.9	3.49	3.82
9 wt% PTB7	657.9	12.1	39.1	15.2	3.14	3.58

Table PP2.1a.2: Photovoltaic characteristic performance of reference PCPDTBT:PC₇₁BM solar cells and PCPDTBT:PC₇₁BM solar cells with varying PTB7 weight percent.

PP 2.1b Organic-Inorganic Base Solar Cells

Research Team

Academic/Post-Doctoral:

UNSW: A/Prof. Ashraf Uddin, Prof. Martin Green, Dr. Thilini Ishwara

Research Students:

UNSW: Matthew Wright, Kah Chan, Rui Lin, Rui Sheng

Funding Support:

ACAP, ARENA, ARC, UNSW

Background

Inorganic-organic hybrid structures have become innovative alternatives for next-generation dye-sensitized

solar cells, because they combine advantages of both systems. Recently, inorganic-organic hybrid solar cells have experienced a dramatic increase in conversion efficiency. Nanocrystalline lead halide perovskites have emerged since 2009 as potential photosensitisers. The performance of a TiO₂ solar cell sensitized with iodide perovskite (CH₃NH₃PbI₃) was optimized further to attain an overall power conversion efficiency of 16%, now reported by multiple groups.

The aim of the polymer:metal-oxide solar cell project is to fabricate and characterize the devices; to establish reproducible benchmark devices (bilayer and multilayer) against which future improvements can be evaluated; to test novel materials including polymers for improved

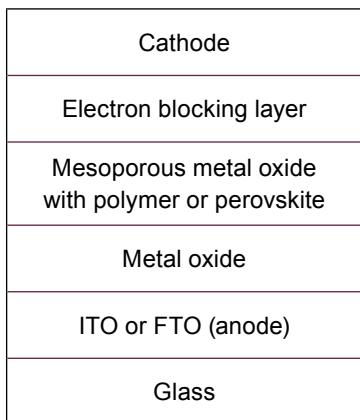


Figure PP2.1b.1: Organic – inorganic base solar cells.

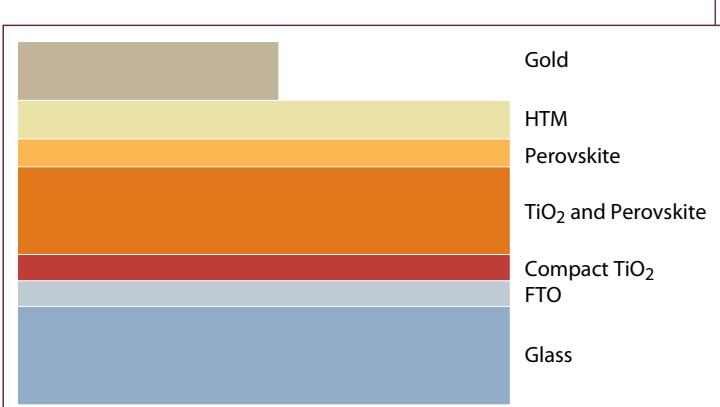


Figure PP2.1b.2: Schematic diagram of perovskite device structure.

photon harvesting, improved infiltration properties, or better compatibility with inorganic material, better metal-oxide nanostructures, SAMs for surface modification, QDs etc. We also plan 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.

Several collaborations with internal and external groups and an Australian company were established. Collaborations with Dyesol and Dr. Wallace Wong (ASI fellow, University of Melbourne) were established to provide novel organic materials (C106- Dyesol and FHBC, WW436- Dr. Wong). The preliminary results using these materials are promising. The processing conditions have not yet been optimized and this is required prior to establishing the degree of improvement possible by these materials. A novel ruthenium dye C106 (Ruthenium(4,4'-bis(5-(hexylthio)thiophen-2-yl)-2,2'-bipyridine)(4-carboxylic acid-4'-carboxylate-2,2'-bipyridine)(bis-isothiocyanate)) provided by Dyesol was applied as a surface modifier of the TiO₂ film. The objective was to improve the compatibility of the TiO₂ surface with the polymer film. The polymer used in these studies was P3HT. As the compatibility of the TiO₂ surface of the porous layer increased, it was expected that more polymer would infiltrate the porous film and result in an increased short-circuit current density (J_{sc}). The surface modified device gave a J_{sc} of more than double compared to an unmodified device. The open-circuit voltage (V_{oc}) was also increased by almost 0.2 V. The increased V_{oc} would be a result of increased spatial separation between the polymer and TiO₂ 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 TiO₂ surface, and could be responsible for slowing down recombination, resulting in increased V_{oc} . The fill factor is improved by optimizing the processing conditions.

FHBC and WW436 provided by Dr. Wong are Hexaperi-hexabenzocoronene compounds used as hole-transporting, solution-processable small molecules.

As infiltration of the porous film should be easier for small molecules than for long chain polymers such as P3HT, it was expected that these small molecules would result in improved infiltration compared to P3HT. However their absorption is blue shifted (~400 nm compared to P3HT absorption ~550 nm) leading to lower J_{sc} . Therefore these materials were used only for the infiltration film. Subsequently a P3HT film was deposited on the device by spin-coating, to partially coat the top portion of the porous film and as an overlayer. Therefore, it was expected that by using this technique J_{sc} would not be compromised. The resultant devices from both compounds showed increased J_{sc} with improvement in V_{oc} as well.

In order to investigate different metal-oxide nanostructures in the hybrid structure, collaboration was established with Prof. Rose Amal's group (School of Chemical and Industrial Engineering, UNSW). The group is currently investigating growth of ZnO nanorods on TiO₂ dense films provided. Future projects planned by the group include growth of TiO₂ nanotubes for the structure.

We have also started work on fabrication and characterization of perovskite solar cell and are trying to achieve high efficiency devices by increasing V_{oc} , J_{sc} and fill factor (FF). We are working towards attaining our goal by studying the exciton recombination mechanism, morphological control of precipitation of the perovskite, developing a sequential deposition method for the control of precipitation, and investigating different metal halide microstructures for the conversion of desired perovskite, amongst other things. As the complexity of solution-processed devices increases, controlling and optimizing layer morphology, texture, exclusivity, charge transfer, and thickness become difficult. The schematic diagram of our perovskite solar cell structure is shown in Figure PP2.1b.2. This device uses ITO as a photo anode, and a layer of compact TiO₂ deposited on the FTO acts as an insulation layer to avoid the device being shunted by hole transport material. Mesoporous TiO₂ is the next layer to come in contact with perovskite molecules to create electrons

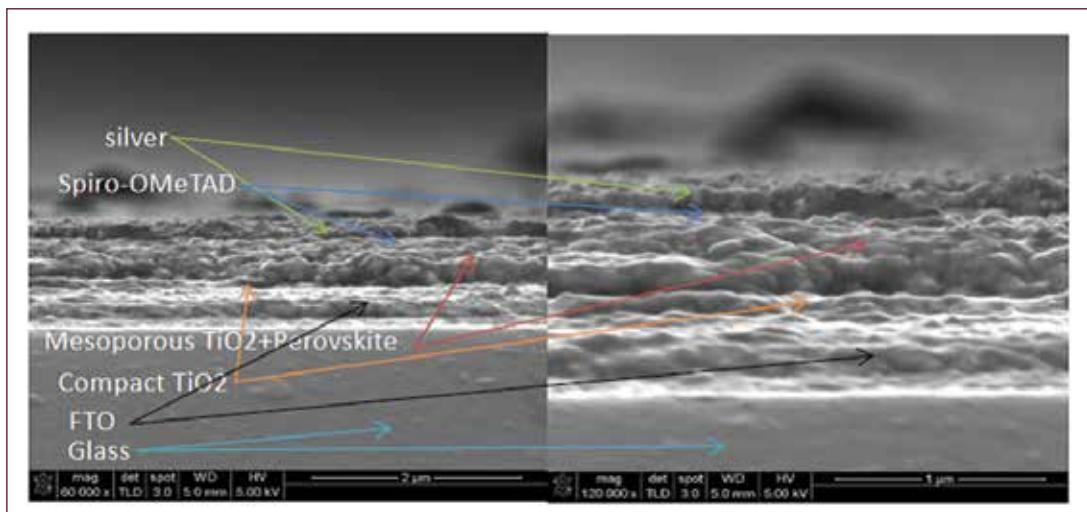


Figure PP2.1b.3: SEM image of perovskite device structure grown at UNSW.

PP 2.1c(a) Printing (Photocurrent Mapping) Lead Institutions: Melbourne/CSIRO

Research Team

Academic/ Post-Doctoral:

UoM: Prof. Andrew Holmes, Dr David Jones, Prof. Ken Ghiggino, Dr Ben Robotham

CSIRO: Dr Gerry Wilson, Dr Scott Watkins, Dr Doojin Vak, Mr Andrew Faulks, Dr Noel Duffy, Dr Andrew Scully

Funding Support:

ACAP, ARENA, VICOSC Victorian Government DBI

Aim

Design and implement a high speed, photocurrent mapping tool for use on large scale (A4) size modules.

Results

A bespoke system has been designed, installed and is now in operation. Images of the system at work on an A4-sized printed solar module are shown in Figure PP2.1c.1.

The system operates by moving the sample along one axis and the light along the other. Current is recorded in a continuous sweep. Images of an aged, printed device are shown in Figure PP2.1c.2. The system has the following specifications: <50μm max resolution, 15×30 cm scan area, ca. 5s/line. 1mm line spacing = 5min scan time, 50μm line spacing = 1.5h scan time.

Work to date has enabled the identification of shorts in the devices that, when removed, have doubled the power conversion efficiency of the devices.

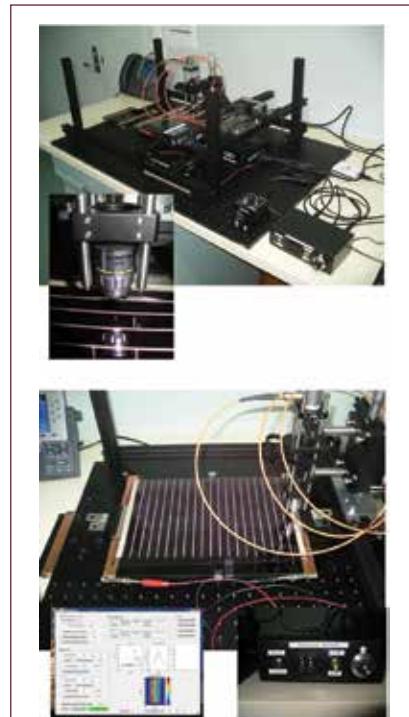


Figure PP2.1c.1:
Photographs of the Photocurrent mapping system and graphical user interface.

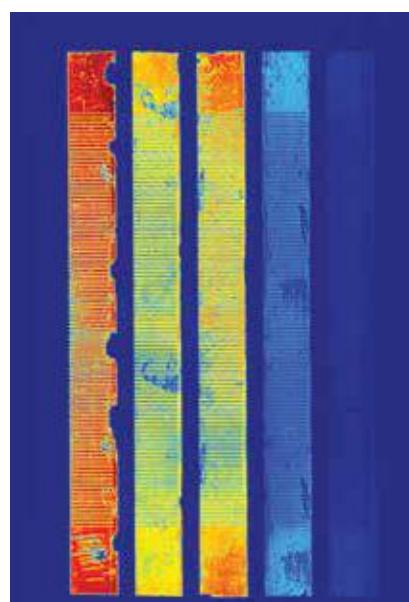


Figure PP2.1c.2:
Photocurrent mapping of an aged printed solar cell. Stripe length is 10cm.

PP2.1c(b) Printing: Melbourne/CSIRO

Aim

To study the use of Flexible Glass as a substrate/encapsulant for devices.

Results

Discussions are still underway with suppliers to procure large quantities of these materials and no work can be reported at this point.

Large-scale printing work by the team has continued under the existing VICOSC projects and know-how from these trials will be made available for this project.

PP2.1c(c) Scale-up: Melbourne/Monash/CSIRO

Research Team

Academic/ Post-Doctoral:

UoM: Prof. Andrew Holmes, Dr David Jones,
Prof. Ken Ghiggino, Dr Ben Robotham

CSIRO: Dr Gerry Wilson, Dr Scott Watkins, Dr Doojin
Vak, Mr Andrew Faulks, Dr Fiona Scholes

Industry:

Solmax (Aramax): Ms Leesa Blazley

Funding Support:

ACAP, ARENA, VICOSC Victorian Government DBI

Aim

To conduct outdoor studies on printed OPV modules.

Results

Panel designs have been agreed with the manufacturers and we are on track for installation in Q2 2014.

PP2.1c(d) Scale-up (Education): CSIRO

Research Team

Academic/ Post-Doctoral:

CSIRO: Dr Gerry Wilson, Dr Scott Watkins, Dr Doojin
Vak, Mr Andrew Faulks, Dr Fiona Scholes

Funding Support:

ACAP, ARENA, VICOSC Victorian Government DBI

Aim

To provide schools and universities with samples of printed solar cells for incorporation into demonstrators and experiments.

Results

Plans have been agreed with STELR and a number of education groups and teachers for the delivery of printed modules throughout 2014.

PP2.1c(e): Novel Coating Processes for Prototypes and Discovery

Research Team

Academic/ Post-Doctoral:

CSIRO: Dr Gerry Wilson, Dr Scott Watkins, Dr Doojin
Vak, Mr Andrew Faulks, Dr Fiona Scholes,
Ms Régine Chantler, Ms Anna Graeser,
Mr Kyeongil Hwang, Ms Yen-Sook Jung

Funding Support:

ACAP, ARENA, VICOSC Victorian Government DBI

Aim

The CSIRO team has developed bespoke coating systems for the deposition of materials for printed solar cells. This work is currently the subject of papers that have been submitted for peer-review. Once accepted for publication, these papers will be recorded in the next ACAP report.

PP2.1d OPV Industrially relevant solvent systems Lead Institution: UoM

Research Team

Academic/ Post-Doctoral:

UoM: Dr David Jones, Prof. Andrew Holmes,
Prof Kenneth Ghiggino, Dr Shirong Lu

Research Students:

UoM: Valerie Mitchell, Sam Farley

Funding Support:

ACAP, ARENA, University of Melbourne

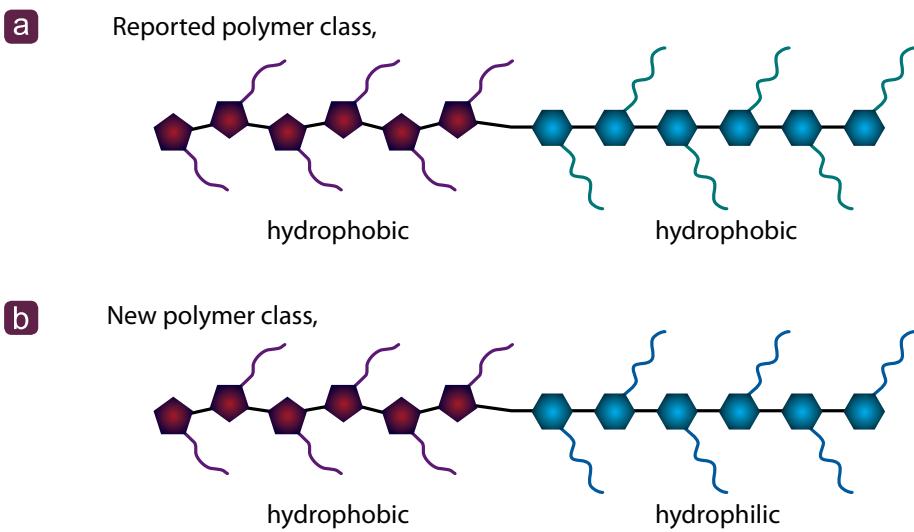


Figure PP2.1d.1: Development of Donor-Acceptor block copolymers soluble in industrial relevant solvent by incorporation of appropriate solubilizing groups.

Background

Organic bulk hetero-junction solar cells have reported efficiencies approaching 10% PCE for single junction devices and over 12% PCE for tandem solar cells. Printed organic solar cell modules have been reported at over 2% PCE and we have reported 2.2% PCE for 10cm x 10 cm printed modules with five solar cells connected in series. However, many of the solvents of choice in the laboratory are chlorinated and are not acceptable in an industrial environment, while BHJ materials are poorly soluble in industrially relevant solvents and bulk hetero-junction formation remains challenging. The aim is to develop high performance materials that are soluble in industrially relevant solvents.

Program

Donor-Acceptor block copolymers have been reported to give relatively high efficiencies for the best examples, up to 3.1% PCE [PP2.1d.1] and have potential to overcome solvent choice issues. Morphology control is essential for high performance organic solar cells and the free energy difference between the Donor and Acceptor driving phase separation and therefore morphology development. In

block copolymers the Donor and Acceptor are covalently linked removing the requirement for similar free energies to control morphology development, and should be different to drive high levels of phase separation. This allows for the inclusion of solubilising units, which are compatible with industrial relevant solvents.

New high performance block copolymers are currently being synthesised, see Figure PP2.1d.1. The synthetic methods have been chosen to ensure a range of solubilising groups can be readily incorporated into hydrophobic-hydrophilic analogues of Donor-Acceptor block copolymers. These new polymers will be soluble in industrially relevant solvents.

The key building blocks are being synthesised for the new Donor-Acceptor polymers.

References

- PP2.1d.1 Yen-Hao Lin, Kendall A. Smith, Chloe N. Kempf and Rafael Verduzco *Polym. Chem.* **4**, 229–232, 2013.
- PP2.1d.2 Wallace W. H. Wong, Jegadesan Subbiah, Jonathan M. White, Helga Seyler, Bolong Zhang, David J. Jones, and Andrew B. Holmes, *Chem. Mater.* **26**, 1686–1689, 2014.

PP2.1e High performance materials – Lead Institution: UoM

Research Team

Academic/ Post-Doctoral:

UoM: Dr David Jones, Dr Wallace Wong, Prof. Andrew Holmes, Dr Jegadesan Subbiah, Dr Yu-Ying Lai

Research Students:

UoM: Bolong Zhang, Dean van As, Calvin Lee, Aaron Song

Academic Partners:

ACAP, ARENA, University of Melbourne

Background

Many high performance materials have been found to be unstable under the processing condition required during printing. There is a need to develop high performance materials, which are stable under current processing conditions. The ability to synthesize high performance materials on a large scale needs to be developed using the inherent advantages of continuous flow systems. One key component of the organic bulk hetero-junction is the design and synthesis of the electron acceptor.

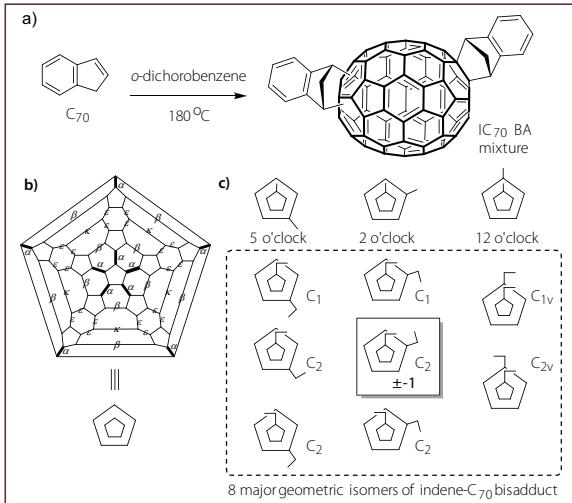


Figure PP2.1e.1: Development of Donor-Acceptor block copolymers soluble in industrial relevant solvent by incorporation of appropriate solubilizing groups.

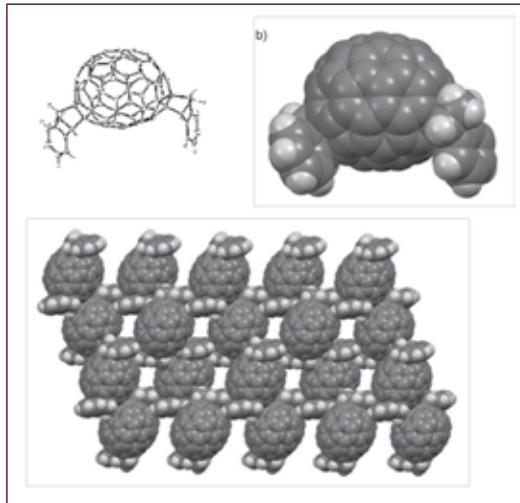


Figure PP2.1e.2: Structure obtained by X-ray analysis of ±1 crystals grown from chloroform solution of IC₇₀ BA a) thermal ellipsoid illustration; b) space filling model and c) packing diagram where disordered CHCl₃ solvent molecules have been omitted for clarity.

Program

High performance organic bulk hetero-junction solar cells can be assembled using the bis-indene adduct of C₇₀ fullerene, Figure PP2.1e.1. The synthesis results in the formation of a number of isomers. Isolation of the major isomers has revealed that bulk hetero-junction performance varies with each regio-isomer [PP2.1e.1]. High performance can be achieved with certain, crystalline bis-indene adducts, see Figure PP2.1e.2 for structure.

The current synthetic program is targeting the selective synthesis of the high performance C₇₀ regio-isomers for high performance organic solar cells.

Reference

- PP2.1e.1 Wallace W. H. Wong, Jegadesan Subbiah, Jonathan M. White, Helga Seyler, Bolong Zhang, David J. Jones, and Andrew B. Holmes, *Chem. Mater.* 26, 1686–1689, 2014.

PP2.1f OPV Device architectures – Lead Institution: UoM

Light Harvesting – Luminescent Solar Concentrators: New Chromophores

Research Team

Academic/Post-Doctoral:

UoM: Dr Wallace Wong, Prof. Kenneth Ghiggino

Research Students:

UoM: James Banal

Background

Integrating photovoltaics into building infrastructures is the next key step towards wide-scale implementation of solar technologies. However, there remain issues with the broader use of solar cells, particularly in urban areas where the amount of light incident on the cell can be restricted compared to open spaces, due to cloud shading or light scattering by local flora. One of the strategies to circumvent this problem is to use light concentrating systems such as parabolic mirrors and solar trackers. These concentrators, albeit effective in concentrating light, are rather bulky for integration in an urban locale and expensive due to the associated electrical and mechanical components required for solar tracking. Furthermore, such concentrators can heat the solar cells, which can accelerate performance degradation.

Luminescent solar concentrators (LSCs) rely on the absorption of solar light by highly luminescent materials embedded in glass or plastic substrates (Figure PP2.1f.1). Subsequent waveguiding of emission to the thin edges of the substrate concentrates the luminescence which can, in principle, be used to improve the output of photovoltaic devices. The simple device configuration of LSCs means photovoltaics can be integrated into urban environments, such as windows and walls, at low cost [PP2.1f.1]. Currently, factors limiting LSC efficiency include reduced fluorescence quantum yield in the solid state arising from dye aggregation [PP2.1f.2] and reabsorption of dye emission (i.e. due to a small Stokes shift). Commercial laser dyes such as rhodamines, coumarins, and perylenes have been used for LSCs. A common feature of such dyes is their highly planar conjugated structure, which is conducive to the formation of non-emissive aggregates, particularly at the high concentration required for total light absorption. Consequently, the fluorescence quantum yield of these dyes in the solid state is much lower than that measured in solution. These dyes also have significant overlap between their absorption and emission spectrum resulting in reabsorption losses [PP2.1f.4].

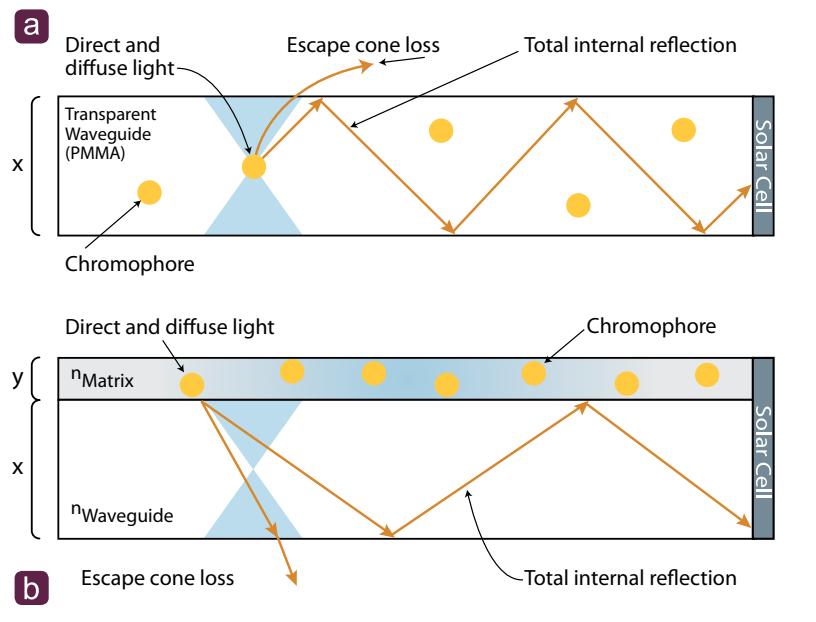


Figure PP.2.1f.1:
Conventional structures for LSC applications:
(a) millimeter-thick (x) waveguides (typically polymer matrices) infused with fluorescent dyes and
(b) micron-thick thin layer matrices (y) cast on top of a waveguide (typically glass). In this study, structure **(b)** is used with a neat film layer.
(n = refractive index).

In this program package module, our aim is to design new chromophores to overcome the limitation of current dyes used in LSC devices.

Approach 1: Aggregation induced emission (AIE)

Twisted aromatic structures have been proposed for use in a number of applications such as in light-emitting devices and as bioprobes. This class of aromatic compounds has interesting fluorescence properties – emission is greatly enhanced in the solid state compared to the compounds in solution. This fluorescence behavior is widely referred to as aggregation induced emission (AIE) [PP2.1f.3].

However, enhancement of chromophore emission does not only occur in the solid state but also when dispersed in a polymer matrix or in frozen solution [PP2.1f.4]. It has been proposed that these conditions block the non-radiative decay pathway due to intramolecular rotation and channel the excitation energy towards fluorescence [PP2.1f.5].

Tetraphenylethene (1) is a compound well known for its AIE behavior (Figure PP2.1f.2). The quantum yield of 1 has been reported to increase as the molecule is rigidified, i.e. phenyl rotations are being hindered thus favoring the radiative pathway [PP2.1f.6]. In order to assess the potential of twisted and contorted aromatic compounds in LSC applications, a series of molecules with phenyl ethene moieties (1-5) were synthesized and fully characterized (Figure PP2.1f.2). The AIE behavior of these compounds was confirmed in photoluminescence experiments in solution and in solid state. A fluorescence quantum yield of close to 50% was recorded for compound 1 in solid state. With the AIE behavior confirmed, the most promising candidate, compound 1, was examined in LSC device configuration (Figure PP2.1f.3). An optical quantum efficiency of 20% was achieved for the LSC device. This proof-of-concept study showed that chromophores exhibiting AIE behavior are promising candidates for next-generation LSC dyes. The results of this study have led to a patent application [PP2.1f.7] and been published [PP2.1f.8].

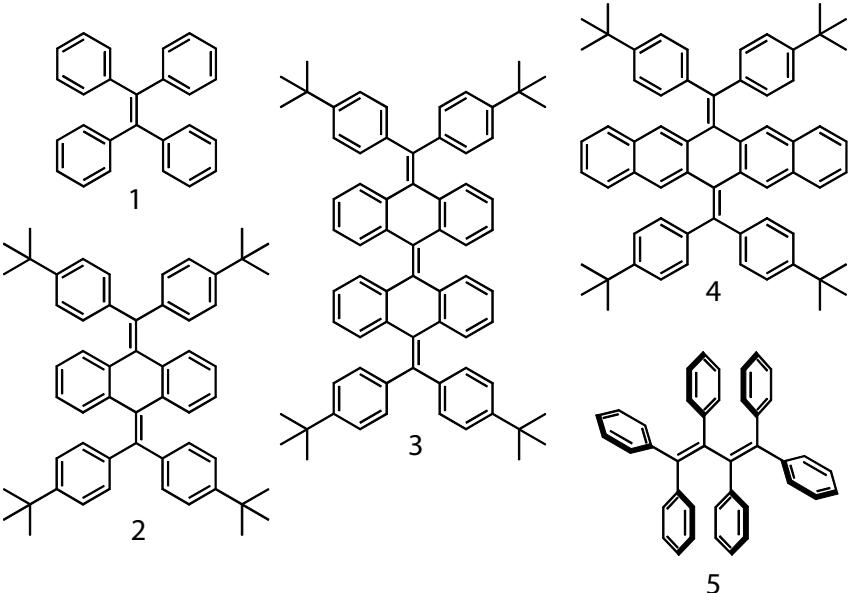


Figure PP2.1f.2: Structures of twisted and contorted aromatics with propeller-like phenyl rings for AIE activation.

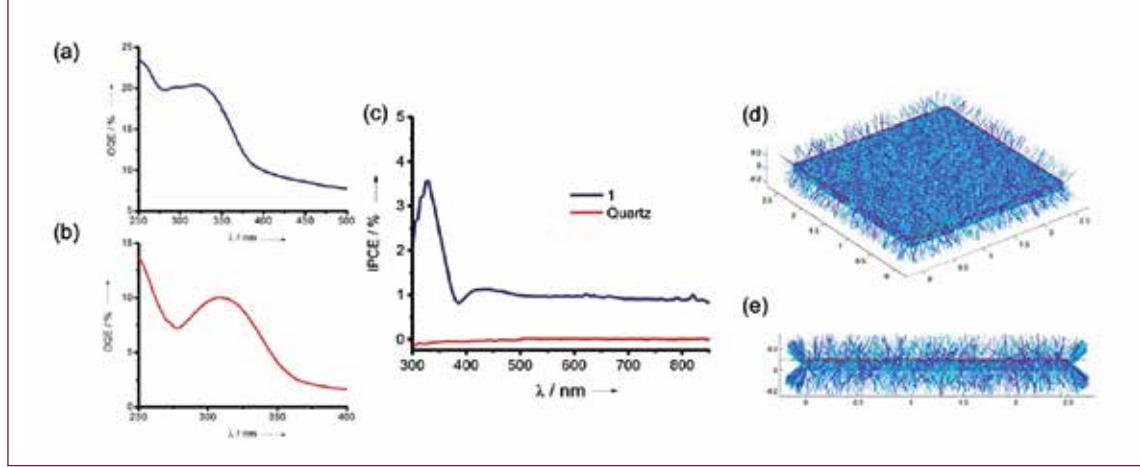


Figure PP2.1f.3: (a) Absorption and emission spectra of chromophore 1 dispersed in PMMA (10% w/w, 5 μm film thickness). (b) Emission from the chromophore film is waveguided to the edges and matches predictions from Monte Carlo ray-tracing simulations. (c) The optical quantum efficiency (OQE) can reach up to 13% (13.2% experiment, 13.4% simulation) for a single material comparable to state-of-the-art phosphor based energy transfer systems that shows negligible losses with increasing concentrator size [PP2.1f.12]. (d) Absorption and emission spectrum of 5

Approach 2: Electronic energy transfer (EET) system

Re-absorption of light in an LSC device is one of the major issues hindering efficiency. Another approach is to use electronic energy transfer (EET) to induce a large Stokes shift to reduce re-absorption. A non-covalent EET approach uses two or more dyes, which absorb light at different wavelengths and most of the emission of the OSC, in the case of efficient energy transfer, originates from the terminal dye that absorbs at the longest wavelength [PP2.1f.9]. The concentration of the EET donor and acceptor species is very low to avoid aggregation effects and to minimize reabsorption. The use of organic light-emitting diode (OLED) materials for EET OSCs has been successfully demonstrated. Typically, OLED fluorophores have a lower quantum yield than laser dyes but have a larger Stokes shift; hence, they are less sensitive to reabsorption effects. However, these materials are still susceptible to concentration quenching [PP2.1f.10]. Trade-off between absorption and quantum yield is unavoidable for materials that have been reported in literature, which limits the possible conversion efficiency of the OSCs.

Our approach is based on using FRET but using fluorophores that exhibit unusual properties in contrast to the dyes that have been used for OSCs. Due to the large Stokes shift and insensitivity of these chromophores to aggregation, the concentration of these materials can be maximized without compromising the absorption efficiency of the OSC. Low concentration doping of the film, with red-emitting acceptors with high quantum yields, shifts the emission to the red region, Figure PP2.1f.4. This large asymmetry in absorption between donor and acceptor, which is not possible with currently reported dyes, minimizes reabsorption losses and maximizes absorption. This results in a slower decrease in performance with increasing LSC device size without the use of rare earth metals [PP2.1f.12] or photophysical processes involving triplet states [PP2.1f.11], which are sensitive to oxygen environments.

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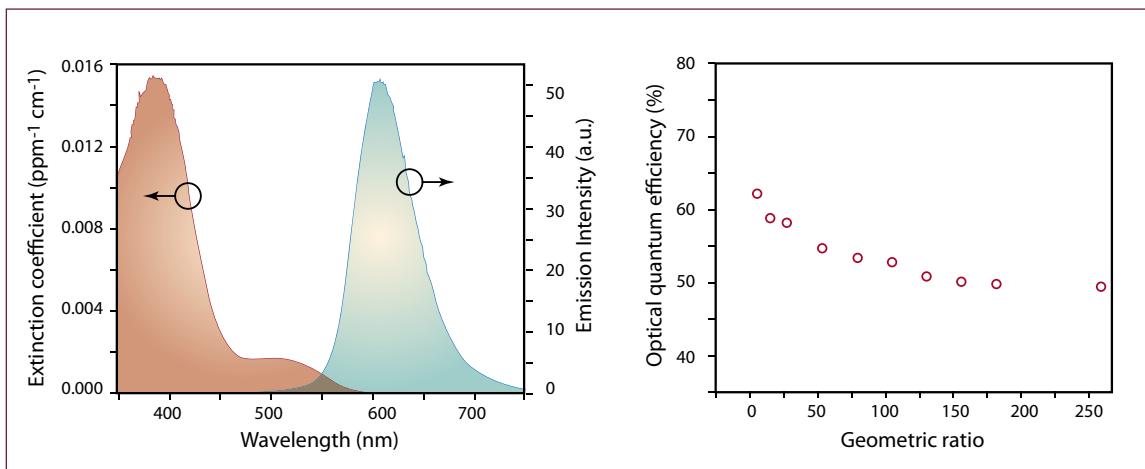


Figure PP2.1f.4. Absorption and emission spectrum of the dye ensemble in polymer matrix (left) and OSC efficiency relative to LSC waveguide size (right).

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PP2.1g OPV Characterisation Lead Institution: UoM

Research Team

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Research Students:

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Funding Support:

ACAP, ARENA, ARC, UoM

Background

Efficiencies of thin-film photovoltaic cells could be further improved with new insights into the role of active material morphology, material defects and degradation mechanisms on device performance. In addition, developing solar cell technologies requires refined methods to characterize performance and durability. In this research program new spectroscopic and other characterization methods are being developed and applied to study light

induced behavior in organic photovoltaic materials.

An instrument was designed and assembled to simultaneously measure the photocurrent and fluorescence generated in a photovoltaic cell with micron scale spatial resolution. The instrument involves the collection of photocurrent and fluorescence information as the solar cell is scanned on a piezo-electric stage, while under illumination from a focused laser beam. Photocurrent and fluorescence images are produced, allowing the identification of defective regions in the solar cell where photocurrent generation is low and, combined with fluorescence information, these can provide insights into charge formation mechanisms. In Figure 2.1g.1 the photocurrent and fluorescence maps of a 20 micron ‘pinhole’ defect in a printed polymer solar cell are shown, illustrating that the detrimental effect on photocurrent extends over a much larger area than the apparent ‘pinhole’ damage.

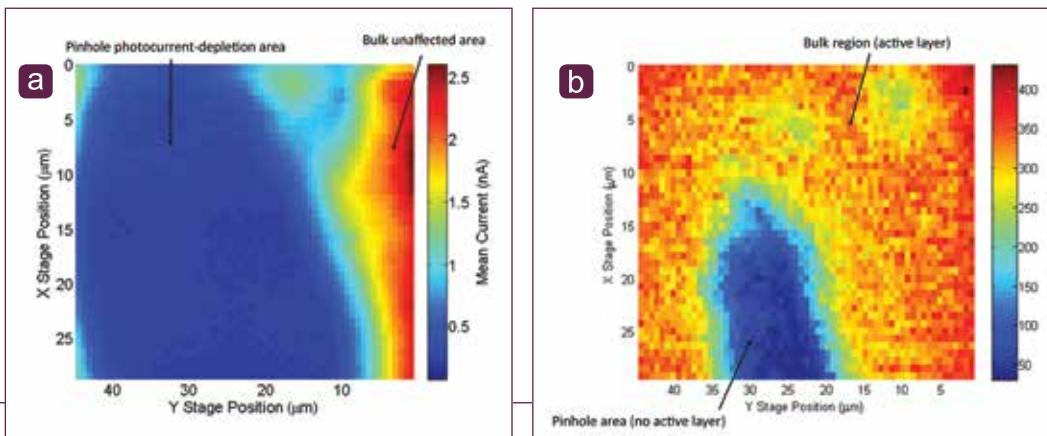


Figure 2.1g.1: Photocurrent (left) and fluorescence (right) images of a pinhole defect in a printed polymer solar cell illustrating the large impact of the defect on the cell performance.

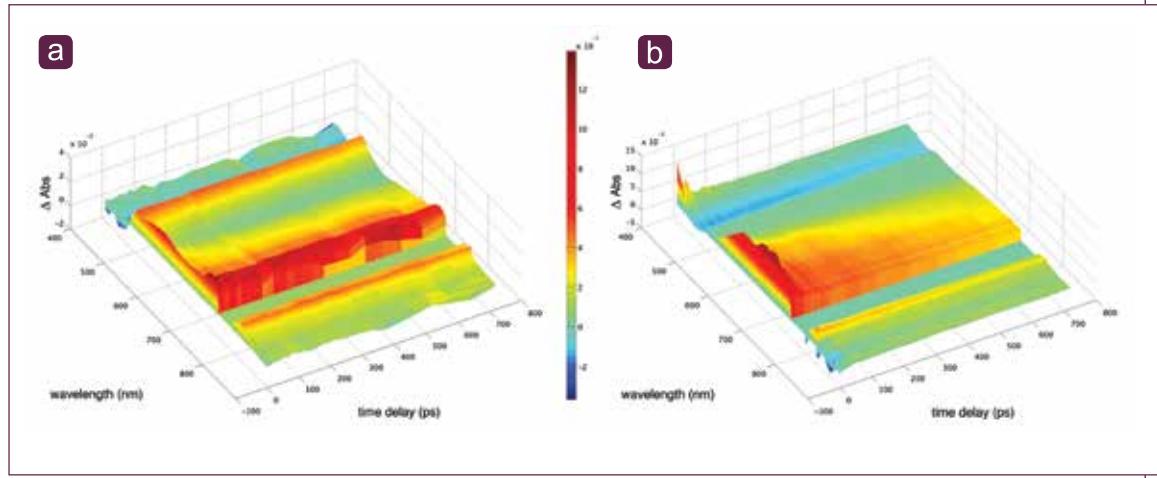


Figure 2.1g.2: Picosecond transient absorption spectra of a blend of PFM and F8BT polymers (left) compared to a block copolymer of PFM-F8BT-PFM (right) showing the spectral evidence of charge separation in the block copolymer following light absorption.

The initial light driven processes in the active materials of thin film polymer solar cells occur in less than one billionth of a second (i.e. $<10^{-9}$ seconds). In order to understand how these very fast processes can be optimized and thus improve solar cell performance, femtosecond transient absorption measurements and dynamic fluorescence measurements on the active polymer materials need to be performed. During the past year a femtosecond laser based transient absorption instrument has been applied to study how

charge separation occurs in new donor-acceptor semiconducting block copolymers synthesised by ACAP collaborators and designed for use in organic solar cells. This work has demonstrated that charge separation processes occur following light absorption in the block copolymer that are not apparent in a simple blend of the constituent polymer materials. These results confirm the important role of the polymer structure in determining the performance as a photovoltaic material.

PP2.1h: Elucidating the role of donor and acceptor in photocurrent generation Lead Institution: UQ

Research Team

UQ: Dr Dani Lyons, Dr Hui Jin, Ms Sarah McGregor, Dr Yuan Fang, Mr Ajeesh Chandrasekharan, Mr Mike Hambisch, Mr Wei Jiang, Mr Ardalan Armin, Mr Martin Stolterfoht, Prof. Paul Burn, Prof. Paul Meredith.

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 thereby reducing cost.

Progress and Results

We have progressed this research in two main areas:

- Non-Fullerene Electron Acceptors – We have designed and synthesized a number of electron acceptors (n-type materials) which are capable of absorbing light in the solar cell junction and generating photocurrent by photo-induced hole-transfer. There is no clear understanding as to why fullerenes are so successful as the electron

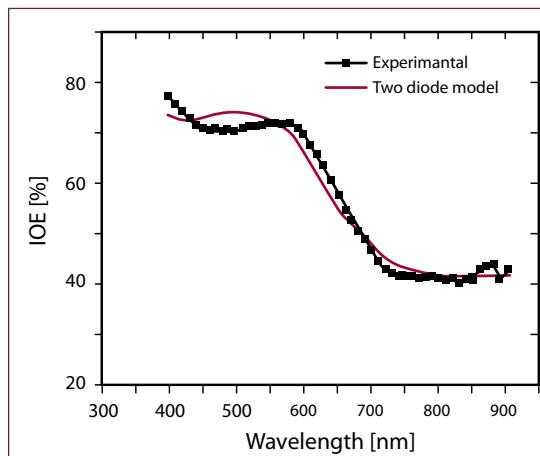


Figure PP2.1h.1: IQE of the DPP-DTT:PC70BM model high efficiency system, modelled as two photodiodes in parallel – the IQE is stepped showing the relative efficiencies of the two photocurrent generating pathways.

accepting component in organic solar cells, and our objective in synthesizing and ultimately testing our new molecules is not only to validate the complementary absorption principle, but also to establish the basic structure-property relationships which dictate the performance

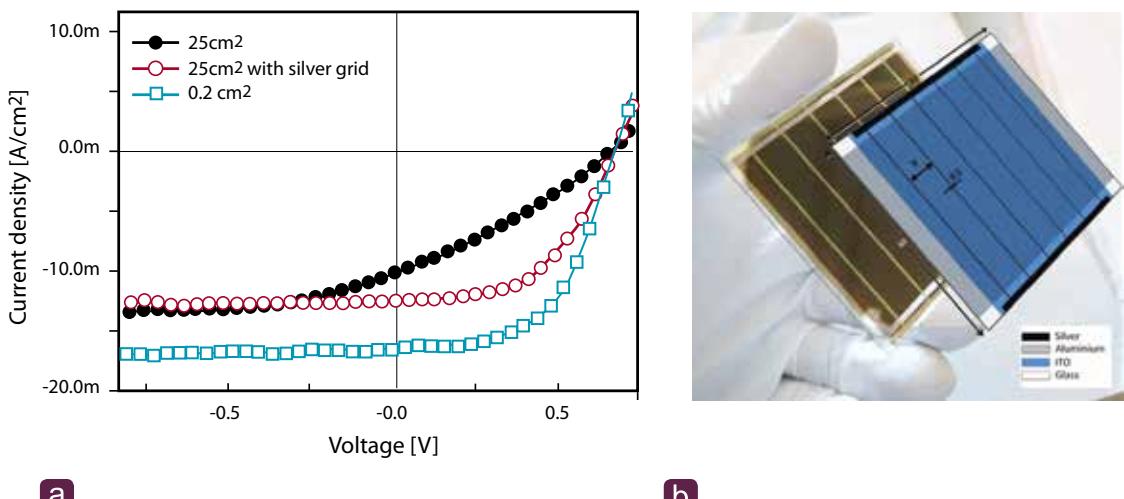


Figure PP2.1i.1: (a) Current-voltage curves for thick (250nm) large area devices under AM1.5G illumination with and without silver grid on glass, as well as a small area solar cell device with the same thickness and structure (b) photograph of large area DPP-DTT:PC70BM solar cell with the silver grid back contact bus bars. The schematic of the device is also shown.

metrics. Going forward we will integrate this family of model non-fullerene molecules into optimized bulk heterojunction solar cells and thoroughly characterize their behaviour, in particular the external and internal quantum efficiency (see PP3.1).

- ii. Fundamental understanding of the charge generating pathways in organic solar cells – We have developed robust methodologies for studying the relative contributions of the various photocurrent generating pathways in organic solar cells. We have shown clearly that photocurrent can be generated via two pathways: i) light absorption in the electron donor followed by photoinduced electron transfer to the acceptor (Channels I and II) light absorption in the electron acceptor followed by

photoinduced hole transfer to the donor (Channel II). Accurate measurement of Internal Quantum Efficiency (see PP3.1) has allowed us to calculate the relative efficiencies of these two channels. We have discovered that several model high efficiency polymer fullerene systems such as PCDTBT:PC70BM predominantly work as Channel II devices. This is counter to conventional thought which holds that most of the photocurrent arises from absorption in the donor component. In fact, the p-type polymer appears to be merely acting as a matrix for the fullerene and hole-transporting medium. We have also demonstrated that both channels can operate simultaneously in different spectral regions with different efficiencies leading to a “stepped” IQE in the new high efficiency system DPP-DTT:PC70BM (Figure PP2.1h.1).

PP2.1i: Characterizing the factors that affect photocurrent collection in sub-module cells - Lead Institution: UQ

Research Team

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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 and Results

We have progressed this research in two main areas:

- i. Lower sheet resistance transparent conducting anodes – indium tin oxide / PEDOT:PSS has been the standard transparent electrode in organic solar

cells and has a sheet resistance of 10-15 Ω/sq. At this sheet resistance we previously showed that current collection pathways are limited to ~1.5 cm. This is the reason that organic solar cell modules are predominantly thin serially connected strips, a complex and wasteful architecture. To address this problem we had previously developed a metal oxide / thin metal / metal oxide anode with a sheet resistance of ~5 ohms/sq and 85% optical transmission. This enabled us to demonstrate a 5cm x 5cm monolithic single junction with a PCE > 3%. We have built on that work and recently demonstrated a 5% 5cm x 5cm monolithic sub-module, which is a new record efficiency. This sub-module was built from the polymer DPP-DTT with the fullerene PC70BM and used a back contact metallic bus bar. In principle, this approach is completely scalable and be followed up with optimizing the structure and targeting larger junction areas. Figure PP2.1i.1 shows the current voltage characteristics of such a sub-module with the striking feature being the maintenance of the fill factor in the 25cm² device with the back contact bus bars.

PP2.1j Hybrid devices Lead institution: Monash University

Research Team

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Funding Support:

ACAP, ARENA, VICOSC, ARC, Monash

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 aim to implement a number of novel device concepts, in particular third generation photovoltaics. 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 in Berkeley, 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 2013 focused on two types of organic-inorganic hybrid solar cells. One is the conventional DSC concept, where the light absorber and charge transporter are two different materials and the other has a hybrid semiconducting material to perform as a light absorber as well as a charge transporter. The aim of our work is to achieve high efficiency in these solar cells.

Conventional DSC devices contain solvent based electrolytes, which would be unstable at high temperatures and be predominantly responsible for the relatively short lifetime of the devices. There is a strong incentive to develop more stable electrolytes. One of strategies is to remove the solvent and use solid-state or gelled electrolytes, incorporating transition metal complexes as redox mediators. In addition, we will investigate the application of metal complexes as redox mediators in p-type DSC and tandem p-n type DSC devices.

Very recently, a new type of solid state thin film solar cells based on organometal halide perovskites has shown some very exciting outcomes of the hybrid solar cells. The devices are made of a metal oxide film (TiO_2 or Al_2O_3), a perovskite sensitizer and a solid-state hole transport material. Due to the extraordinary light absorption and charge transport properties of the

perovskites, this new type of solar cells has achieved 15% power conversion efficiency in a relatively short time.

Activities

PP2.1j(a): Solid-state Dye-sensitized solar cells

Dye-sensitized solar cells (DSCs) have the advantage of being able to operate in diffuse sunlight with the possible application of indoor light reutilization technology. An aspect crucial for the industrial application of DSCs is a robust electrolyte system. The redox mediator is the critical component of the electrolyte as it is responsible for transferring charge from the counter electrode to the working electrode (Figure PP2.1j.1). Here dye regeneration needs to occur following light induced electron injection into the semiconductor. In our own research we have been exploring the development of thermodynamically stable cobalt (II)/(III) complexes as DSC redox mediators. Here we have reported a new cobalt redox mediator, based on a hexapyridyl ligand, which results in DSC efficiencies of 8.3% in comparison to the archetypal $[Co(bpy)_3]^{2+/3+}$ couple (7.8%). Most importantly, the lab scale devices made with this redox mediator exhibit much improved stability under full sun aging experiments compared to those based on $[Co(bpy)_3]^{2+/3+}$, highlighting the pivotal role played by high denticity metal complex in the future development of DSC redox mediators. The DSC stability was tested using full sun illumination conditions and the devices made using hexapyridyl ligand showed an increase in device efficiency for first 20 hours, which remained constant at an efficiency of $\approx 8\%$ for the next 80 hours. However, the devices made using bpy ligand lost $>80\%$ of the performance in first 20 hours.

The most efficient dye-sensitized solar cells (DSCs) reported to date are based on cobalt coordination compounds as redox mediators dissolved in volatile organic solvents. In 2013, solid-state charge transport materials based on transition metal coordination compounds were investigated at Monash. Use of such metal complexes as hole conducting materials in DSCs will open new avenues of research into the field of perovskite solar cells and DSCs. An impressive efficiency of 5.6% has been achieved for the devices based on organic dyes and further detailed characterization of the devices is in progress.

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

The application of organic-inorganic halide perovskites in solar cells has recently resulted in very promising efficiencies. A planar structure of the solar cell (such as that shown in Figure PP2.1j.2) makes it more feasible for manufacture compared with traditionally complex DSC mesoporous structures. Researchers at Monash University have developed two novel deposition methods to produce perovskite films with uniform microstructures of fine grain size and desirable film thickness. Compared to the normal mesoporous structure, the planar perovskite is more uniform and much simpler to fabricate. Actually, the cell exhibits a *p-i-n* structure,

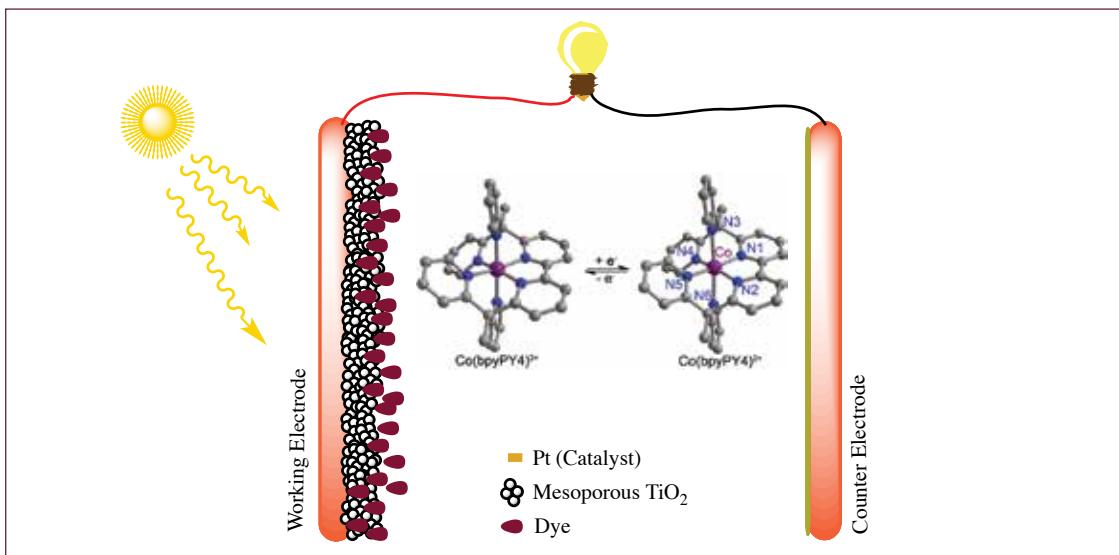


Figure PP2.1j.1: A schematic diagram showing the components of dye-sensitized solar cells and the pivotal role played by the redox mediator. High thermodynamic stability of the redox mediator results in overall stability of the DSC as well.

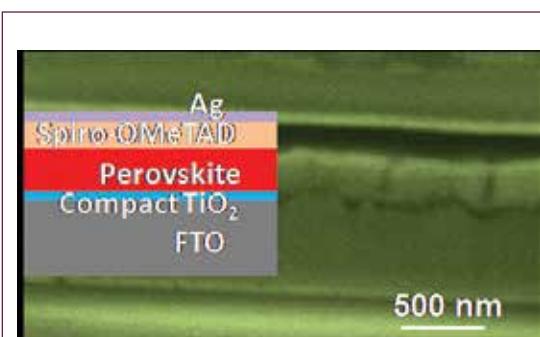
where p is the hole conductor Spiro-OMeTAD, i is the perovskite layer, and n is the compact TiO_2 layer. In a planar structure, each layer should have good contact with the adjacent layers; otherwise it would induce a high series resistance. Also, each layer should fully cover the adjacent area to avoid charge recombination. Thus a homogenous perovskite layer is crucial in order to achieve a high efficiency device. Generally, this could be achieved by employing an expensive vapor deposition process. However, we were able to develop a solution-based process to fabricate planar perovskite solar cells. By controlling the morphology of the perovskite, a high efficiency of 14.3% has been achieved with a photovoltage above 1V as shown in Figure PP2.1j.2(b).

In 2014, the team will develop methods to control and characterize the morphology (micro- and nanostructure) and to elucidate the correlation between morphology and device performance. A second focus will be the study and improvement of stability of the devices at different environmental conditions.

PP2.1j(c): An efficient planar perovskite solar cell via morphology control

Introduction

Recently, a new type of high efficiency solar cell has been developed using an organic-inorganic perovskite as light absorber and semiconductor. $\text{CH}_3\text{NH}_3\text{PbI}_3$ and $\text{CH}_3\text{NH}_3\text{PbI}_{3-x}\text{Cl}_x$ are two of the most commonly used compositions. This material has the crystal structure of ABX_3 perovskites, similar to those of CaTiO_3 . Here A is an organic cation, B the metal, and X the halide. Three different configurations are typically used in the literature as shown in Figure PP2.1j.3: (a) a traditional mesoporous structure, which is similar to the solid-state DSC where the perovskite injects the excited electrons to mesoporous TiO_2 ; (b) a super mesoporous structure, in which the semiconductor TiO_2 is replaced by an insulator oxide that only acts as a scaffold but also as an electron conductor; and (c) a planar structure, where a $p-i-n$ structure was formed in a layered assembly. The planar structure shows a much simpler structure and is easier to manufacture.



a

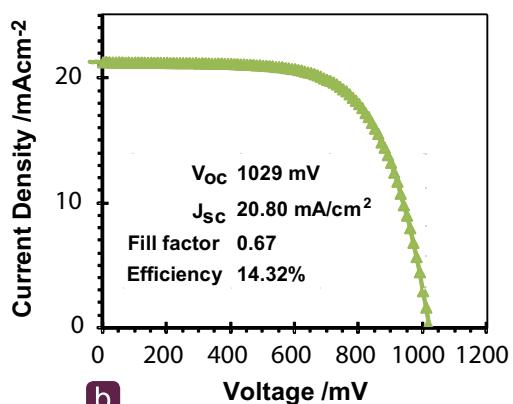
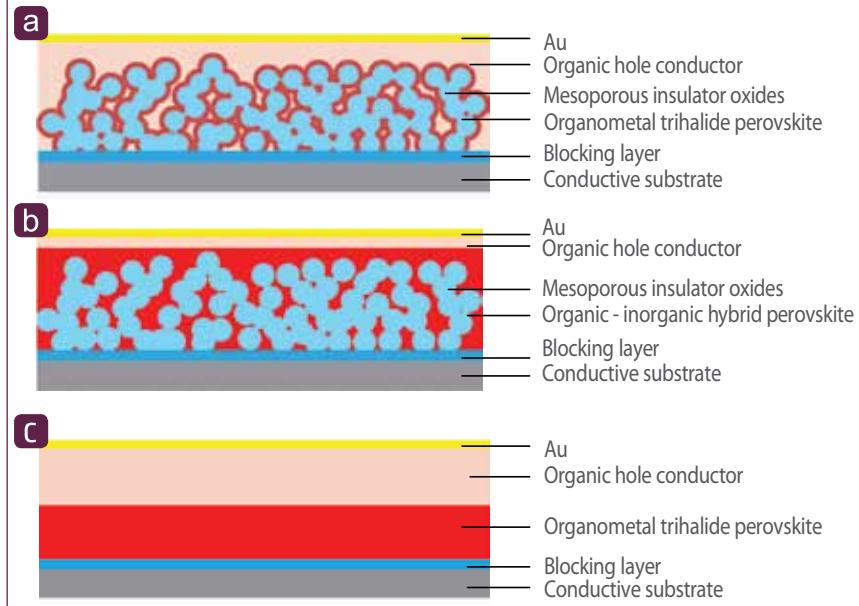


Figure PP2.1j.2: (a) Cross-section SEM image; and (b) I-V curve of a planar perovskite solar cell generated by employing a new fast precipitation method

Figure PP2.1j.3:
Schematic diagram of different structure configurations of perovskite solar cells:
(a) a traditional mesoporous structure,
(b) a meso-superstructure, and
(c) a planar structure.



This project is focusing on the development of planar perovskite solar cells via solution processes. In a planar structure like Figure 1 (c), firstly a compact TiO_2 (*n*-type semiconductor) is coated on the conductive substrate (here FTO) to form a blocking layer. Then the perovskite layer (photoactive layer) is coated on the blocking layer, followed by a deposition of a hole conductor layer (here Spiro-OMeTAD) and a charge collector (Ag or Au). The compact TiO_2 layer is usually prepared by spray pyrolysis of Titanium diisopropoxide bis(acetylacetone). The perovskite layer and the hole conductor layer are deposited by spin-coating. Ag/Au is deposited by the thermal evaporation. There are only a few solvents that can dissolve a high concentration of perovskite, as e.g. N,N-Dimethylformamide (DMF). When the perovskite DMF solution is used for the spin-coating, large dendritic perovskite crystals are formed which generate plenty of large voids as clearly shown in Figure PP2.1j.4 (a). Ideally, each layer should be well covered by the following layer. Otherwise voids lead to a current leakage which reduces the cell performance due to charge recombination. Moreover, large voids in the perovskite film enable direct contact between the hole conducting layer and the compact blocking layer. In this case electrons in the blocking layer would recombine with the holes in the hole conductors. Thus, thin-film solar cells with large dendritic perovskite crystals are not suitable for high performance devices.

Fast precipitation deposition method

The precipitation or crystallisation of the perovskite from the solution includes two steps: nucleation and crystal growth. In a normal spin-coating process, the DMF is slowly removed as it has a high boiling point (153°C and a vapor pressure of 3.5hPa at 20°C). The slow drying process allows the growth of large crystals, resulting in the dendritic structure. In order to constrain the crystal growth, a fast nucleation process that would lead to a large amount of nuclei to form before crystal growth in the solution is more designable.

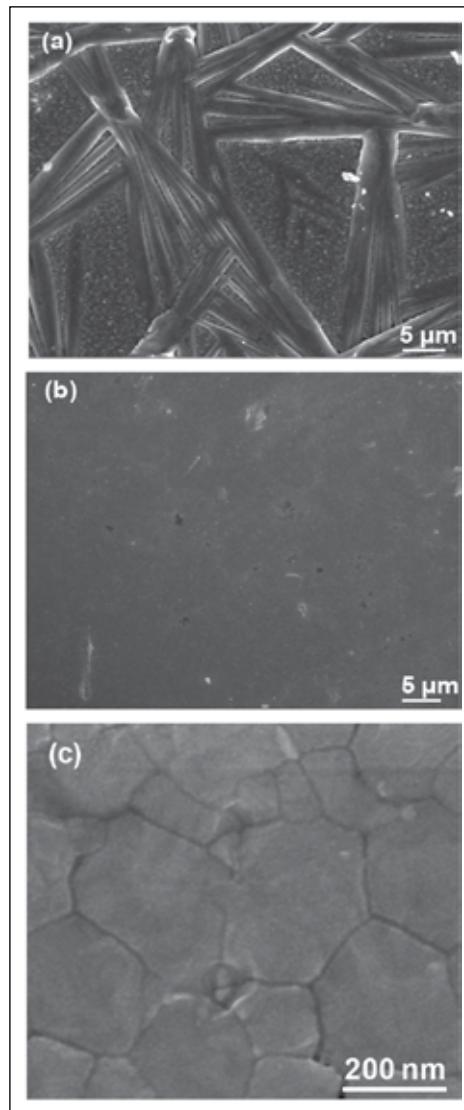


Figure PP2.1j.4: SEM images of the perovskite film made by **(a)** the normal method and **(b)** and **(c)** the new method.

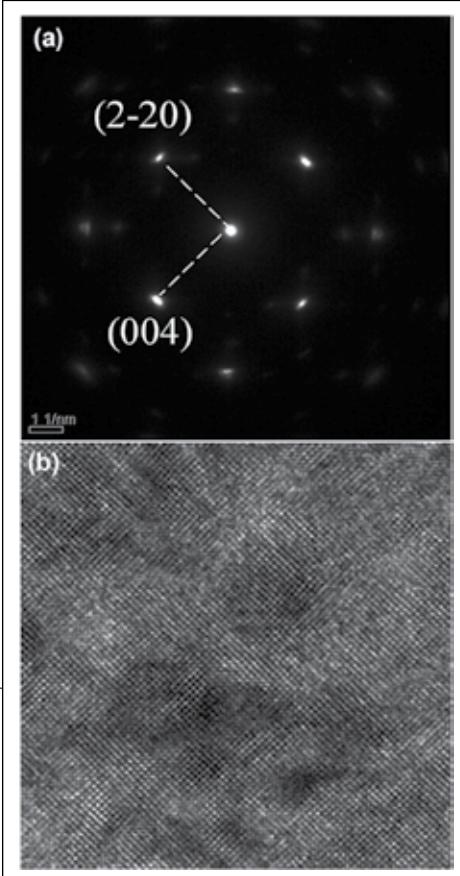


Figure PP2.1j.5: (a) An electron diffraction pattern and (b) a high resolution TEM image of the perovskite made by the fast precipitation method.

In this project a fast precipitation method has been developed for controlling the morphology of the perovskite. During fast precipitation, a large number of nuclei are formed and the crystals hindered by each other, preventing large dendritic grains from forming. Thus, a fine and more uniform dense perovskite layer is formed. Figure PP2.1j.4(b) shows an SEM image of a perovskite film prepared by the new fast precipitation method. Compared to the normal spin-coating method (Figure PP2.1j.4(a)), this new technique can form a perovskite film with a nearly full coverage of the blocking layer. The fast precipitation method produced a uniform film consisting of ~300 nm grains compactly covering on the substrate, as shown in Figure PP2.1j.4(c). An SEM image (Figure PP2.1j.2(a)) of the cross-section of the device, made using the new method, showed a film consisting of single perovskite

Table PP2.1j.1: Photovoltaic characteristics of the planar perovskite solar cells made by a normal spin-coating method and a fast precipitation method.

	Voc (mV)	Jsc (mAcm ⁻²)	FF	PCE (%)
Normal method	811 ± 62	10.5 ± 1.4	0.56 ± 0.2	4.6 ± 1.1
New method	1000 ± 22	20.9 ± 0.4	0.67 ± 0.1	13.9 ± 0.4

grains, approximately 300nm in both the lateral and vertical dimensions. The electron diffraction pattern and high resolution TEM image (Figure PP2.1j.5) showed the grain is a single tetragonal perovskite crystal. With 13.9%PCE, the new processing technique achieved a much higher solar cell performance compared to cells produced by the spin-coating technique, as shown in Table PP2.1j.1. All the photovoltaic parameters were improved, especially the photocurrent which was doubled and the efficiency which tripled.

Future work

The new deposition method helps forming a dense homogenous perovskite layer that greatly improved the power conversion efficiency. Further work needs to be conducted to study the mechanism in the new deposition process. In addition, the deposition condition requires further optimisation. In particular, the deposition speed and time are very important for the formation of a dense and uniform perovskite layer and the grain morphology would affect the solar cell performance as well. These will need to be further investigated for optimisation.

PP2.2 Thin film Inorganic (CZTS) - Lead Institution: UNSW

Research Team

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Industry Partners:

Guodian, Baosteel

Funding Support:

ACAP, ARENA, ARC, Guodian, Baosteel, UNSW

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

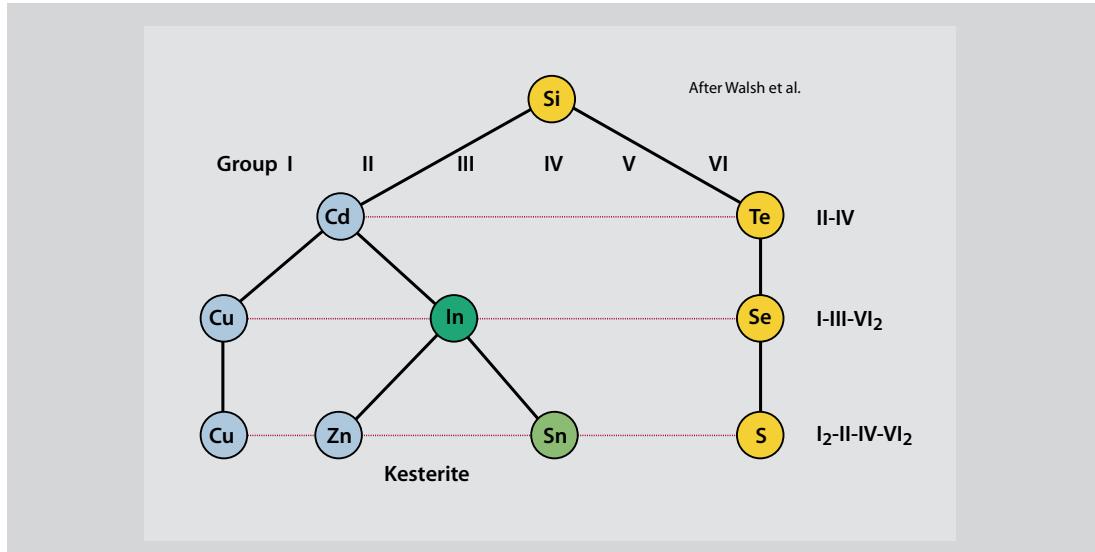


Figure PP2.2.1: “Synthetic silicon” - portion of the periodic table showing pathways to engineering semiconductors with 4 valence electrons/atom.

“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 12 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 investigating 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 $\text{Cu}_2\text{ZnSn}(\text{S}, \text{Se})_4$ (CZTSS(e)) compound semiconductor based on such reasoning has emerged as a promising candidate for absorber materials for thin film solar cells. Analogous to the chalcopyrite structure of CIGS, $\text{Cu}_2\text{ZnSnS}_4$ (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 8.4% have been achieved so far for CZTSS(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. The Centre’s work in the CZTS area takes a different fabrication direction. We have adopted the PVD fabrication method, a viable high throughput manufacturing process for CZTS-based solar cells. This vacuum-based fabrication method is also believed to be the route for extracting the full potential for high efficiency CZTS solar cells. Evidence for this arises in the similar case of CIGS where the same hydrazine solution method produces

cells of only 12.2% efficiency, while the vacuum method yields the present efficiency record of 20.8%.

The CZTS solar cell research was initiated by simply adapting the device structure from the relevant chalcopyrite (CIGS) solar cells with a standard Mo back contact, a CdS buffer layer, and a bilayer $\text{ZnO}/\text{ZnO:Al}$ window as shown in Figure PP2.2.2. For 2013, all such constituent layers necessary for a complete CZTS cell have been investigated and optimised in parallel. The efficiency of CZTS thin film solar cells at UNSW has been driven up to 4.5% since the first completed CZTS solar cell in July 2013 (see Figure PP2.2.5). 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 (5%) but lower than that using the electrodeposition method (7.3% with anti-reflection coating (ARC), equivalent to around 6% without ARC). Key factors limiting our present CZTS cells performance were analysed and corresponding strategies have been planned. In addition to the research into CZTS solar cells on soda-lime glass, a new research strand into the development of “CZTS solar cells on stainless steel” has been established involving collaboration with and financial support from Baosteel.

Achievement highlights

PP2.2.1: Infrastructure upgrade

Achievements

Mantis evaporator was commissioned in September 2013;

A new RTP sulfurization furnace allowing versatile chalcogenide heat treatment recipes was delivered and tested in Dec 2013;

A sputter machine allowing an in-situ sulphur (S) atmosphere was delivered in Dec 2013;

Chemical Bath Deposition (CBD) setup for the buffer layer was commissioned in June 2013;

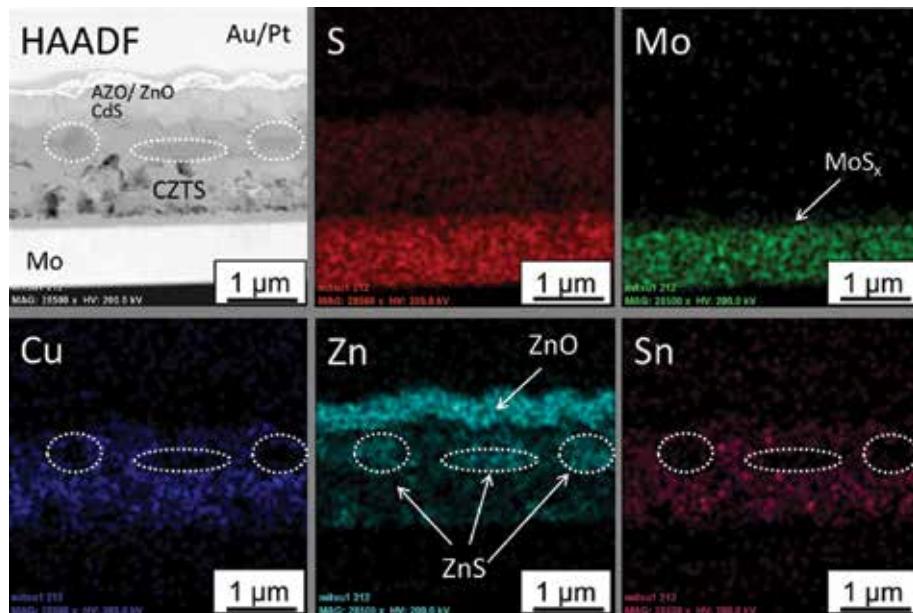


Figure PP2.2.3: HAADF and EDS scanning transmission electron microscopy (STEM) mapping images for Cu, Zn, Sn, S, and Mo, obtained from stacked metal precursor of SLG-Mo-Zn/Cu&Sn.

MREII2014 funding was awarded for a new XRF characterization facility to enhance fast feedback on chemical composition determination of CZTS absorber and associated precursor materials.

PP2.2.2 CZTS cells on soda lime glass

Achievements

All constituent layers shown in Figure PP2.2.2 necessary for a complete CZTS cell have been investigated and optimized in parallel. The quality of Mo, ZnO:Al and CdS layers are comparable with those reported in the world record CZTS and CIGS cells. Due to the limitation of the present sputter system used for CZTS precursors, fabrication was focused on the approach of sulphurization annealing of metal precursors. With the stacked metal precursors, CZTS solar cells on soda lime glass with the highest efficiency of 4.5% were demonstrated in 2013.

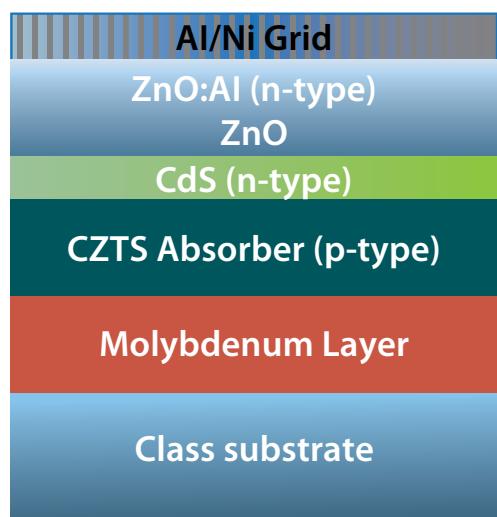


Figure PP2.2.2: Schematic of CZTS solar cell on soda lime glass.

PP2.2.2.1 CZTS absorber

A two-stage fabrication method has been applied to synthesis of the CZTS absorber layer, specifically metal precursor deposition followed by sulphurization annealing. Mechanisms involved in both steps were investigated and corresponding processes were optimized. Both the order of stacked-metal precursors and the following sulphurization annealing conditions were found to significantly impact the corresponding cell performance. The first working CZTS solar cells and the impact of metal stacking order was demonstrated in June 2013 [see Figure PP2.2.5] and subsequently published [2.2.1]. Within the desired chemical composition range (Cu/Zn+Sn in the range of 0.8-0.86, and Zn/Sn around 1.2), the best CZTS solar cells achieved so far were with the stacked metal precursor of SLG/Mo/Zn/Sn&Cu. The possible formation mechanism of CZTS film from such metal precursors was proposed in a second paper [2.2.2]. Voids, secondary phases and even Sn metals were found present in the CZTS absorber [see Figure PP2.2.3], which in turn are detrimental to CZTS device performance. Despite the general understanding that the desired CZTS composition of Cu-poor and Zn-rich is required for achieving appropriate doping through native defects and avoiding a detrimental Cu_{2-x}S secondary phase, it was also revealed in our work that Zn facilitates the growth of CZTS [2.2.3]. Further optimization is required to improve the CZTS absorber quality.

PP2.2.2.2 Other constituent layers (Mo, CdS, ZnO/ZnO:Al)

Standard base-line processes for the other constituent layers, including Mo, CdS, ZnO/ZnO:Al bilayer, were fully established in June 2013. The obtained quality of each layer is comparable to those reported in the highest efficiency CZTS and CIGS solar cells.

PP2.2.2.3 CZTS device

The first working CZTS solar cell on soda-lime glass was demonstrated in June 2013 and was improved to 4.5% in Dec 2013, as illustrated in Figure PP2.2.4 & Figure PP2.2.5. The enhanced CZTS device performance is

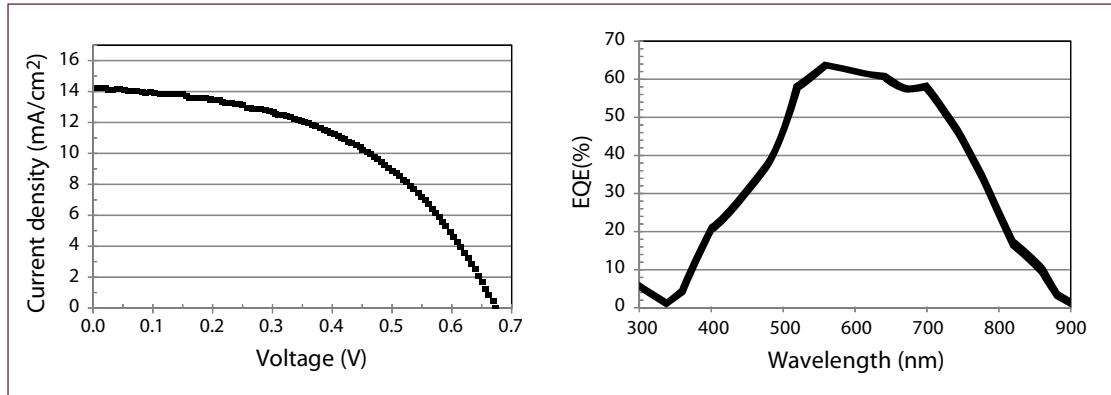
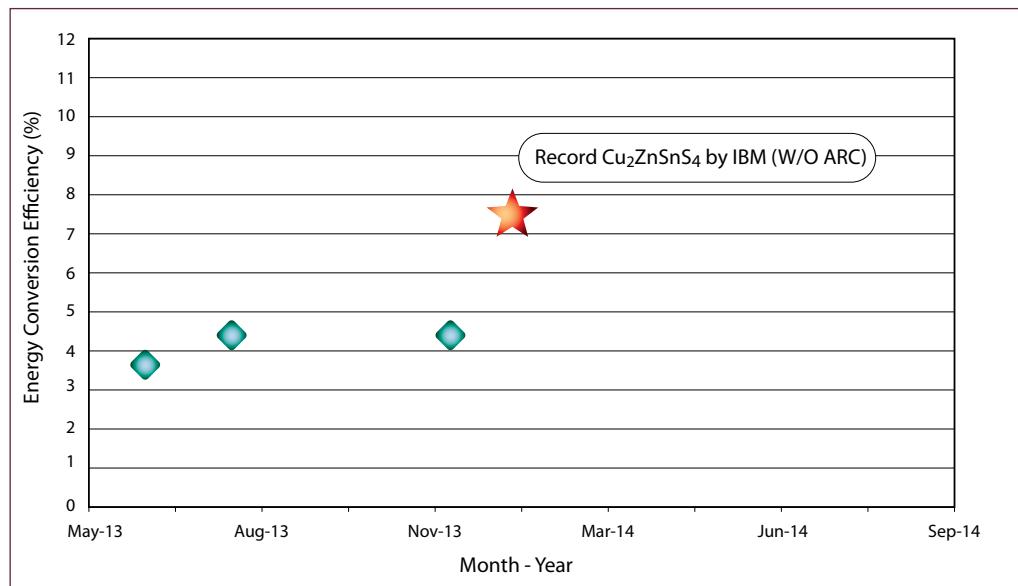


Figure PP2.2.4: I-V and EQE curves of 4.5% CZTS solar cells on soda-lime glass.

Figure PP2.2.5: Progress of CZTS ($\text{Cu}_2\text{ZnSnS}_4$) solar cell on soda-lime glass.



mainly due to the improvement in CZTS absorber quality, such as bigger grains and better crystallinity. Since the first working CZTS solar cells were demonstrated, strategies have been directed to aid in identifying the key factors limiting the present CZTS solar cell performance.

PP2.2.4 Key factors limiting present CZTS solar cells performance

As shown in Table PP2.2.1, compared with the theoretical Shockley-Queisser limit of 29%, the more severe losses for CZTS cells are in the large V_{oc} deficit and in the FF, rather than in the J_{sc} . Compared with the current world record of 8.4% CZTS cells, our demonstrated CZTS solar cells have a comparable open circuit voltage (V_{oc}) but relatively lower short circuit current (J_{sc}) and fill factor (FF). In terms of J_{sc} loss, optical losses due to the reflection from ZnO:Al window will contribute to low J_{sc} but can be largely avoided by an ARC layer of MgF_2 similar to CIGS cells. However, the current loss is more severe compared with that of chalcopyrite CIGS. This is believed to be due to the current collection loss, which is reflected by a typical triangle-shaped quantum efficiency curve with a gradual slope at the bandgap, instead of an ideal square shape with a steep increase at the bandgap edge. Such collection losses should be

due to a short collection length, the sum of the space charge width and the diffusion length. Space charge width and absorber lifetime therefore require further investigation. In terms of FF loss, analysis showed that the low FF at present is mainly due to high series resistance and low shunt resistance, resulting from undesired secondary phases, and a large amount of voids and thick highly resistive MoS_2 found in the vicinity of the Mo/CZTS interface, as well as the resistivity of the CZTS absorber material. The latter seems less dominant. As for V_{oc} , the V_{oc} deficit is around 0.8V, significantly higher than 0.42V for the CIGS solar cell. With band alignment and preliminary photoluminescence studies carried out in 2013, such a large V_{oc} deficit is likely to be due to the presence of both unfavourable conduction band alignment between CZTS and CdS (cliff-like conduction band offset) and higher CdS/CZTS interface recombination velocity. Simulation results indicate this could result in a saturated V_{oc} at 600–700mV. To summarise, the most dominant factors identified are: (1) CZTS absorber quality; (2) CZTS/Mo interface; and (3) CZTS/CdS buffer interface. Efforts have been made to seek solutions to these issues.

Solar Cell	Eg/eV	η /%	Voc/mV	Jsc/mA/cm ²	FF
CZTSe	1.0	9.15	377	37.4	65
SQ	1.0	30.9	748	48	88
CZTS	1.5	8.4	661	19.5	66
SQ	1.5	31.5	1210	29	91
CZTS UNSW	1.5	4.42	598	15	49
CZTSSe	1.15	10.1	517	30.8	64
SQ	1.15	32.8	887	42	89
CIGS ZSW	1.15	20.3	730	35.7	78

Table PP2.2.1: The comparison of chalcogenide solar cells performance together with Shockley-Queisser (SQ) ideal parameters.

PP2.2.2.4 Strategies to tackle the interface problems

CZTS/buffer layer interface engineering

- Studies on band alignment at the interface of CZT/CdS: the estimated conduction band offset (CBO) between CZTS and CdS by XPS and Soft-X-ray absorption spectroscopy indicate there is an unfavorable cliff-like CBO. [2.2.7].
- Alternative buffer options: To reduce the absorption loss by CdS, higher bandgap ZnS and In_2S_3 and their hybrid with CdS were synthesized and characterized [2.2.8]. Preliminary completed device results show that the hybrid buffer of $\text{In}_2\text{S}_3/\text{ZnS}$ yields better device performance. Further investigation is required to confirm repeatability and the improvement mechanism.

Mo/CZTS interface engineering

- Strategies for tackling defective Mo/CZTS interface: It was confirmed that the chemical instability of Mo with sulphur atmosphere and with CZTS mainly contributes to the defective interface. An immediate means of rectification is the insertion of an intermediate layer between CZTS and Mo. For

such purposes, the intermediate layer candidate needs to meet the requirements of: (1) low impact on the crystallinity of overlying CZTS film; (2) no additional series resistance contribution; (3) chemically stable in contact with both CZTS and Mo.

- Preliminary results from using the intermediate layer: A few intermediate layer candidates have been tried to solve this interface problem by studying their impact on the CZTS absorber and corresponding device performance. Three intermediate barrier layer candidates were investigated, including TiB_2 [2.2.4] and ZnO [2.2.5] and Ag [2.2.6]. Both TiB_2 and ZnO intermediate layers were found effective in reducing all associated interface defects (such as the case of TiB_2 shown in Figure 2.2.6) but slightly deteriorate the overlying CZTS crystallinity. It was found, as expected, that inserting the intermediate layer leads to higher FF, Jsc, lower Rs but also to lower Voc (See Figure 2.2.7). In contrast, it seems that Ag plays a totally different role while improving CZTS cell efficiency. Ag was found to act as an alloying agent to form $(\text{Ag}, \text{Cu})_2 \text{ZnSnS}_4$.

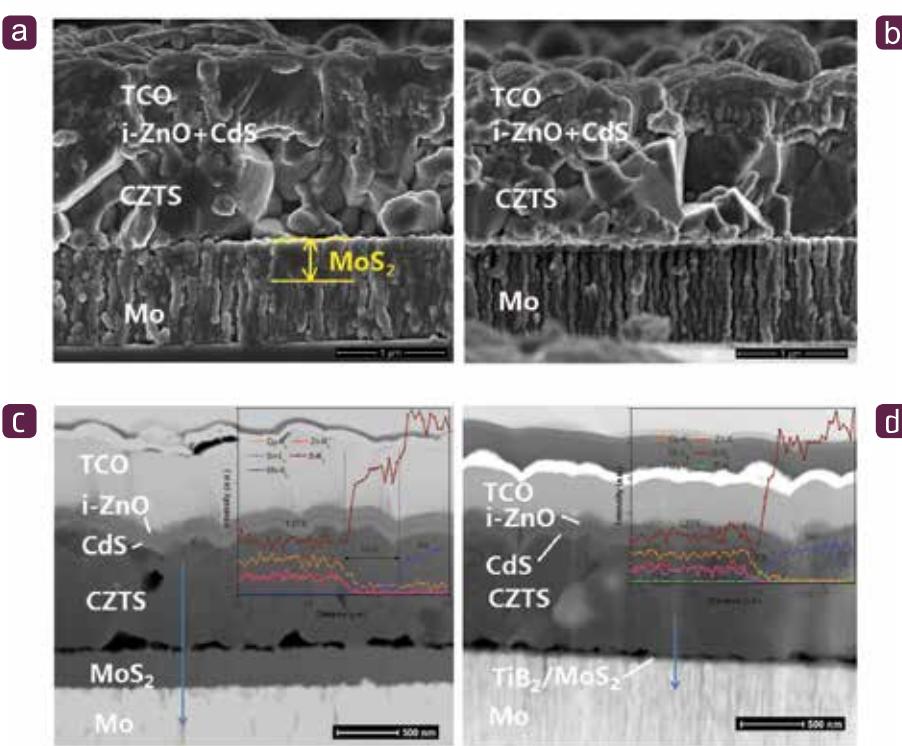


Figure 2.2.6: SEM cross sectional images of CZTS devices (a) without the TiB_2 layer, (b) with 30 nm TiB_2 layer. Cross-sectional TEM images of (c) without the TiB_2 layer (insert: EDS line scan taken along the arrow direction) and (d) with 30 nm TiB_2 layer (insert: EDS line scan taken along the arrow direction).

PP2.2.3 CZTS solar cells on stainless steel

Assigned Key Resources

CIs: Dr Xiaojing Hao, Prof. Martin Green, A/
Prof. Alistair Sproul, Dr Yansong Shen

Researchers: Dr Fangyang Liu, Lei (Adrian) Shi

A new project based on CZTS solar cells was established by collaborating with industrial partners, Baosteel. This new project commenced in January 2014. The aim of this research strand is to exploit technologies of $\text{Cu}_2\text{ZnSnS}_4$ (CZTS) solar cells on stainless steel for building integrated photovoltaic (BIPV) application. The general device design is shown in Figure PP2.2.8.

References

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| <p>2.2.1 Chen J., Yan C., Li W., Song N., Lin F., Huang S., Hao X.J., Green M. A., "Cu₂ZnSnS₄ thin film solar cell fabricated by magnetron sputtering and sulfurization", MRS Symposium Proceedings/ MRS Online Proceedings Library (Boston, US), Dec. 2013, (in press, accepted 29th Jan 2014).</p> <p>2.2.2 Li W., Chen J., Yan C., Liu F., Hao X.J., "Transmission electron microscopy analysis for the crystallization process of Cu₂ZnSnS₄ films from sputtered Zn/CuSn precursor", Nanotechnology, (in press, accepted March 2014).</p> | <p>2.2.3 Yan C., Chen J., Liu F., Song N., Cui H., Ng B., Stride J. A., Hao X. J., "Kesterite Cu₂ZnSnS₄ solar cell from sputtered Zn/(Cu&Sn) metal stack precursors", Journal of Alloy and Compounds, (in press, accepted March 2014).</p> <p>2.2.4 Liu F., Sun K., Li W., Yan C., Cui H., Jiang L., Hao X.J., Green M. A., "Enhancing the Cu₂ZnSnS₄ solar cell efficiency by back contact modification: inserting a thin TiB₂ intermediate layer at CZTS/Mo interface", Applied Physics Letters, Vol 104, 051105 (2014).</p> <p>2.2.5 Li W., Chen J., Yan C., Hao X.J., Liu F., Green M. A., "The effect of ZnS segregation on Zn-rich CZTS thin film solar cells" Solar Energy Materials and Solar Cells (submitted).</p> <p>2.2.6 Cui H., Liu X., Liu F., Hao X. J., Song N., Yan C., "Boosting Cu₂ZnSnS₄ (CZTS) solar cells efficiency by a thin Ag intermediate layer between CZTS absorber and back contact", Applied Physics Letters, Vol 104, 041115 (2014).</p> <p>2.2.7 Yan C., Liu F., Song N., Ng K.B., Stride A. J., Cowie B., Tadich A., Hao X.J., "Band alignments of different buffer layers (CdS, Zn(O,S) and In₂S₃) on Cu₂ZnSnS₄".</p> <p>2.2.8 Hao X.J., Liu F., Yan C., Green M. A., "Alternative buffer options for Cu₂ZnSnS₄ solar cells", Proc. 23rd International Photovoltaic Science and Engineering Conference and Exhibition, (Taipei, Taiwan) 2013 (Oral presentation).</p> |
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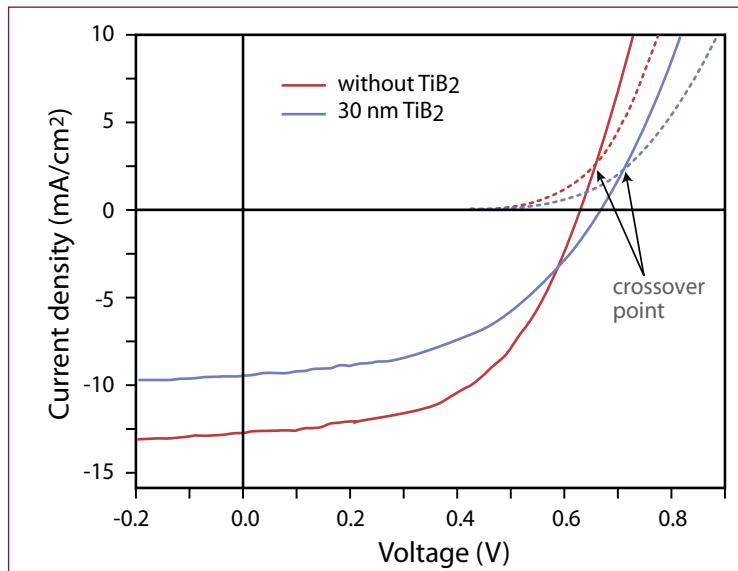
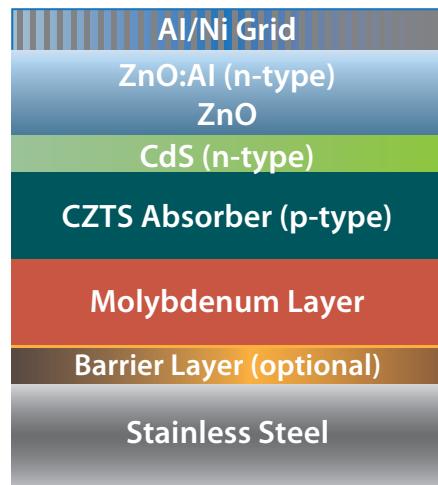


Figure 2.2.7: I-V curve and CZTS cell performance with various TiB₂ intermediate layer thickness.

Figure PP2.2.8: Schematic of CZTS solar cell on stainless steel.



PP2.3 Thin-Film Inorganic Cells (Si)

Lead Institution: UNSW

Research Team

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UNSW: Dr Sergey Varlamov, Dr Anthony Teal, Dr Jialiang Huang

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Academic Partners:

HZB (Germany), FZU (Czech Republic)

Industry Partners:

SRDA

Funding Support:

ACAP, ARENA, ARC, SRDA, UNSW

Background

The significance of thin-film crystalline Si PV technologies arises from using less semiconductor material, which can be expensive, and from reduced bulk recombination in a smaller material volume, which can potentially lead to higher cell voltages. Additionally, thin-film PV manufacturing can benefit from monolithic cell-module integration allowing low-cost fully inline-compatible processing, adaptable to a variety of substrate sizes and shapes. So far these advantages have been outweighed by relatively low efficiencies as compared to Si wafer cells. This strand aims at significantly improving the performance of thin-film Si devices to make them competitive with the mainstream Si wafer PV.

UNSW introduced the thin-film silicon on glass (CSG) technology that holds the record efficiency worldwide of 10.5% for a single junction thin-film silicon cell. The efficiency has peaked at this level due to a high defect density in solid-phase crystallised (SPC) Si films used in the record-performance device. The breakthrough in the performance can come 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. Having the defect density comparable to that in the mc-Si wafers, the liquid-phase crystallised Si on-glass (LPCSG) cells have a potential to reach the 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 (ARC) can be applied to the front glass surface and the

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 as described in the PP1.3a strand for Si wafer based tandem cells. 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. A promising approach to substrate cell metallisation is using selective laser melting and doping, which have been demonstrated to work for Si wafer cells.

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 (strands PP1.3a iv and v).

PP2.3 (i): Superstrate Liquid-Phase Crystallised Silicon on Glass Cells

Aim

The superstrate LPCSG cell design is shown in Figure PP2.3.1. In 2013 research on LPCSG cells focused on intermediate layer (IL) optimisation, emitter diffusion and Si film texturing for light-trapping.

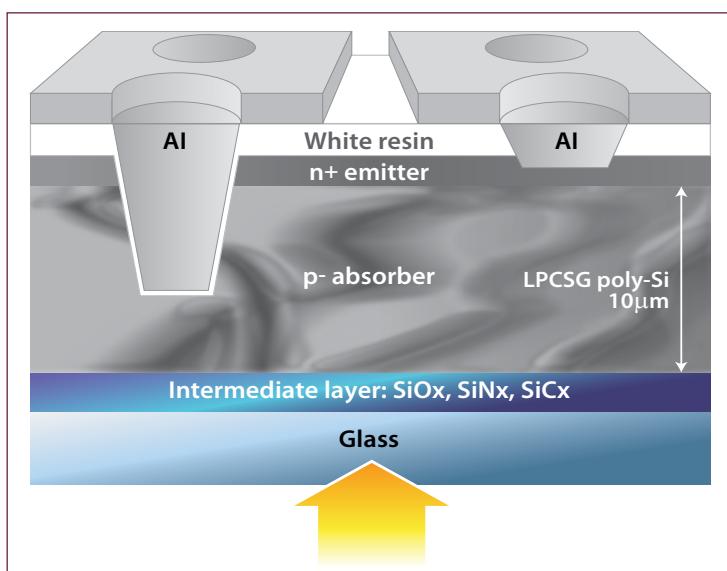


Figure PP2.3.1: Single junction superstrate liquid-phase crystallised silicon on glass cell design.

The IL was found to play the most critical role in LPCSG cells as it serves a few important functions: Si adhesion, antireflection (AR) and low absorption, impurity diffusion barrier, dopant source, and interface passivation. A process on bare glass is impossible due to almost immediate delamination as soon as a Si film melts, along with serious impurity contamination from the

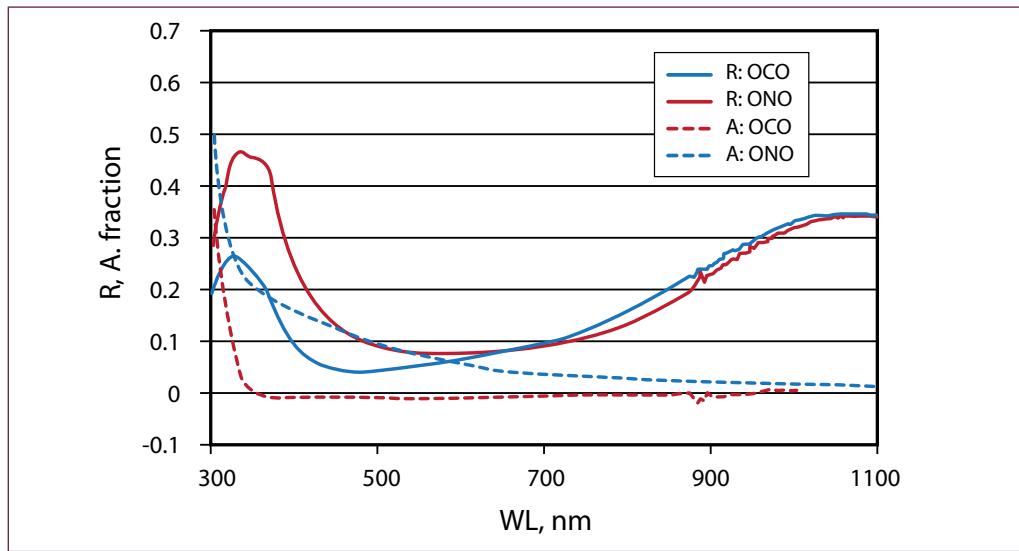


Figure PP2.3.2: Reflection (solid line) and absorption (broken line) of triple layer intermediate dielectrics OCO (blue) and ONO (red) (OCO = oxide/carbide/oxide; ONO = oxide/nitride/oxide).

glass, poor electronic quality of the interface, and lack of any AR effect. Three transparent dielectrics, SiO_x , SiC_x , SiN_x , all with melting points above that of Si, deposited by different methods (sputter, PECVD) were investigated in 2013. It was found than none, as a single layer dielectric, has satisfactory performance and combinations of different dielectrics were required. It was established that SiO_x was required both next to the glass to stop impurities and next to Si for satisfactory adhesion and good interface passivation. At the same time a SiN_x or SiC_x layer is required for antireflection.

As a result, triple layer stacks, such as $\text{SiO}_x/\text{SiC}_x/\text{SiO}_x$ and $\text{SiO}_x/\text{SiN}_x/\text{SiO}_x$, were developed where the middle layer added a necessary AR effect (Figure PP2.3.2). As an acceptable compromise that takes into account all IL properties and effects on LPCSG cells, a triple layer stack of $\text{SiO}_x/\text{SiN}_x/\text{SiO}_x$ (ONO, 100nm/50nm/15nm) and $\text{SiO}_x/\text{SiC}_x/\text{SiO}_x$ (OCO, 100nm/17nm/22nm) were developed and used in cell process optimisation.

Very few effects of different parameters on the structural and electronic quality of LPCSG material were noticed. As long as the laser crystallisation is conducted within a window between full Si melting, at the low laser dose end, and an adhesion failure at the high dose end, a structurally similar material is formed with a defect (dislocation) density between 1×10^5 and $1\times 10^7\text{cm}^{-2}$ (Figure 2.3.3, left) depending on a particular location. This concentration is a few orders of magnitude less than the dislocation density of about $1\times 10^7\text{cm}^{-2}$ in SPC Si (Figure PP2.3.3, right). There are large variations in the electronic properties, such as the carrier mobility, both within the same film sample and between identically processed samples. A very high Hall mobility up to $400\text{cm}^2/\text{V.s}$, similar to the mobility in c-Si wafers, was

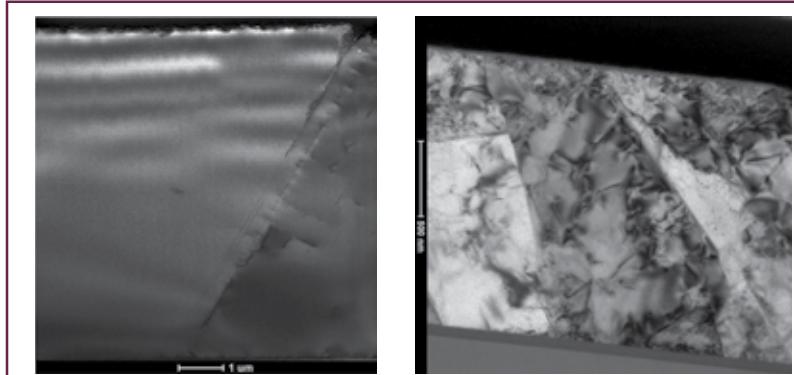


Figure PP2.3.3: (left) LPCSG film, dislocation density $\sim 1\times 10^6\text{cm}^{-2}$; (right) SPC film, defect density $\sim 1\times 10^{10}\text{cm}^{-2}$.

measured at some locations, while more typical values are $250\text{--}350\text{cm}^2/\text{Vs}$. This is still a lot higher than the Hall mobilities of about $50\text{cm}^2/\text{Vs}$ in SPC poly-Si.

An absorber layer prepared by liquid phase laser crystallisation is uniformly doped with B to $1\text{--}3\times 10^{16}\text{cm}^{-3}$ resulting in sheet rho of about $1000\Omega/\text{sq}$. A cell emitter is then formed by diffusing P from a spin-on-dopant (SOD) source to achieve sheet rho of about $200\text{ohm}/\text{sq}$. Two diffusion processes were developed: one by conventional thermal diffusion and another by diode laser induced transient heating. The best performance (V_{oc} up to 585mV) is achieved by the thermal diffusion, and reasonably high V_{oc} up to about 530mV is achieved by the laser-induced diffusion to date. It is expected that, after more optimization, the more manufacturable laser diffusion can result in the performance matching conventionally processed cells.

To facilitate LPCSG cell development, a photoluminescence (PL) imaging tool was designed and built which allowed characterisation of poly-Si thin films on glass for the first time. The tool uses a short wavelength LED (465 to 630nm) as an excitation source to improve the light absorption in a thin Si layer and a set of filters to minimise fluorescence noise from the

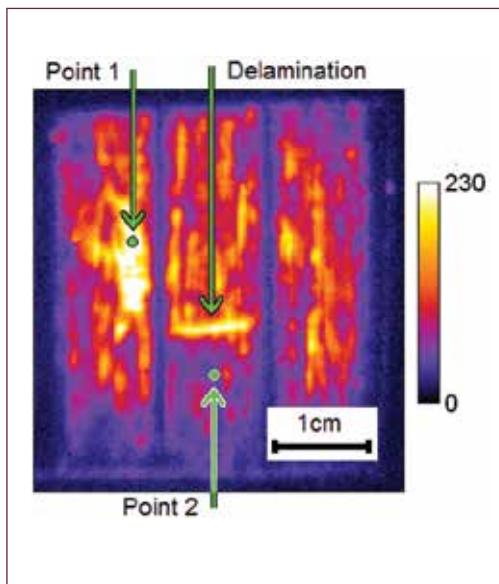


Figure PP2.3.4: PL Image of LPCSG sample with measured Hall mobility; point 1: $412 \text{ cm}^2/\text{Vs}$; point 2: $230 \text{ cm}^2/\text{Vs}$.

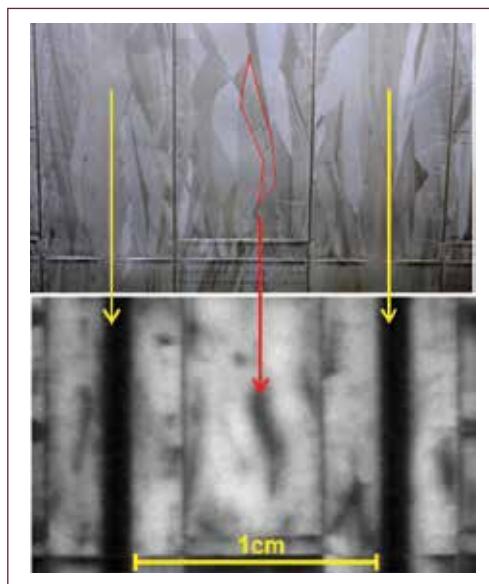


Figure PP2.3.5: SEM (top) image of LPCSG sample and corresponding PL map (bottom).

glass. Observed PL intensity images can be qualitatively correlated with the electronic quality of poly-Si, such as mobility and minority carrier lifetime and thus provide very useful and immediate feedback for process optimisation at any stage of cell fabrication. For example, Figure PP2.3.4 shows a PL image of a LPCSG sample where the Hall mobility was measured at points 1 and 2. A much higher PL intensity corresponds to point 1 with a mobility of $412 \text{ cm}^2/\text{Vs}$ compared to lower intensity point 2 with mobility of $230 \text{ cm}^2/\text{Vs}$. Figure PP2.3.5 shows a PL image of another LPCSG sample compared to a

corresponding SEM image. Dark vertical lines in the PL image correspond to poorly crystallised Si between the scans identified in the SEM as having no visible grain structure; and a grain with high defect density in its SEM image corresponds to a darker area in the PL image.

In summary, research on LPCSG cells in 2013 resulted in successful development of intermediate layers critical for both film crystallisation and for the cell performance, as well as improved emitter diffusion with the record achieved V_{oc} of 585mV and the introduction of the PL imaging tool for poly-Si thin films on glass.

PP2.4: Third Generation Approaches Lead Institution UNSW

Modulation of properties in nanostructures can be used to engineer the bandgap of materials, the phonon energies or the light trapping properties. Silicon based nanostructures aim 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. Hot carrier cells aim to capture the energy of above bandgap photons in a device whereby their energy is extracted at high voltage and high current or the efficiency of a standard silicon cell in a down-converter configuration is optically boosted.

PP2.4.1 Hot Carrier cells

Background

The hot carrier cell is a device theoretically capable of efficiencies equivalent to a six level tandem cell but with a relatively simple monolithic two terminal structure. The key to such a device is slowing the rate of carrier cooling on an absorber and then extracting the energy before carriers have time to cool to the lattice temperature, see Figure 2.4.1(a).

UNSW has paved the way towards investigating restriction of phonon energies in bulk and in nanostructured materials as a means of restricting carrier cooling. More recently slow carrier cooling rates in quantum well nanostructures

are investigated. In addition, a lot of work has been carried out at UNSW on energy selective contacts using double barrier resonant tunneling with several proofs of concept.

Modelling of transport and phonon and electron dynamics is a key part of this work and experiment and model are now coming together. Nitride materials are seen as highly promising as absorbers because of their large phonon band gaps which restrict phonon decay and hence carrier cooling. Indium nitride is a promising material for proof of concept, but its low abundance requires other analogues. Transition metal nitrides offer possibilities of abundant materials but with large phonon bandgaps. Hafnium nitride (HfN) and zirconium nitride (ZrN) in particular fit all these requirements and have small to zero bandgap for absorption of a wide range of photon energies.

Full devices will either have selective contacts on an efficient absorber to extract carriers at high voltage (see Figure 2.4.1(b)), or have an absorber with slowed carrier cooling operating in open circuit, and emitting a wide range of photon energies through an optical filter onto a standard solar cell. This second optical approach has the advantage that only optical properties need be optimized not electrical transport and is very promising at least for proof of concept devices and quite possibly for final high efficiency devices.

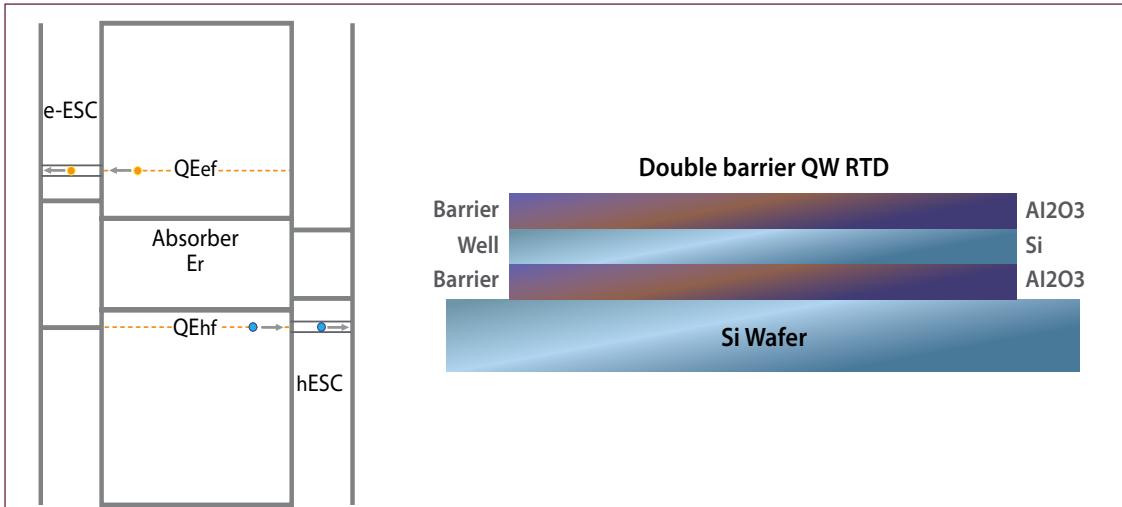


Figure PP2.4.1: Schematic diagrams for (a) the Hot carrier solar cell; (b) double-barrier QW structure.

PP2.4.1(i) Model phonon dispersion in bulk materials and nanostructures

Aim

Develop models of phonon dynamics, electron-phonon interaction and efficiency models to be fully consistent and predictive of real material systems.

Actions

- Optimise models to calculate phonon dispersion of bulk and nanostructure materials
- Develop model to estimate hot carrier solar cell efficiency using realistic material parameters

Key resources

Hongze Xia, Yu Feng, Dr Shujuan Huang, Dr Santosh Shrestha, Prof. Gavin Conibeer

Progress in 2013

InN/ $\text{In}_x\text{Ga}_{1-x}\text{N}$ multiple quantum-well superlattices (MQW-SL) with wurtzite crystal structure are studied as the absorber of the hot carrier solar cell. Such a structure will exploit both the significant hot-phonon-bottleneck effects of the component materials and the known slowed carrier cooling in MQWs. The former is due to the large contrast of the atomic masses, and hence a large bandgap between high-lying and low-lying phonon modes. The phonon bandgap effectively stops Klemens decay, i.e. one high-lying phonon decaying into two low-lying phonons, and produce hot population on the polar modes, feeding energy back to electrons. InN and $\text{In}_x\text{Ga}_{1-x}\text{N}$ have very similar lattice structures, with almost the same lattice constant. This benefits the solar energy conversion, in terms of both the carrier transport and the reduction of recombination sites. The 1-dimensional superlattice structure ensures a continuous electronic energy spectrum and hence a broadband absorption. The absorption is further enhanced by the small electronic bandgap of InN.

The dispersion relations of phonon modes in superlattices have been computed with a 1-dimensional atomic-plane model. Since the epitaxial growth is

intended to be along the high-symmetry $\Gamma - \text{A}$ direction for both InN and $\text{In}_x\text{Ga}_{1-x}\text{N}$ layers, the periodicity of MQW-SL and hence the zone-folding is along this direction. For simplicity we assumed that the mode frequency of each zone-folded mini-band only depends on the vertical component of the wave-vector (i.e. along $\Gamma - \text{A}$). The justification for this assumption partly comes from the high concentration of electron-emitted polar phonons around the zone-centre, where the dispersions are relatively flat compared to the mini-gaps. In the wurtzite structure, periodic atomic planes with alternating elements align perpendicularly to the $\Gamma - \text{A}$ direction. If only considering the vertical component of wave-vectors, all atoms in one atomic plane vibrate in phase and can be treated as one uniform displacement. The phononic model adopted here treats a 1-dimensional chain with an equal length of the superlattice periodicity, taking into account the plane-to-plane force constants. The plane-to-plane force constants are calculated by adopting the conventional Keating potentials for all bonds. A sample phononic dispersion relation is shown in Figure PP2.4.2. The electronic structures, involving the wavefunctions and energies of all the states, can be calculated by using the Kronig-Penney model for superlattices. In equilibrium conditions space charges occur in the well layers (negative) and in the barrier layers (positive) due to the difference of their electron affinities. The electron affinity of $\text{In}_x\text{Ga}_{1-x}\text{N}$ is significantly lower than that of InN, giving a larger off-set of the conduction band edge rather than that of the valence band edge. A sample electronic dispersion relation is shown in Figure PP2.4.3.

PP2.4.1(ii) Investigate HC absorber using bulk materials

Aim

Determine appropriate bulk materials for slowed carrier cooling through reduced phonon modes. Fabricate materials of high quality and characterize for carrier cooling.

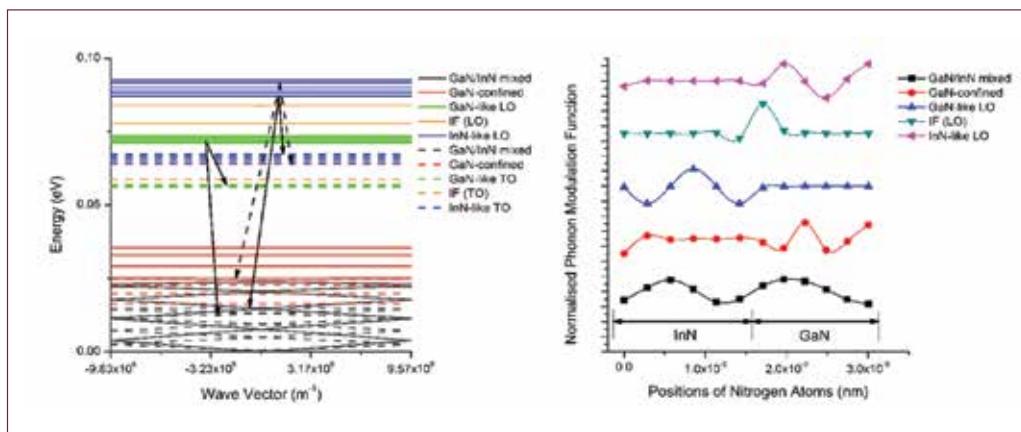


Figure PP2.4.2: The left figure indicates the phonon decay paths and the sample dispersion for a SL structure with 3 layers of unit cells inside each layer (barrier or well). The right figure shows the phonon modulation function of a representative mode from each category of modes, computed from the eigenfunctions of the lattice dynamic equation. The transverse modes have similar modulation functions and hence only that part of the longitude modes is shown.

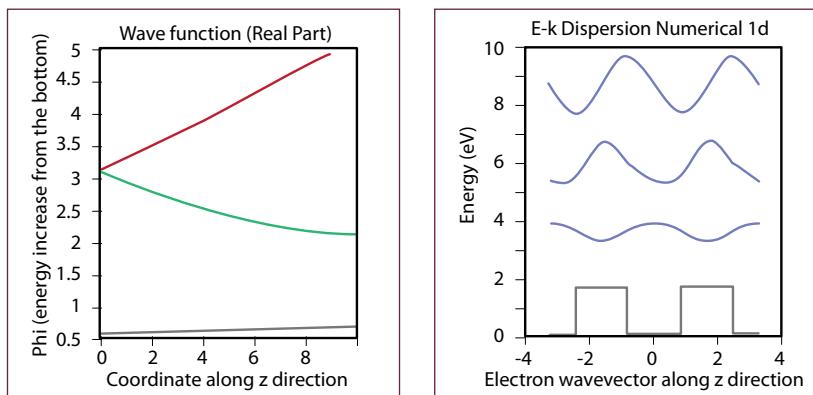


Figure PP2.4.3: The electronic dispersion relation and the zone-center wave functions for a SL structure with 3 layers of unit cells inside each layer (barrier or well). The wave vector is along the Γ -A crystal direction.

Actions

- Establish fabrication of HfN and ZrN by sputtering and ALD
- Fabricate group IV compounds, particularly SiSn
- Characterise structural and optical properties
- Investigate hot carrier dynamics

Key resources

UNSW: Dr Santosh Shrestha, Simon Chung, Neeti Gupta, Dr Xiaoming Wen, Prof. Gavin Conibeer

Progress in 2013

Hafnium nitride thin films

Hafnium nitride (HfN) has been shown, both theoretically and experimentally, to have a large optical phonon (OP) - Acoustic phonon (AP) bandgap. This gap is big enough to prevent Klemens' decay- the main route of carrier cooling. Hence this material is expected to show slow carrier cooling rate suitable for the hot carrier solar cell.

Sample fabrication

Thin films of HfN_x were grown using a magnetron sputtering system by DC sputtering of a 4 inch Hf. All HfN_x films were deposited with substrates heated to approximately 450°C with films deposited for 1 hour.

Characterization

X-ray diffraction (XRD) was used to identify the crystal structure of the deposited HfN_x films using ω -2 θ and glancing angle (GA) XRD scans for the analysis. Figure PP2.4.4 shows the corresponding ω -2 θ XRD scans of HfN_x thin films deposited with varying N_2 gas flow

ratios. The XRD intensity from 30° to 50° has been multiplied by 20X for comparisons with the Si(400) $\text{K}\alpha_1$ and $\text{K}\alpha_2$ peaks. $\text{HfN}(200)$ peaks are observed at 39.76°, 39.61° and 39.44° for samples deposited with N_2 flow ratio of 0.1, 0.2 and 0.4 respectively. The reduction in the $\text{HfN}(200)$ peak intensity can be attributed to thinner films in higher N_2 growth conditions. HfN_x peak positions shift to lower 2 θ with increased nitrogen content corresponding to strain introduced with thinner films and changes in film composition.

Figure PP2.4.5 shows GA-XRD measurements of HfN_x films deposited in different N_2 deposition conditions. Several HfN peaks can be observed in our samples signifying the samples are multi-crystalline. Epitaxy growth of HfN on Si is not expected due to the large lattice mismatch between silicon and HfN. The sample deposited with N_2 gas flow ratio of 0.1 shows four distinct peaks, $\text{HfN}(111)$ at 34.24°, $\text{HfN}(200)$ at 39.82°, $\text{HfN}(220)$ at 57.63°, $\text{HfN}(311)$ at 68.82° and a small peak at 72.50° representing the $\text{HfN}(222)$ peak.

Raman spectra measurements we performed using a Renishaw inVia Raman microscope. Raman modes were excited by the 514nm of an Ar^+ laser. The Raman spectrum in Figure 2.4.6 shows two distinct peaks of the first order acoustic modes ($120 - 180\text{cm}^{-1}$) and first order optical modes ($480 - 560\text{cm}^{-1}$). The large gap between the first order acoustic and optical modes is the consequence of the large mass difference between Hf and N atoms. Three other modes are observable: second order acoustic modes ($230 - 340\text{cm}^{-1}$), optical – acoustic modes ($\sim 440\text{cm}^{-1}$) and optical + acoustic modes

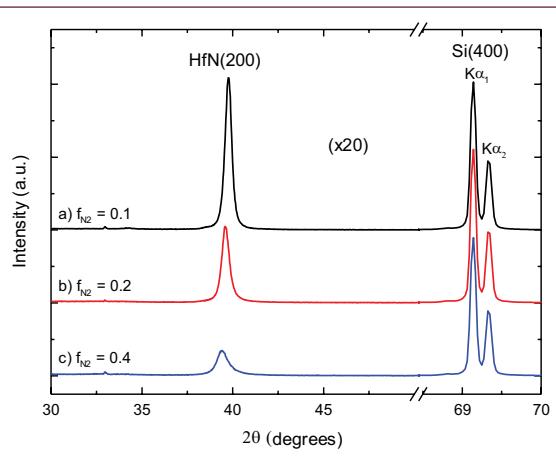


Figure PP2.4.4: ω - 2θ XRD scans of HfN_x thin films deposited on $\text{Si}(100)$ with varying N_2 gas flow ratios, f_{N_2} = a) 0.1, b) 0.2 and c) 0.4.

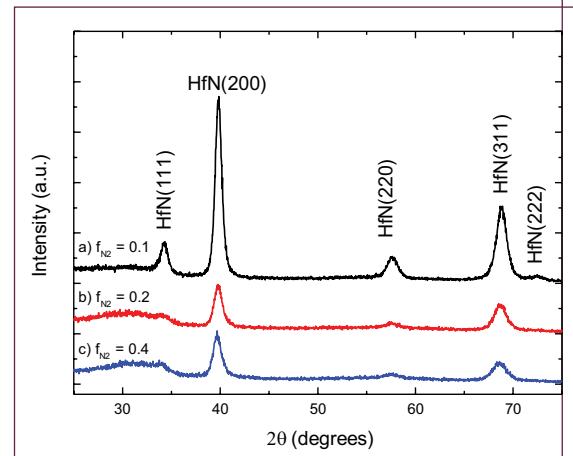


Figure PP2.4.5: GA-XRD scans of HfN_x thin films deposited on $\text{Si}(100)$ with varying N_2 gas flow ratio, f_{N_2} = a) 0.1, b) 0.2 and c) 0.4.

($\sim 650 \text{ cm}^{-1}$). For stoichiometric HfN , which is rock salt structured, first order Raman peaks are forbidden by symmetry. The first order peaks observed can be attributed to point defects of the polycrystalline HfN_x film. This is encouraging as we aim to exploit the large gap in the phonon DOS to slow down carrier cooling.

Ultrafast transient absorption was performed on a sample of HfN deposited on quartz to detect the electron cooling (relaxation). The fs pump-probe experiments were performed with a transient absorption spectrometer (FemtoFrame II, IB Photonics). The excitation source is a 400nm pulse from an OPA laser (TOPAS, Spectra Physics) with 100fs duration and 1kHz repetition rate, pumped by a regenerative amplifier (Spitfire, Spectra Physics) seeded by a Ti: Sapphire laser (Tsunami). The probe beam of white light continuum was generated by focusing amplified ultrashort pulses onto BBO crystal, and detected by a polychromator-CCD detector.

HfN can be metallic, semi-metallic or semiconducting, depending on the ratio between Hf and N , according to the reported literature. It is basically nonluminescent and therefore, the conventional PL and time-resolved PL techniques cannot be applied. Therefore, we utilize an ultrafast transient absorption (TA) technique (pump-probe) on it. We choose 400nm as excitation based on the measured absorption spectrum and probe in the visible region.

Figure PP2.4.8 shows the TA spectra of HfN film as a function of time delay. Immediately after the ultrashort laser irradiation, electrons are excited to the high-excited state. An ultrafast Auger (electron-electron) scattering occurs in as short as 400fs, a bleaching peak appears in 520-700nm and an excited state absorption band in 470nm. The ultrafast formation of the hot carrier distribution suggests HfN has a partly metallic property, sufficient free electrons and effective e-e scattering. After this short period, a stable (ns lifetime) linear-like distribution of carrier forms. This distribution basically depends on the temperature of the carriers. The TA spectra in 570 - 750nm exhibit bleaching while 470-

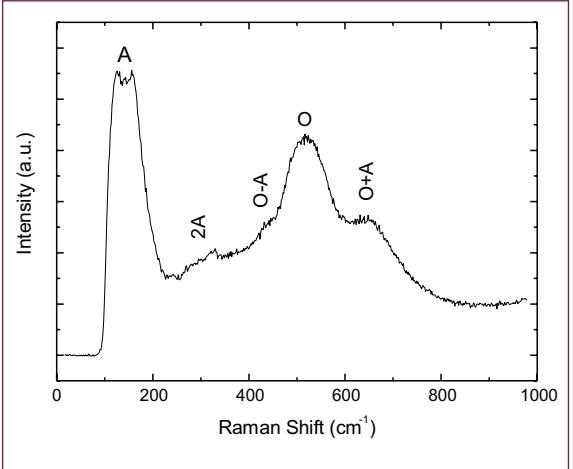


Figure PP2.4.6: Raman spectra for HfN_x film deposited with N_2 flow ratio of 0.1 on $\text{Si}(100)$ substrate.

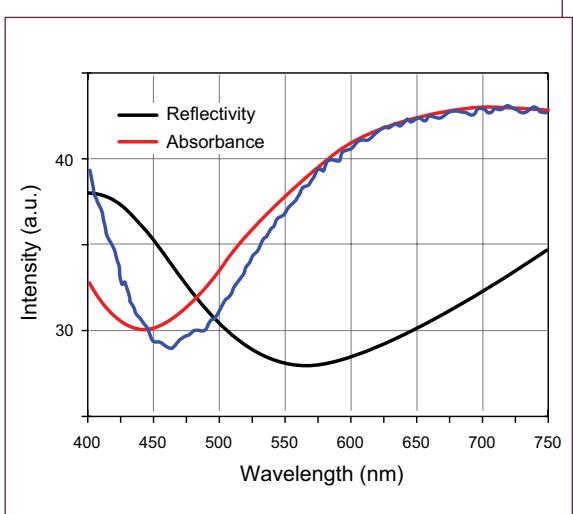


Figure PP2.4.7: Reflectivity and absorption spectra of HfN (the black and red). The blue is the differential of reflectivity, similar to the absorption. Evident structure can be obtained in the visible region, which indicates the specific optical properties, different from metals and semiconductors.

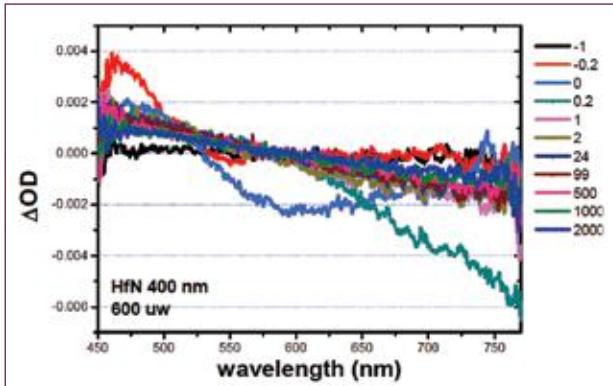


Figure PP2.4.8: Transient absorption spectra of HfN with 400 nm excitation. Spectra for various time delays in picoseconds (ps) are indicated. There is significant redistribution of carrier energy at time delays less than 1ps associated with elastic e-e scattering. This is followed by a relatively stable energy distribution out to 1000ps indicating long carrier lifetimes at elevated temperature.

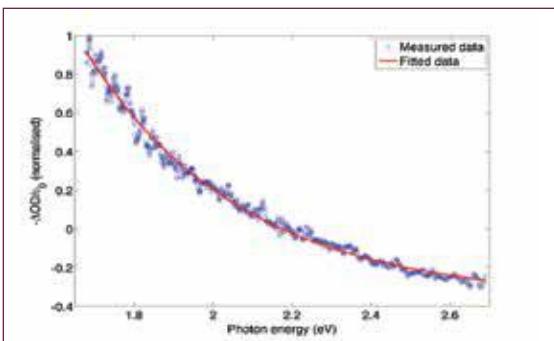


Figure PP2.4.9: The measured values and exponentially fitted values of $-\Delta OD / \alpha_0$ for $t=0.4$ ps. This time-evolution of carrier temperature $T(t)$ in Figure PP2.4.10 indicates that the temperature of carriers decreases slowly. An exponential fitting demonstrates an ultra-long decay time of carrier temperature, around 0.9ns. This can be treated as the carrier thermalisation time constant of the HfN thin film.

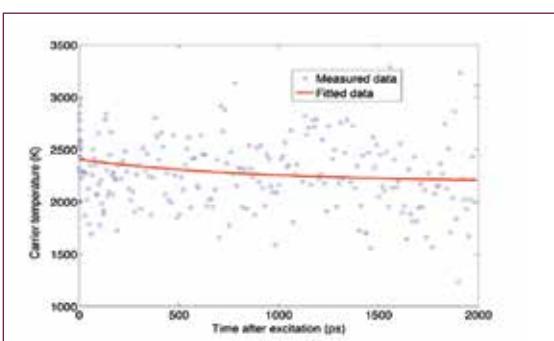


Figure PP2.4.10: Time evolution of carrier temperature after excitation. The thermalisation time is approximately 0.9ns from exponential fitting.

570 appears as excited state absorption. It should be emphasized that such electron stable distribution is obviously different from the semiconductors or general metals. Obviously, such specific TA spectra correspond to a special electron transient distribution. Further theoretical study is required for the detailed electron transient distribution based on the transient absorption spectrum.

Temperature of hot carriers in HfN can be extracted as a function of time from the measurement of transient absorption. The relative transmission variation has been retrieved from the measured TA data. Here denotes the transmission without state-filling, while is the variation of transmission due to laser excitation, and both are functions of wavelength. Such a variation originates from the variation of absorption, for states in the conduction bands are partially occupied (state-filling). From Figure PP2.4.8, the excited carriers can be seen to lose their energy, so that carrier statistics become more concentrated at low energy levels

with time. Exponential fitting provides an estimation of the carrier temperature for each time slot.

The fitting strategy for the TA measured results is based on the transient reduction of the absorption coefficient, which is due to state-filling after laser excitation. The relative variation on transmission, $\Delta Tr/Tr_0$, can be directly related to the time-varying carrier statistics (PRB **83**, 153410, 2011).

$$\frac{\Delta Tr(\epsilon; t)}{Tr_0} \approx a_0(\epsilon)[f_e(\epsilon_e; t) + f_h(\epsilon_h; t)]d$$

Re-expressing this equation using the optical density variation ΔOD :

$$\Delta OD \approx -a_0(\epsilon)[f_e(\epsilon_e; t) + f_h(\epsilon_h; t)]d$$

where $a_0(\epsilon)$ is the absorption coefficient without state-filling and d is the thickness of the film. The absorption coefficient for a metallic material can be approximated by $\sqrt{\epsilon}$. $f_e(\epsilon_e; t)$ and $f_h(\epsilon_h; t)$ are the occupation numbers of the electrons and holes in the conduction band and

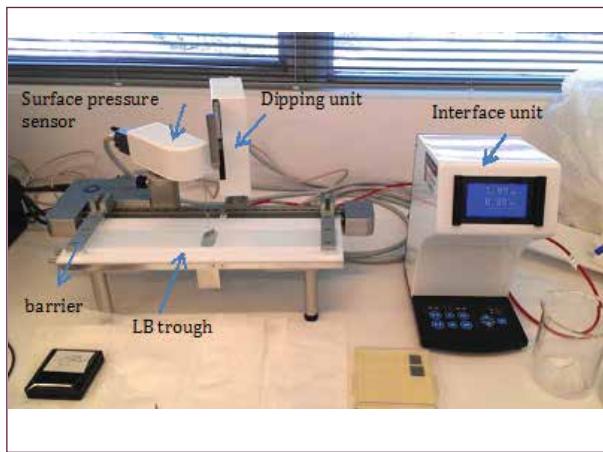


Figure PP2.4.11: a customised LB system for nanoparticle deposition, installed in Room 1013 Chemical Engineering Building UNSW.

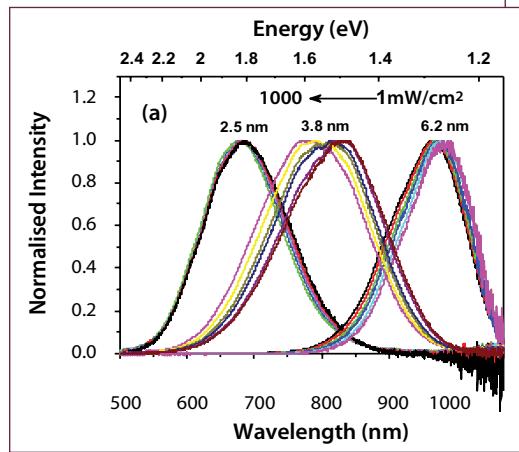


Figure PP2.4.12: Excitation fluence dependent PL spectra for 2.5, 3.8 and 6.2nm Si NCs.

the valence band, respectively. Both occupations follow Maxwell-Boltzmann statistics in non-degenerate regime, and thus can be fitted by an exponential function. If assuming symmetrical bands and carrier dynamics, ΔOD can be fitted using a single exponential function.

$$\Delta OD \sim -\sqrt{\epsilon} \cdot e^{-\epsilon/2kT(t)}$$

Exponential fitting procedures have been conducted between $-\Delta OD / \alpha_0$ and ϵ . It results in the carrier temperature for each time slot. The exponentially fitted values of $-\Delta OD / \alpha_0$, for $t=0.4ps$, $t=84ps$ and $t=1860ps$, are shown in Figure PP2.4.9. It is shown that the shape of spectrum changes slowly, indicating a long cooling time of hot carriers.

PP2.4.1(iii) Investigate HC absorber using nanostructures

Aim

- Measure carrier cooling rates in a range of QW nanostructures obtained from collaborators to determine carrier cooling mechanisms.
- Fabricate QD nanostructure arrays from colloidal nanoparticles to modulate phonon dispersions.

Actions

- Establish NP deposition by LB
- Characterise structural and optical properties
- Investigate hot carrier dynamics

Key resources

UNSW: Dr Shujuan Huang, Pengfei Zhang, Shu Lin, Sanghun Woo, Dr Xiaoming Wen, Dr Santosh Shrestha, Prof. Gavin Conibeer

Progress in 2013:

Establish a process to deposit NPs on a substrate

The Langmuir-Blodgett (LB) deposition technique is conventionally used for the fabrication and characterisation of single and multilayer films with precise control of thickness, molecular orientation

and packing density. In recent years, it has been applied to metallic nanoparticle depositions for the formation of highly ordered arrays.

We have employed an LB system to fabricate gold (Au) and silicon (Si) nanoparticle layers. An LB system has been set up at UNSW. We have designed the trough top for nanoparticle deposition to optimise the dispersibility. The system is shown in Figure PP2.4.11, which consists of a trough, a pair of barriers, a surface pressure sensor, a dipping unit for film transferring and an interface controller.

Silicon nanocrystals:

The silicon nanoparticles used in this study were synthesized using a non-thermal plasma and surface processed with a 5:1 mixture of mesitylene and 1-dodecene. As-synthesized Si NCs are covalently capped with a ligand (1-dodecene) through a liquid-phase thermal hydrosilylation reaction.

Table PP2.4.1:

Sample description for Si NCs			
Sample	1	2	3
diameter (nm)	6.2	3.8	2.2

The excitation dependent steady state PL, as shown in Figure PP2.4.12, and time-resolved PL were performed to obtain initial experimental data.

The temperature of hot carriers can be extracted from the data. The fitting strategy for the PL measured results is based on the band-to-band recombination. As silicon is an indirect-gap material, the close-to-gap recombination has to be assisted by phonon absorption or emission.

Using such measurements, the ratio of the thermalisation time to the recombination time was deduced for each of these three specimens. For each sample, the ratio is larger when a more intensive illumination is used. This can be attributed to the filling of band-edge states, which prevents further decay of high-energy

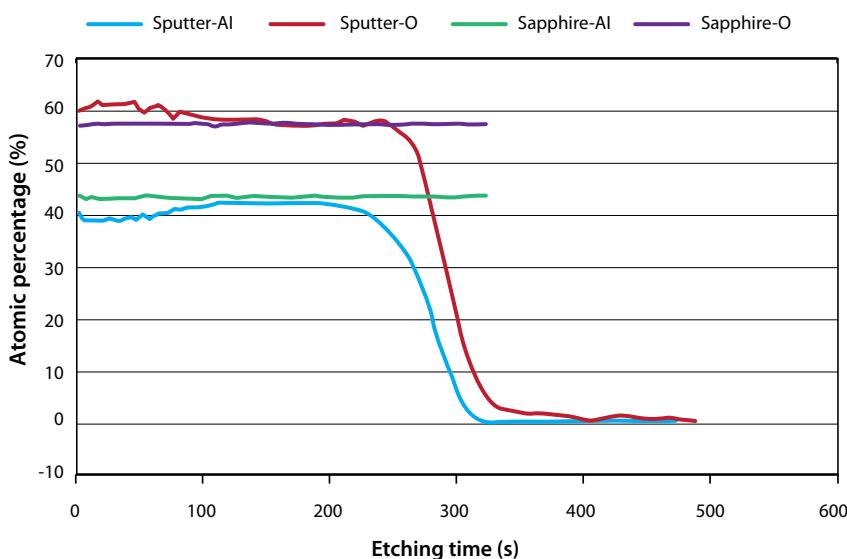


Figure PP2.4.13: XPS depth profiles of Al_2O_3 grown at 500°C and reference sapphire.

states. By comparing results for different samples, Samples 2 and 3 have demonstrated a much larger ratio than that of Sample 1. It is noted that particles in Sample 1 have the largest size and do not demonstrate a significant confinement effect. This implies that in the regime of quantum confinement, the thermalisation time becomes longer than its bulk counterpart.

PP2.4.1(iv) Investigate Energy Selective Contacts

Aim

Establish high quality resonant tunneling structures. Move on to triple barrier structures with asymmetric wells for improved selection and carrier rectification.

Actions

- Fabricate double barrier QW structures using thin film deposition
- Fabricate double barrier QD structures using Langmuir-Bodgett deposition of colloidal nanoparticles
- Investigate resonant tunnelling properties

Key resources

UNSW: Dr Santosh Shrestha, Dr Shujuan Huang, Pengfei Zhang, Yuanxun Liao, Xi Dai

Progress in 2013

Al_2O_3 and Si have been grown using RF sputtering with films grown in a layer-by-layer mode. In Figure PP2.4.13 the aluminium and oxygen content of an Al_2O_3 film grown at 500 °C is shown as a function of thickness of the film (etch time). For comparison, oxygen and aluminium depth profiles from a sapphire wafer are also shown. Composition of the Al_2O_3 film and sapphire were measured with X-ray photoelectron spectroscopy (XPS). The result shows that the oxygen-to-aluminium ratio O/Al = 1.32 for the sapphire sample which is lower than the expected value of 1.5. This may be due to the loss of oxygen during Ar etching. The O/Al ratio of the sputtered Al_2O_3 film is 1.5 on the surface but it gradually decreases with depth and becomes equal to sapphire's stoichiometry.

Crystallinity of the materials is a very important issue for resonant tunnelling devices which are based on the interference of the multi-reflection of carriers between the interfaces of two different crystal structures. In Figure PP2.4.14 XRD spectrum of a 26nm Al_2O_3 film sputtered at

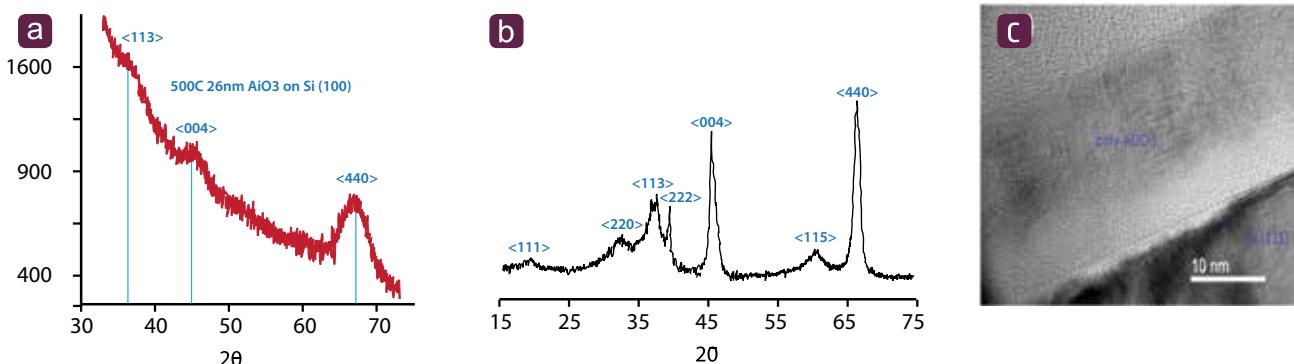


Figure PP2.4.14: (a) XRD of a 26nm thick film of Al_2O_3 grown on Si (100). (b) The reference γ - Al_2O_3 XRD data from [6], and (c) TEM image of a 19nm poly γ - Al_2O_3 film on Si(111).

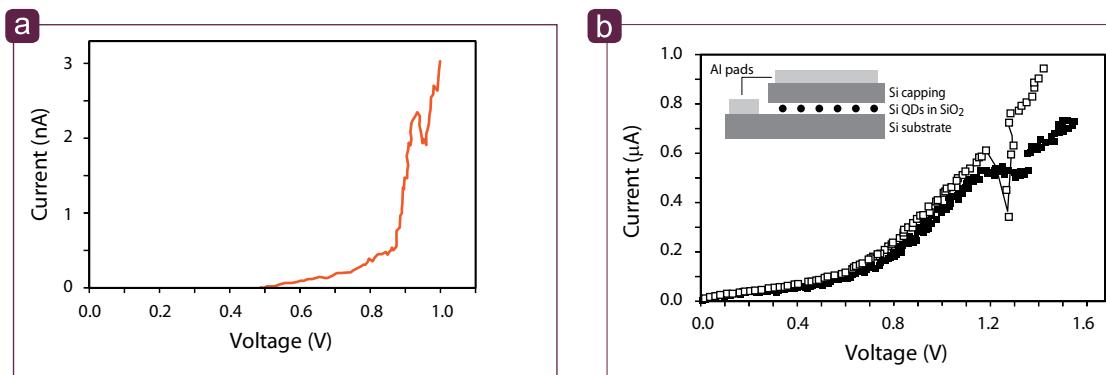


Figure PP2.4.15: (a) Results of a room temperature I-V measurement on a typical Al₂O₃/Si/Al₂O₃ structure. (b) Results of two consecutive I-V measurements at room temperature on a typical SiO₂/Si QD/SiO₂. The open and filled data points represent the first and the second measurements, respectively. From [Shrestha et al., SOLMAT 94 (2010) 1546].

500 °C is shown, clearly exhibiting the three main γ-Al₂O₃ XRD peaks at 67° (440), 45.5° (004) and 36.5° (113), at nearly the same angles as the bulk reference sample [6], which indicate that this thin film has good crystallinity. This is also demonstrated by the Transmission Electron Microscope (TEM) image of an Al₂O₃ film.

Several double barrier structures (Al₂O₃/Si/Al₂O₃) have been fabricated to study resonant tunnelling through these structures and their applicability as Energy Selective Contacts. In the I-V data of Figure 2.4.15(a) negative differential resistance is observed at ~0.9V which demonstrates resonant tunnelling. For comparison, an I-V measurement on a SiO₂/Si QD/SiO₂ is shown in Figure PP2.4.14(b) in which the full width at half maximum (FWHM) of the resonant peak is more than 400 meV. The observed FWHM of the resonant peak in this work is ~65meV which is more than 6 times narrower than previous results.

PP2.4.1(v) Fabricate complete hot carrier devices

Aim

Fabricate complete hot carrier devices:

- Electrically coupled devices of slowed carrier cooling absorber with energy selective contacts.
- Optically coupled device operating at open circuit to illuminate standard solar cell through a DBR optically selective band pass filter.

Actions

- Fabricate combination of absorber with ESCs both with collaborators and in-house
- Characterise carrier cooling and I-V properties under with concentration
- Fabricate absorbers to operate in open circuit

- Fabricate chirped DBR band pass filters and combine with absorber
- Characterise carrier cooling, optical emission spectra and efficiency of test cells

Key resources

UNSW: Yu Feng, Jeffrey Zhang, Suntrana Smyth, Steven Limpert, Yuanxun Liao, Dr Xiaoming Wen, Dr Siva Karuturi, Dr Santosh Shrestha, Prof. Gavin Conibeer

Progress

Complete hot carrier cell devices consisting of absorbers and energy selective contacts or with optical emission are topics for investigation in 2014 and 2015. They will build on the individual results for absorbers and contacts shown here.

PP2.4.2 Silicon nanostructure tandem cells

Background

Silicon nanocrystals in a dielectric matrix can be used to engineer the bandgap of an amorphous thin film material. This is of use in tailoring the absorption and Voc in a nanostructure PV cell, such as to allow tuning of an upper cell element in a tandem solar cell based on a silicon bottom cell.

UNSW has developed a wide range of technology on engineering such as bandgap engineering in Si quantum dot nanostructures self-assembled in a solid state multi-layered material grown by sputtering or CVD. Fabrication of materials in a Si rich Si oxide in multilayers allows formation of fairly uniform QDs on phase separation of the excess Si on annealing at high temperatures. Doping both n- and p-type doping of such structures has allowed PV devices with Voc up to 520mV to be fabricated.

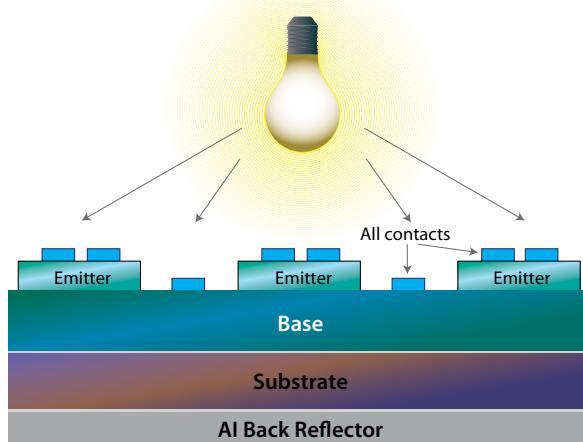


Figure PP2.4.16: Schematic of the structure used to optimise photocurrent using an Al back reflector.

PP2.4.2(i) Optimisation of homojunction Si QD device

Aims

Improved understanding of fabrication, characterization and doping of materials and devices to optimize efficiency.

Actions

- Sputter Si rich oxide materials with improved characterization
- Further investigate doping parameters
- Optimise device structure through lithography
- Develop transparent substrates for direct through vertical devices

Key resources

UNSW: Terry Yang, Xuguang Jia, Ziyun Lin, Dr Ivan Perez-Wurfl

Progress in 2013:

Optimisation of homojunction device

Light trapping to boost current

We have surpassed the expectation for the proposed current enhancement by more than a factor of three. Compared to a cell without any light trapping, the application of an Aluminium backreflector gave a current enhancement of up to 46%. Silver nanoparticles gave an even more impressive result increasing the current by up to 109%.

Devices are fabricated on quartz substrates in the substrate configuration. This means that the devices were designed such that illumination was applied from the top of the structure. The substrate is used as a support for the device as well as the back reflector as shown in Figure PP2.4.16.

The amount of light absorbed by these structures is limited by the thinness of the structure and the relatively low Silicon content. Furthermore, light trapping is not possible using a textured substrate as the material is deposited by sputtering which is not as conformal as CVD

or ALD, for example. Furthermore, the thinness of the layer does not allow the typical chemical texturing used in standard Si solar cells. The most straightforward way to increase light absorption, and therefore short circuit current, is with the use of a metal back reflector. The efficiency of a back reflector can be further enhanced (or substituted) with the use of plasmonic effects that could increase the optical absorption path by scattering incoming light. The first deliverable for this milestone was the demonstration of a 30% increase in the short circuit current using the above mentioned techniques.

A sample was chosen such that the current was as high as possible for multiple devices contained within the same insulating substrate. This sample will be referred to as SM2A from here on. The devices showed a reasonable uniformity within the sample to allow a statistically significant comparison between cells with and without a back reflector. The resistivity of the base had to be chosen to be as low as possible to reduce its effect on the current without compromising the quality of the diodes fabricated.

The results of the photocurrent enhancement are summarised in the table below. Notice that the lowest enhancement is 31.3%. The average enhancement across the sample was 40% with a maximum enhancement of 46.1%.

	5mm ² device	1mm ² devices		
	Device A	Device B	Device C	Device D
I _{sc} without Reflector (μA)	18.7	4.1	4.6	4.6
I _{sc} with Reflector (μA)	27.3	5.4	6.7	6.4
% increase using Al (M2A)	46.1%	31.3%	45.1%	37.5%

Table PP2.4.2

Summary of photocurrent enhancement achieved with an Aluminium back reflector on sample SM2A.

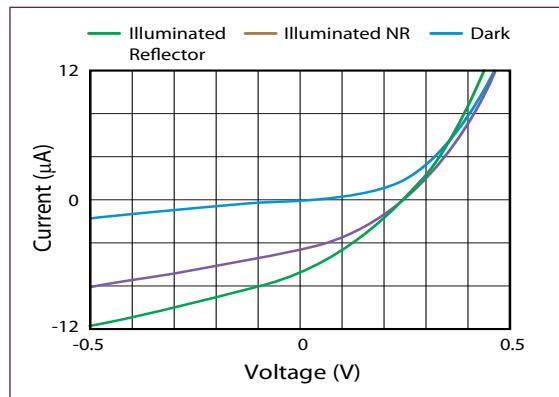


Figure PP2.4.17: A typical dark and illuminated I-V curve for a device tested on sample SM2A. Three curves are shown: Illuminated with Reflector (green), Illuminated with No Reflector (gray) and in the Dark (blue).

PP2.4.2(ii) Develop heterojunctions devices

Aim

Use wide gap materials as heterojunction partners, in order to optimise absorber layer for one doping type.

Actions

- Investigate and fabricate heterojunction partners: ZnO, ZnS, ITO, SiC
- Integrate with Si QD absorber layers in test devices
- Optimise for material, absorption, thicknesses etc

Key resources

UNSW: Xuguang Jia, Lingfeng Wu, Tian Zhang, Prof Gavin Conibeer

Progress in 2013:

An important first step in this work is to fabricate devices that can be contacted vertically. This is to avoid the problems associated with long lateral paths to contacts that give high series resistance because of the inherent high resistivity of Si nanostructure material. To this end, conductive substrates have been investigated which do not absorb light or contribute voltage to the device.

Wide bandgap semiconductor as back contacts

A thin, highly doped, wide bandgap material, used as a back contact, can dramatically reduce the series resistance in the device.

Silicon rich silicon carbide (SRC) layers have been investigated as the back contact for a p-i-n structure. The SRC layers are deposited directly on quartz. The films are doped with Phosphorous. After 1100°C annealing for 1 hour, the SRC layers show a sheet resistance of an order of magnitude smaller than that of bilayered SRO layers of similar thickness and with the highest Silicon content of interest (~66% Si by Volume).

One complication of using SRC as a conductive substrate is the unavoidable absorption loss caused by the layer itself. The SRC layer has to be as thin as possible to reduce this loss. In the interest of investigating the effectiveness of SRC as a conductive substrate, we chose a relatively thick layer that would be easier to handle and characterise. With

enough evidence to prove the effectiveness of SRC we were then able to optimise the thickness without significantly sacrificing its conductivity.

A 237nm thick phosphorous doped SRC layer was deposited on quartz, annealed and characterised prior to using it as a substrate. The measured sheet resistance of this film was 5kΩ/square. The layer was then used as a substrate for a standard p-i-n structure. The full stack was annealed again, devices were fabricated and characterised. It was possible to demonstrate a working device on this structure. Dark and light I-V characteristics of a 1mm² diode is shown in Figure PP2.4.18.

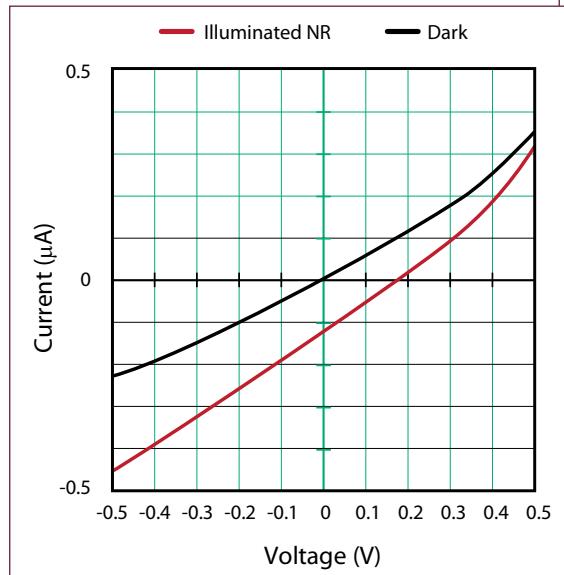


Figure PP2.4.18: I-V characteristics of a standard p-i-n structure on an SRC substrate.

The measured I_{sc} and V_{oc} are lower than those of a standard p-i-n structure deposited directly on quartz. The reason for this lower performance is mainly due to the absorption of light in the SRC layer, which is most probably not converted into current.

Metals as back contacts

Sputtering is the most common technique used to deposit refractory metals. The deposition itself is straightforward but much optimisation is needed to ensure the stress in the films is low enough to avoid the films desquamating from the substrate. Early on in the optimisation process we identified severe difficulties obtaining good quality films with W and Ta. We concentrated our efforts then on improving the quality of Mo thin films. It was found that a good indicator of the compatibility of the film with a high temperature process was the minimisation of pinholes in the film. To accurately quantify the density of pinholes we developed a technique based on the optical transmission of Mo thin films. We have been able to use this characterisation technique to quantify the pinhole density down a 1/100,000 total area of the film. Figure PP2.4.19 shows the measured optical transmittance of two Mo films deposited on quartz.

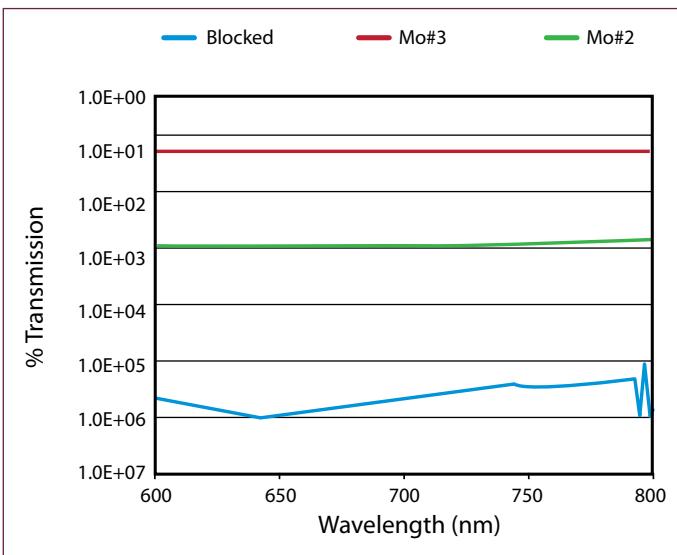


Figure PP2.4.19: Optical transmission of two Mo films on quartz.

The transmittance was measured using a Perkin Elmer Lambda 1050 spectrophotometer. The measurement has been optimised by ensuring a baseline calibration compatible with measurements of very low transmittance.

The resistivity, surface roughness and the areal density of pinholes of the optimised Mo layer are reported in the table below.

Substrate deposition temperature (°C)	Film thickness (nm)	Surface roughness (nm)	Sheet resistance (Ω/square)	Area of pinholes (% of total area)
420	350 ± 50	0.84 ± 0.2	2.35 ± 0.8	0.0018

PP2.4.2(iii) Model absorption and electrical properties of materials and devices

Aim

Improve understanding of absorption and origin of photovoltage in order to optimise growth of good devices.

Actions

- Modify and develop optical models appropriate for nanostructures
- Develop device models with transport, absorption and efficiency calculation
- Use these to optimise nanostructures and growth
- Feedback into PP2.3.2(i)

Key resources

UNSW: Xuguang Jia, Ziyun Lin, Lingfeng Wu, Dr Ivan Perez-Wurfl

Progress

Optical models have been developed previously. [Jia et al J of Non-crystalline solids, 362 (2013) 169]

Device models have also been developed and applied to existing cells [Perez-Wurfl et al Solar Energy Materials and Solar Cells, 100 (2012) 65].

Creation of a database relating defects and their mitigation

Having identified electronic defects as the main limitation of this technology, most of our research efforts were focused on finding the most effective method to mitigate and/or eliminate these defects. Our first choice for passivation was the use of hydrogen. In the course of this study it was found that phosphine was even better than hydrogen at passivating defects.

Taking into account the difficulty in quantifying the amount and nature of electronic defects, we considered various methods to monitor them. The most straightforward characterisation that could be used is based on ellipsometry and optical transmittance. However, when the defect density is significantly lower than the atomic density, these techniques are not sensitive enough to distinguish such defects. Even in the case where the defects could cause up to 1% increase in the optical absorption, this change would be within the uncertainty of the measurements, so it would not be possible to differentiate between material of good and bad quality.

These techniques are not sensitive enough to distinguish such defects. Even in the case where the defects could cause up to 1% increase in the optical absorption, this change would be within the uncertainty of the measurements, so it would not be possible to differentiate between material of good and bad quality.

Table PP2.4.3
Characteristics of the best overall Mo film used as a substrate for a SiQD p-i-n structure

PP2.4.2(iv) Investigate other materials based on Si or Ge QDs

Aim

To determine if other matrices can give better transport and if other QD species give better quantum confinement and tuning.

Actions

- Fabricate Si QD materials in silicon nitride
- Fabricate Ge Qs in silicon nitride and silicon oxide
- Characterise and compare to Si QDs in oxide
- Potentially fabricate heterojunctions of two QD materials

Key resources

UNSW: Terry Yang, Keita Nomoto, Haixiang Zhang, Dr Santosh Shrestha, Prof Gavin Conibeer

Progress in 2013:

Si QDs in silicon nitride have been grown in previous projects. [Di et al. Nanoscale Research Letters, 6(1), (2011) 612].

Ge QDs in SiN_x have been grown with good quality demonstrated [Lee et al, Applied Surface Science 290 (2014) 167] in silicon oxide [Zhang et al. Nanotechnology, 22 (2011)125204].



These materials continue to be characterised for suitability for use in heterojunction structures with Si QDs in SiO_2 .

Conclusion

The 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.

Hot carrier dynamics offer the potential for the highest efficiencies, whether in an electrically coupled device or in boosting silicon or GaAs cell efficiencies in an optically coupled device.

Si QD tandem cell materials offer the ability to boost the voltage in a silicon solar cell and hence its efficiency.

Both circumvent the Shockley-Queisser limit and so offer routes to devices in the high 20% range or well over 30%.

Progress in 2013 has seen development in all the main areas of hot carrier cell work, with new materials HfN being sputtered and characterised to show long hot carrier lifetimes, nanoparticles of both Si and AgS_2 , also with long carrier lifetimes, improved modeling of phonon modes and progress on energy selective contacts. The Si QD work has seen improvements in the current of homojunction cells, progress on back contact materials for heterojunctions, modeling of both optical and device properties and progress of growth of QDs in other material systems.

5. RESEARCH REPORTS

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 particular 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.

PP3.1: Methods to Characterize the Optical and Electrical Properties of Organic and Other Thin Film Earth Abundant Solar Cells – Lead Institution: UQ Research Team

UQ: Dr Hui Jin, Mr Ardalan Armin, Mr Martin Stolterfoht, Dr Paul Shaw, Dr Andrew Clulow, Prof. Paul Burn, Prof. Paul Meredith.

Background

Emergent solar cell technologies such as organic photovoltaics and perovskites present new challenges with respect to understanding the basic physical processes underpinning charge generation and extraction. For example, organic solar cells operate in the thin film junction limit, and the photoactive materials (organic semiconductors) are disordered semiconductors, the charge transport physics of which is very different to conventional inorganic semiconductors. UQ has previously developed 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 which are operationally relevant. UQ has also established

skills in neutron and x-ray structural techniques and the development of predictive structure-property relationships from the molecule to device level. Furthermore, UQ has recently demonstrated the close coupling of optical and electrical effects in organic solar cells derived from their behaviour as thin film, low finesse electro-optical cavities. In the PP3.1 program, UQ will apply this expertise to new materials and architectures in OPV and other earth abundant technologies such as perovskites – and serve as a valuable resource to our partners Monash, CSIRO and Melbourne. UQ also plans to share 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.

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.

Thin Film Organic Solar Cells: Optical Cavity Effects and Hot Excitons

Organic solar cells are thin film multi-layer devices where the junction is often in the order of 100nm or so. This means that the optical field distribution in the junction region is significantly affected by cavity effects such as interference and parasitic absorption of light in the non-

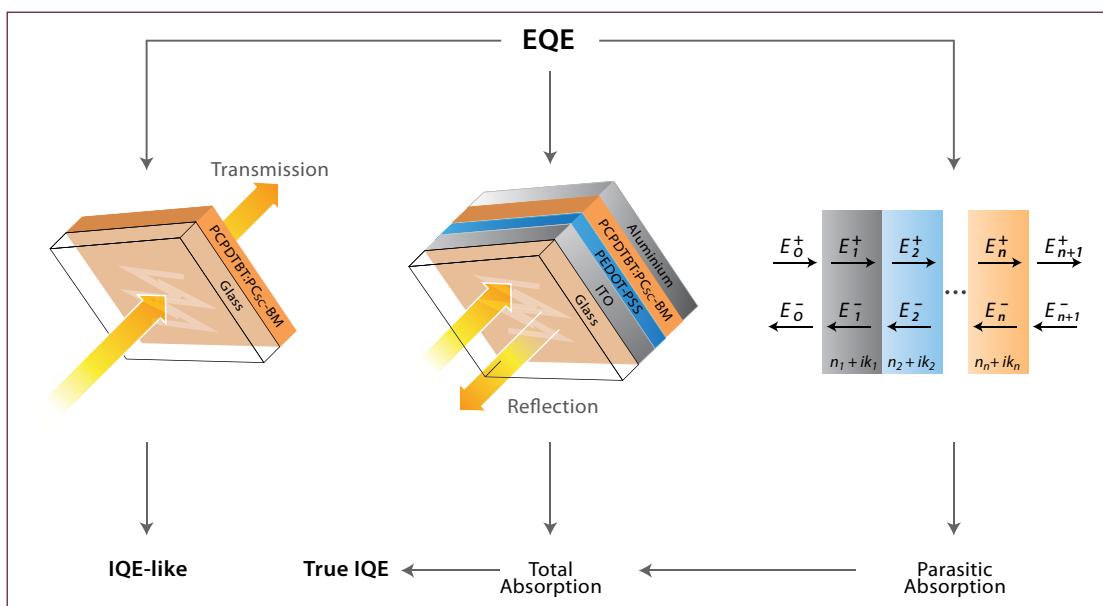


Figure PP3.1.1

active layers of the cell (Figure PP3.1.1). The optical field distribution as a function of wavelength defines the free carrier photo-generation profile, which in turn affects the shape of the external quantum efficiency (EQE). This is demonstrated in Figure. PP3.1.2, particularly by the thickness dependence of the results in Figure. PP3.1.2(b). To optimise an organic solar cell structure – for example when testing a new material, it is necessary to fully understand and model the physics to arrive at an appropriate cell structure. Furthermore, the internal quantum efficiency (IQE) of any solar cell provides important information as to the basic charge generation processes and their efficiencies. For example, an energy dependence of the IQE was recently used to justify an apparent observation of “hot excitons” in a solution processed organic solar cell [PP3.1.1]. To accurately calculate the IQE from the measured EQE one must determine the number of photons absorbed by the junction as a function of wavelength. This in turn requires measurements and simulations of the junction and whole device as a low finesse multi-layer structure.

In this work we have studied these optical effects in a model polymer: fullerene solar cell and developed a

robust and accurate methodology for measuring the IQE. In so doing, we are able to optimise new junction materials rapidly prior to laboratory fabrication. We have also shown that the aforementioned energy dependence of the IQE in the Grancini report [PP3.1.1, PP3.1.2] was due to a failure to account for such effects rather than hot excitons (Figure PP3.1.3). This work was recently published in the journal ACS Photonics [PP3.1.3].

References

- PP3.1.1 Grancini, G. et al. Hot exciton dissociation in polymer solar cells. *Nat. Mater.* 12, 29–33, 2013.
- PP3.1.2 Armin, et al. Measuring internal quantum efficiency to demonstrate hot exciton dissociation. *Nat. Mater.* 12, 593–593, 2013.
- PP3.1.3 Armin et al. Quantum efficiency of organic solar cells: electro-optical cavity considerations. *ACS Photonics*, 2014 doi.org/10.1021/ph400044k.

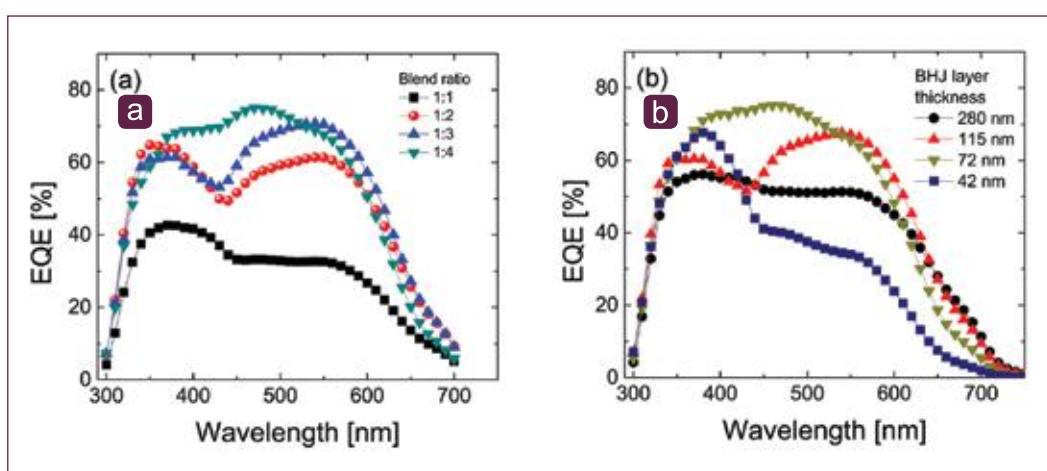


Figure PP3.1.2: EQE spectra of PCDTBT:PC70BM organic solar cells: (a) Measurements in devices with various blend ratios of acceptor to donor. (b) Measurements in devices with a fixed blend ratio of 1:4 and different thicknesses of the active layer. The similarity between EQE spectra in Figures (a) and (b) suggest that the action spectra are mainly governed by the active layer thickness and not by the blend ratio.

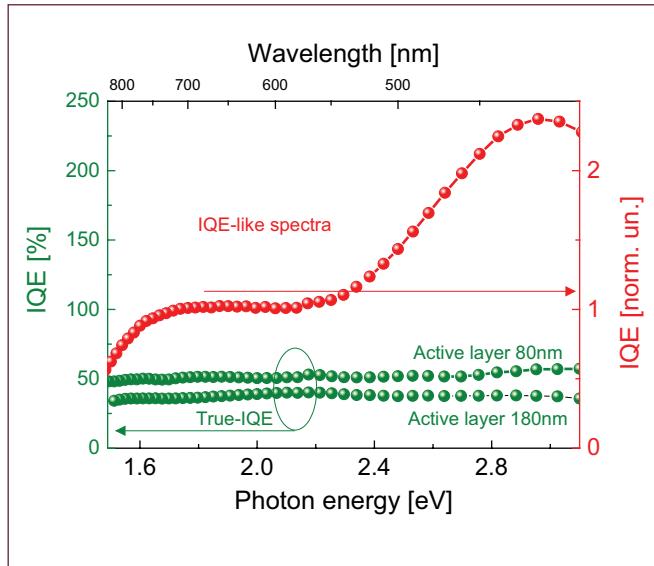


Figure PP3.1.3: True-Internal Quantum Efficiency (IQE) spectra taking into account optical interference effects and ‘parasitic absorptions’, and the “IQE-like” spectrum obtained following the procedure reported by Grancini et al. [PP3.1.1] for the same PCPDTBT/PC60BM device. True-IQE spectra are shown for junction thicknesses of 80nm and 180nm – the former being optimised for efficiency and the latter similar to the device reported by Grancini et al. (200nm). The “IQE-like” spectrum of the 80nm device is also presented. No dependence of the exciton dissociation on photon energy is observed in the “true-IQE”, which is spectrally flat within the measurement certainty (~5%). This is also the case for the 180nm device. However, and similar to that reported by Grancini et al. [PP3.1.1], the “IQE-like” spectrum shows strong photon energy dependence (> 200% increase at 3 eV versus 2 eV)

PP3.2: Plasmonic and Nanophotonic Light-Trapping

Research Team

Academic/ Post-Doctoral:

ANU: A/Prof. Kylie Catchpole, Dr Tom White, Dr Dibakar Chowdury, Dr Qunyu Bi, Dr Niraj Lal

UNSW: Dr Supriya Pillai, Dr Yang Yang, Dr. Craig Johnson, Dr Henner Kampwerth, Dr. Hamid Mehrvarz, Prof. Martin Green,

Research Students:

ANU: Mr Chog Barugkin

UNSW: Yajie Jiang, Claire Disney, Qi Xu

Funding Support:

ACAP, ARENA, UNSW

PP3.2a Photoluminescence Spectroscopy (PLS)- Lead Institution ANU

Background

As high efficiency solar cell technologies mature, harvesting the near infrared (NIR) photons becomes essential 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. Plasmonics has several advantages over conventional geometrical textures as it can be used for thin crystalline silicon and multi-crystalline silicon where pyramid texturing is not feasible. It can also be applied to a planar semiconductor layer, avoiding the need to etch the active region of the device. Furthermore, the surface plasmon resonance can be tuned to couple with the desired wavelength range by controlling the parameters of the plasmonic particles. It is beneficial to apply plasmonic structures at the rear rather than front of a solar cell, as, in this way, loss of short wavelength light can be avoided. To obtain good light trapping with plasmonic particles, it is necessary to include a reflector structure as well as the particles.

Approach

During 2013, we have demonstrated experimentally that a back reflector structure with Ag plasmonic particles embedded between the dielectric and diffuse coating layers can support excellent light trapping performance, which is comparable with the traditional inverted pyramid texturing structure. Figure PP3.2a.1

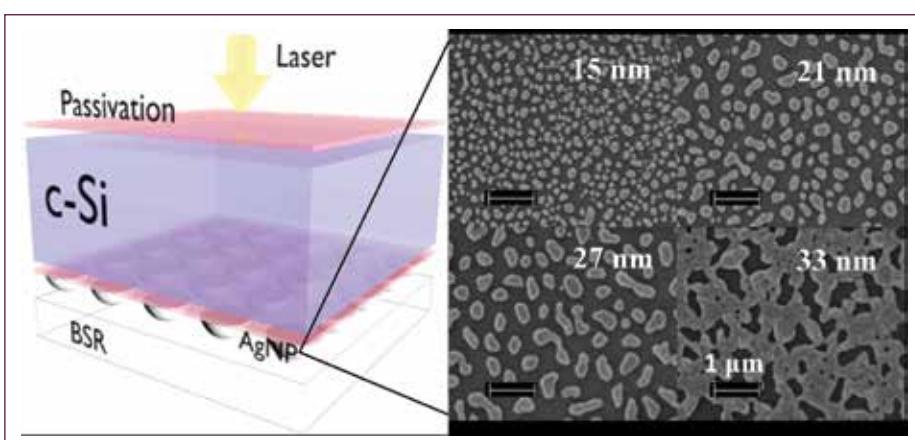


Figure PP3.2a.1: Structure of passivated silicon samples with Ag nanoparticles and diffused white paint as BSR on the rear side. (Inset) SEM images of nanoparticles formed from various mass thicknesses of evaporated Ag, followed by annealing.

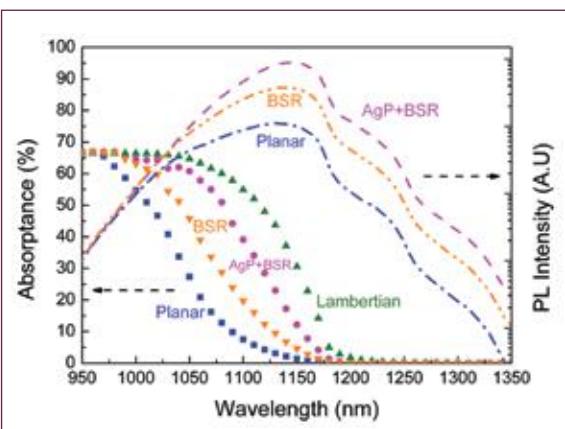


Figure PP3.2a.2: (Primary Y-Axis, left) Absorption spectra of 10nm Al_2O_3 passivated planar sample (blue squares), sample with only diffuse coating as BSR (orange downward triangles) and sample with Ag+BSR (magenta dots). For comparison, the absorption expected with an ideal Lambertian light trapping on the rear is also shown (green upward triangles); (Secondary Y-Axis, right) Photoluminescence spectra of the planar sample (dash dot blue line), sample with BSR (dash dot dot orange line) and the sample with Ag+BSR (dashed magenta line) used to obtain the absorption spectra.

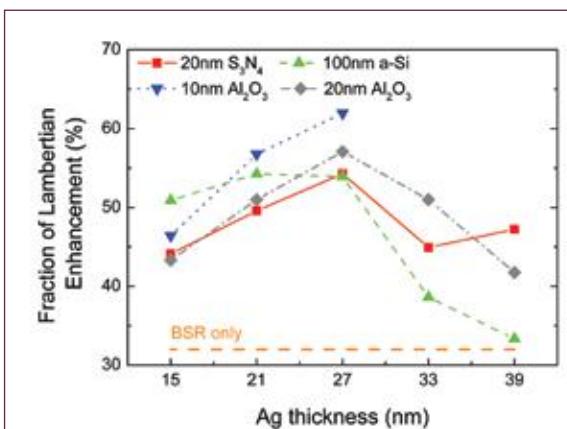


Figure PP3.2a.3: The fraction of Lambertian enhancement in calculated photocurrent, as a function of Ag film thickness for various passivation layers. Enhancement due to only BSR structure is presented as a baseline here (dashed orange line).

shows a schematic of the light trapping structure applied at the back of a silicon wafer. The inset shows scanning electron micrographs of metal nanoparticles deposited on the surface of the silicon wafer at various mass thicknesses. We use spectrally-resolved photoluminescence to quantify the absorptance, which allows parasitic absorption to be excluded and provides a rapid method for assessing light trapping.

Results

The photoluminescence results and corresponding absorptance for a range of back reflector structures are shown in Figure PP3.2a.2. Photoconductance based measurements of the effective carrier lifetime at relevant injection levels also show that surface passivation is not degraded with these light trapping structures.

Figure PP3.2a.2 shows the experimental enhancement values as a function of Ag film thickness, for various passivation layers. The best performing case is 62% of Lambertian enhancement in absorption, obtained with 27nm thick Ag on 10nm Al_2O_3 passivated wafer (Figure PP3.2a.3). This case has a path length enhancement of 11, obtained by dividing the absorptance of the sample with nanoparticles and BSR by the absorptance of the planar sample in the weakly absorbed, long wavelength range. We can compare this to the standard light trapping scheme of inverted pyramid texture, where the average path length enhancement of weakly absorbed light is 16. The inverted pyramid texture on the front surface of solar cells can provide both light trapping and anti-reflection. Since our plasmonic Ag+BSR structure is only on the rear of the cell, we only compare the light trapping properties between the two, not anti-reflection.

The method of extracting band to band absorption from photoluminescence spectra 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. With self-assembled plasmonic Ag particles, excellent optical enhancement can be

achieved for photovoltaic applications without sacrificing the electrical performance of the device. 10nm ALD aluminum oxide combined with nanoparticles formed from a 27nm thick Ag film, together with a diffuse back reflector, has provided the best light trapping among all those structures, with performance comparable with the light trapping provided by inverted pyramids. The combination of plasmonic particles with a back reflector is particularly promising for application to thin film cells, and multi-crystalline silicon solar cells where conventional random pyramid texturing is not feasible.

Further work

Work during 2014 will focus on using this photoluminescence method described here to rapidly assess a range of light trapping structures for light trapping and passivation.

PP3.2b Light trapping characterisation - Lead Institution: UNSW

Background

Back metal contacts in solar cells act as a metal reflector as well as a carrier collection layer. Minimising electrical losses due to recombination at a metal semiconductor interface form part of extensive studies, however optical losses such as plasmonic absorption losses could be associated with these structures and it is important to minimise such losses. This is particularly important when placed in proximity to scattering media like textures on the front of the cell that can introduce an angular dependence to the light incident on the rear. For a typical dielectrically displaced rear reflector involving a Si/dielectric/metal layer stack, the plasmonic losses are caused by the excitation of surface plasmon polaritons (SPP) at the metal dielectric interface when the SPP resonance condition is fulfilled. When the angle of incoming light approaches the resonance angle ($\Phi_i = \Phi_r$, Φ_r indicating the angle of maximum SPP coupling to the dielectric-metal interface) of the system, the evanescent waves travel parallel along the Si-dielectric interface. The tail of the evanescent

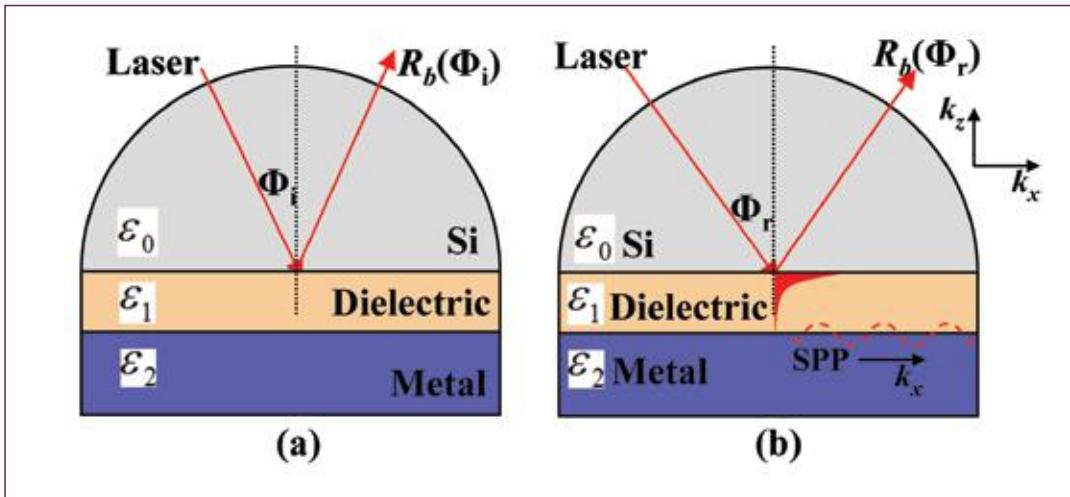


Figure PP3.2b.1: (a) Schematic of a dielectrically displaced rear reflecting system of solar cell (b) system at resonance resembling an Otto configuration. SPPs are excited by a laser beam when $\Phi_i = \Phi_r$, the resonance angle, at the metal interface.

wave originating at the onset of total internal reflection (TIR) is brought into contact with a metal-dielectric interface that supports SPPs, see Figure PP3.2b.1.

Approach

This optical loss mechanism for solar cells needs to be avoided and can occur on smooth surfaces as well, contrary to the belief that this occurs only on rough surfaces. So far there has been no experimental demonstration of angular measurements from the rear. One of the promising aspects of this work was the use of Si hemisphere as a substrate that enables incident light to pass through the air-silicon interface without refraction and gives us the total angular distribution. The experimental measurement was realised using a novel custom-built 1D optical setup for characterizing intensity of the reflected light at various internal incident angles at the Si-dielectric interface. In our preliminary work we have checked the accuracy of our measurements with simulations. We have experimentally confirmed the existence of such SPP excitation in a standard solar cell rear structure and are investigating factors that could affect the degree of such losses.

Results

Measured results for the Si/SiO₂/Air, Si/SiO₂/Ag and Si/SiO₂/Al scheme are shown in Figure PP3.2b.2. For the case with no metal, total internal reflection occurs at an angle of $>17^\circ$ after which reflection is max and no SPP losses are evident. For the structures with metal, as the light angle approaches the critical angle Φ_c , R_b decreases and is at its minimum at an angle of around 24.5° (Si- SiO₂ interface). This angle corresponds to the resonance angle Φ_r of the propagating SPP. The excitation of SPPs is shown as a dip in the reflection plot. Note the difference in R_b between Al and Ag at angles near Φ_r where SPPs are excited. Our results here show that the type of metal could affect the intensity of losses. The thickness of the dielectric layer can also affect the shape and intensity of the reflectance dip (not shown here).

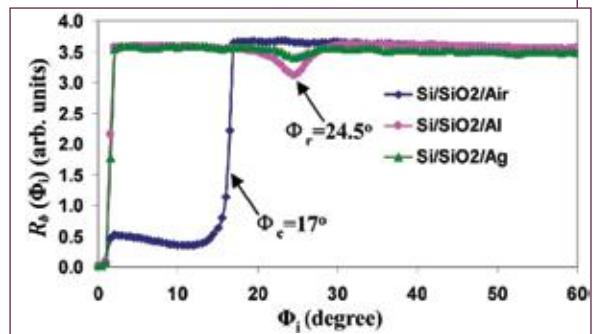


Figure PP3.2b.2: Measured rear Si reflectivity at 1310nm for non-polarised incident light from structures Si/SiO₂/Air, Si/SiO₂/Al and Si/SiO₂/Ag over the angle range of 2° to 56° for SiO₂ thickness of 300nm.

Future Work

Development of a 2D optical set up is underway to allow any combination of illumination and detection angle. This will allow a more detailed understanding of the angular response from various light trapping structures under study at UNSW.

PP3.2c: Plasmonics for Thin-Film Photovoltaics - Lead Institution: UNSW

We aim to investigate the use of nanosphere lithography (NSL) for plasmonic thin-film applications. More details will be given in subsequent reports.

PP3.2d: Optical properties of silver - Lead Institution: UNSW

Background

Plasmonics is an emerging field of study with application not only for photovoltaics but also in the field of bio-sensors, opto-electronics, waveguides, microscopy, photonics to name a few. Plasmonics open up new ways to construct optically thick but physically very thin photovoltaic absorbers, due to their strong scattering, concentration and absorption of light, finding application in light trapping for solar cells. The last decade has seen a dramatic increase in this area, with a huge number of theoretical studies.

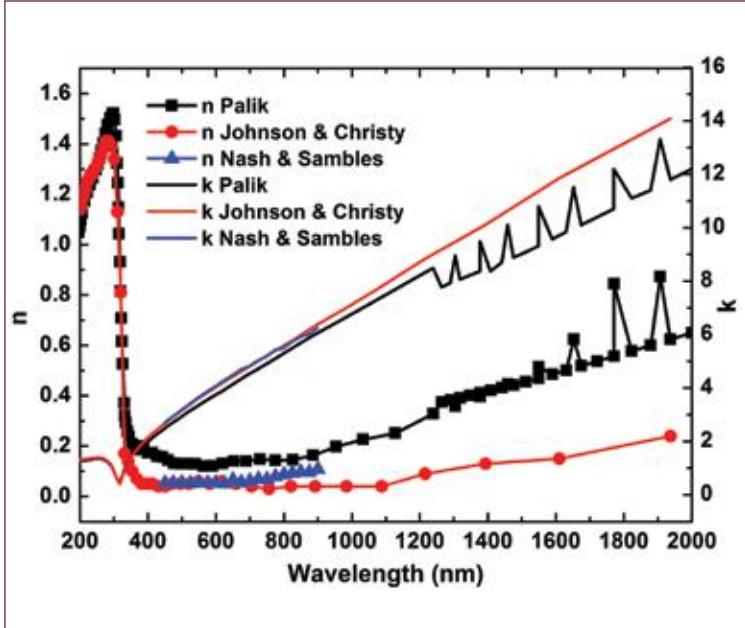


Figure PP3.2d.1: Comparison of the optical constants of silver by Palik (composite data in region of interest), Johnson & Christy and Nash & Sambles.

Silver is the most popular plasmonic material because of its large relaxation time, low absorption and high radiative efficiencies. However, different sets of optical constants for silver in the literature vary appreciably in the visible region of the electromagnetic spectrum making it difficult to conduct reliable theoretical analysis.

Palik [3.2d.1], Johnson and Christy [3.2d.2] and Nash and Sambles' [3.2d.3] data set are the most popular as evidenced in literature. Figure PP3.2d.1 shows a comparison of the optical constants for these data sets. The variations may seem small, but these differences magnify to give large differences in the calculated plasmonic light-trapping effectiveness.

Quality factors or figures-of-merit can be calculated and used as criteria for determining likely plasmonic performance [3.2d.2-3.2d.4]. Significant difference can be seen in the quality factors using the three widely used sets of optical constants in the literature as in Figure PP3.2d.2.

Palik's handbook of optical constants is one of the mostly cited references, but their data for silver combine the work of four research groups using different sample preparation methods. It is clear that this causes obvious inconsistencies in their values. Another heavily cited source for the optical constants of evaporated silver films is Johnson and Christy. However this set of values is not considered to be reliable as

their samples were exposed to air when conducting the measurements. Nash and Sambles claim to have the best data for silver as they avoided measurement on the surface exposed to air. However, their results are limited to a narrow spectral range of 450-900nm, not of prime interest for most solar applications.

Future work

Subsequent work will look into experimental determination of the most accurate set of optical constants for silver that will prove the importance of optimising calculations for plasmonic applications, with 80% of the literature in plasmonic research presently citing questionable data. Accurate and reliable data will help optimise plasmonic light trapping in solar cells and assist calculations for related applications.

References

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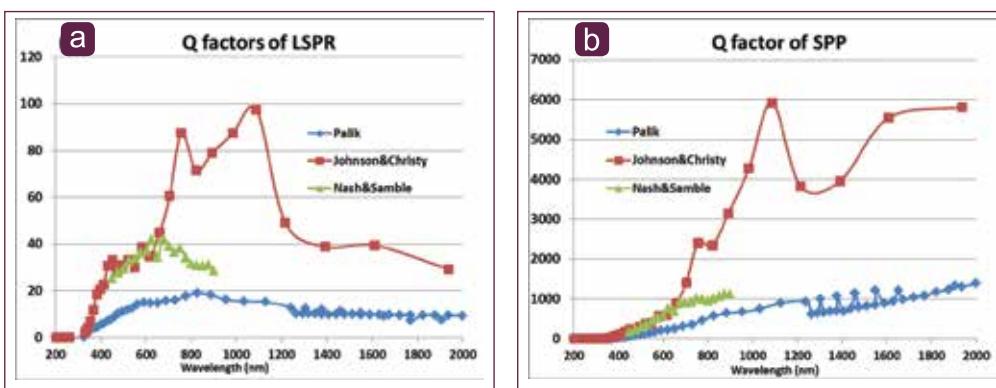


Figure PP3.2d.2: Quality factors for three published sets of silver optical constants for (a) localized surface plasmons and (b) surface plasmon polaritons.

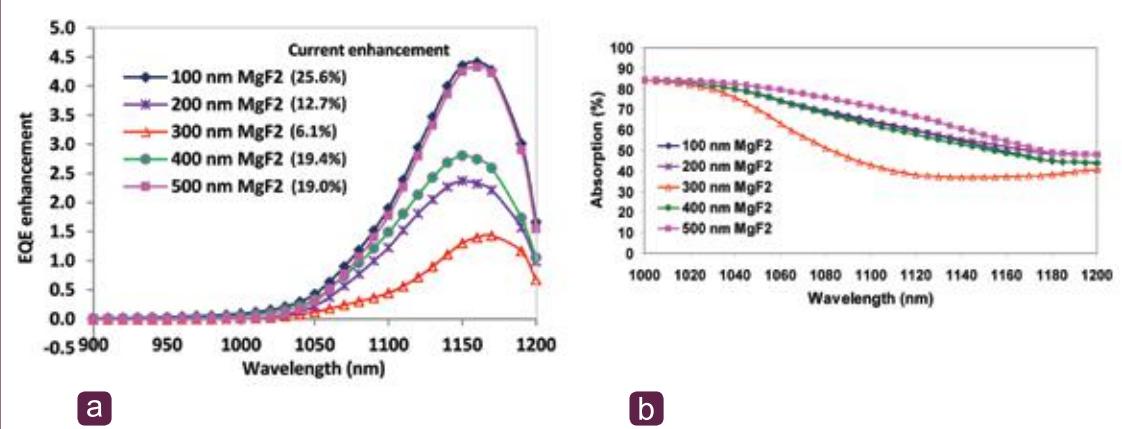


Figure PP3.2e.1: (a) EQE enhancements by the double layer reflector Ag MNP/MgF₂/Ag using different thicknesses of MgF₂ when compared to the Al mirror case. Data in the bracket is the corresponding current enhancement as a percentage compared to the Al mirror reference, calculated from 900nm to 1200nm. (b) Optical absorption by devices with double layer Ag MNP/MgF₂/Ag reflector using various MgF₂ layer thicknesses.

PP3.2e : Novel Light trapping in Si based solar cells – Lead Institution: UNSW

Background

Light trapping in Si based solar cells (400 micron thick) has been achieved using plasmonics excited in metal nanoparticles. In previous years we have identified the different design considerations for solar cells such as size/shape, location of the metal nanoparticles, effect of dielectric spacer layer thickness and also the thickness of the passivation layer required for a plasmonic solar cell. As this is an emerging area of study for photovoltaic applications, the theory of plasmonics is now well understood, with the field on an established footing. However, in 2013, we found that the initial benefits can be undone by the gradual tarnishing of the metal, due to the fact that an oxide and/or sulphide layer forms over the metal surface on exposure to air over time. Metal particles tend to undergo a morphological change during tarnishing, resulting in poor performance. To overcome this problem we looked at over-coating the particles with a dielectric layer along with a rear side reflector.

Approach

Silver metal nanoparticles were deposited using a self-assembly technique and particles deposited were similar to those shown in Figure. P3.2a.1. MgF₂ was used as an over-coating layer. The dielectric over-coating film can provide better adhesion and better protection of the metal nanoparticles that would otherwise be easily removed during handling processes. It allows isolation of the layer of Ag nanoparticles from the metal back reflector that could potentially otherwise interfere with the scattering properties of the first layer. The thickness of MgF₂ is critical to achieving good light trapping considering the interaction between light reflected/scattered from the two reflecting-layers. An optimisation of the Ag MNP / MgF₂ / Ag double reflector was also carried out in 2013.

Results

The EQE and current enhancement (Figure PP3.2e.1 (a)) as well as the absorption data (Figure PP3.2e.1 (b)) are shown for different thicknesses of MgF₂. It shows that the case of 100nm and 500nm thick MgF₂ provide the highest EQE enhancement of nearly 4.5-fold at 1160nm. When the MgF₂ layer is around 300nm thick, both EQE and current enhancement are at their minimum. For this thickness, we notice a clear suppression of EQE enhancement when compared to the case with MNP only (not shown here). This is due to interference effects and highlights the importance of proper choice of over-coating layer thickness.

At normal incidence 100nm - 200nm MgF₂ and also 500nm MgF₂ results in good reflection due to constructive interference. Minimum reflection due to destructive interference occurs when MgF₂ thickness increases to 350nm. However these results do not directly explain the higher enhancements seen for MgF₂ thickness of 400nm compared to the thickness of 200nm and the minimum when the thickness is 300nm from our experimental results. This occurs because the angular dependence cannot be ignored as phase shift in the layer becomes important, together with the additional phase shift introduced by the metal layer. This results in the onset of interference effects. We predict from our results that the forward-scattered light by metal nanoparticles have an angular distribution with its peak intensity located within the angular range of 30°-40°. Ongoing work using the characterization technique described in PP3.2b will help ascertain our findings. We find that MgF₂ with a thickness of 100nm can effectively prevent the degradation of nanoparticles and also minimize undesirable interference effects between two reflecting-layers.

Future work

The effect of plasmonic degradation and the effect of light trapping on thinner Si wafer based cells will be subject to further investigation. Future work will also look into novel light trapping structures on the rear.



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5. RESEARCH REPORTS

PROGRAM PACKAGE 4. Manufacturing Issues

Overview

PP4, manufacturing issues, aims at delivery of a substantiated methodology for assessing costs of the different technologies under investigation by ACAP. The overall cost target is to exceed 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. The aim is to provide a common basis for evaluating the relative costs of the technologies and/or development by ACAP to assist identification of potential roadblocks.

PP4 Cost Evaluations – Lead Institution: UNSW, CSIRO

Key Resources

UNSW: Dr Anita Ho-Baillie, Prof. Martin Green

Others: Considerable input on processing sequences from UNSW researchers and those from CSIRO will be mandatory for successful completion of this package.

The overall cost target for the 8-year ACAP program is to exceed the US Government's SunShot targets for photovoltaic costs, for one or more of the technologies, in at least one major SunShot targeted application, as deduced by a substantiated costing methodology. The relevance of this cost reduction target is that its 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. The levelised cost of electricity targets for the SunShot program are shown in Figure PP4.1, for three different applications.

The SunShot targets by 2020 are \$1/Watt (W), \$1.25/W and \$1.50/W in US dollars for utility-scale, commercial rooftop and residential rooftop photovoltaic (PV) systems respectively. This involves substantial cost reduction from the 2010 benchmark price of \$6/W, \$5/W and

\$4/W, respectively, as shown in Table PP4.1. Table PP4.1 also shows the calculated benchmark levelised cost of electricity (LCOE) for Phoenix, Arizona and New York City in the United States of America based on assumptions listed in Table PP4.2. The SunShot LCOE targets are depicted in Figure PP4.1. LCOE is calculated by equation below, where the numerator includes the operating costs (C_n) over the life (n) of the system by year, such as the installed cost, financing costs, credits for incentives, operating and maintenance costs (O&M), taxes, insurance etc. The denominator of the equation is the energy output (Q_n) of the system by year. Future costs and energy production benefits are discounted by d due to the depreciation of the time value of money.

$$LCOE = \frac{\sum_{n=1}^N \frac{C_n}{(1+d)^n}}{\sum_{n=1}^N \frac{Q_n}{(1+d)^n}}$$

PP4.1

Table PP4.1: Benchmark 2010 and Sunshot 2020 Targets for Solar Prices and Levelised Cost of Electricity (LCOE) [PP4.1.1].

PV Market	Benchmark 2010			Sunshot 2020
	Price (US\$/W _{DC})	LCOE (US\$/kWh)		Price (US\$/W _{DC})
		Phoenix	New York City	
Utility Scale	4.00	0.18	0.24	1.00
Commercial Rooftop	5.00	0.25	0.34	1.25
Residential Rooftop	6.00	0.22	0.28	1.50

Table PP4.2: Assumptions for LCOE calculations [PP4.1.1].

	Utility Scale		Commercial Rooftop		Residential Rooftop	
	2010	2020	2010	2020	2010	2020
System Lifetime (yrs.)	30	30	30	30	30	30
Annual Degradation (%)	1.0	1.0	1.0	1.0	1.0	1.0
Inverter Replacement Price (\$/W⁺)	0.17	0.10	0.20	0.11	0.25	0.12
Inverter Replacement Labour (\$/W⁺)	1000	1000	3000	3000	600	600
Inverter Lifetime (yrs.)	15	20	15	20	10	20
O&M Expenses (\$/kw-yr)	19.93	6.5	23.5	7.5	32.8	10.0
Pre-Inverter Derate* (%)	90.5	93.5	90.5	93.5	90.0	93.0
Inverter Efficiency (%)	96.0	98.0	95.0	98.0	94.0	97.0
System Size (kW_{DC})	20,000	30,000	200	300	5.0	7.5

+ at time of replacement

* includes losses in wiring, soiling, connections, and system mismatch

ACAP will concentrate on technological improvements that reduce to \$/Watt cost and improve the energy conversion efficiency of the photovoltaic module component of the total system costs. The more promising of the technologies developed under the ACAP program will be costed in detail and compared to similarly detailed costings for established silicon wafer and thin-film technologies. The expertise of partners in the wider AUSIAPV network will be drawn upon to provide reliable

estimates of the costs of other system components at any given point in time to generate the corresponding LCOE for selected locations.

References:

- PP4.1.1 The U.S. Department of Energy (2012), "SunShot Vision Study February 2012", DOE/GO-102012-3037.

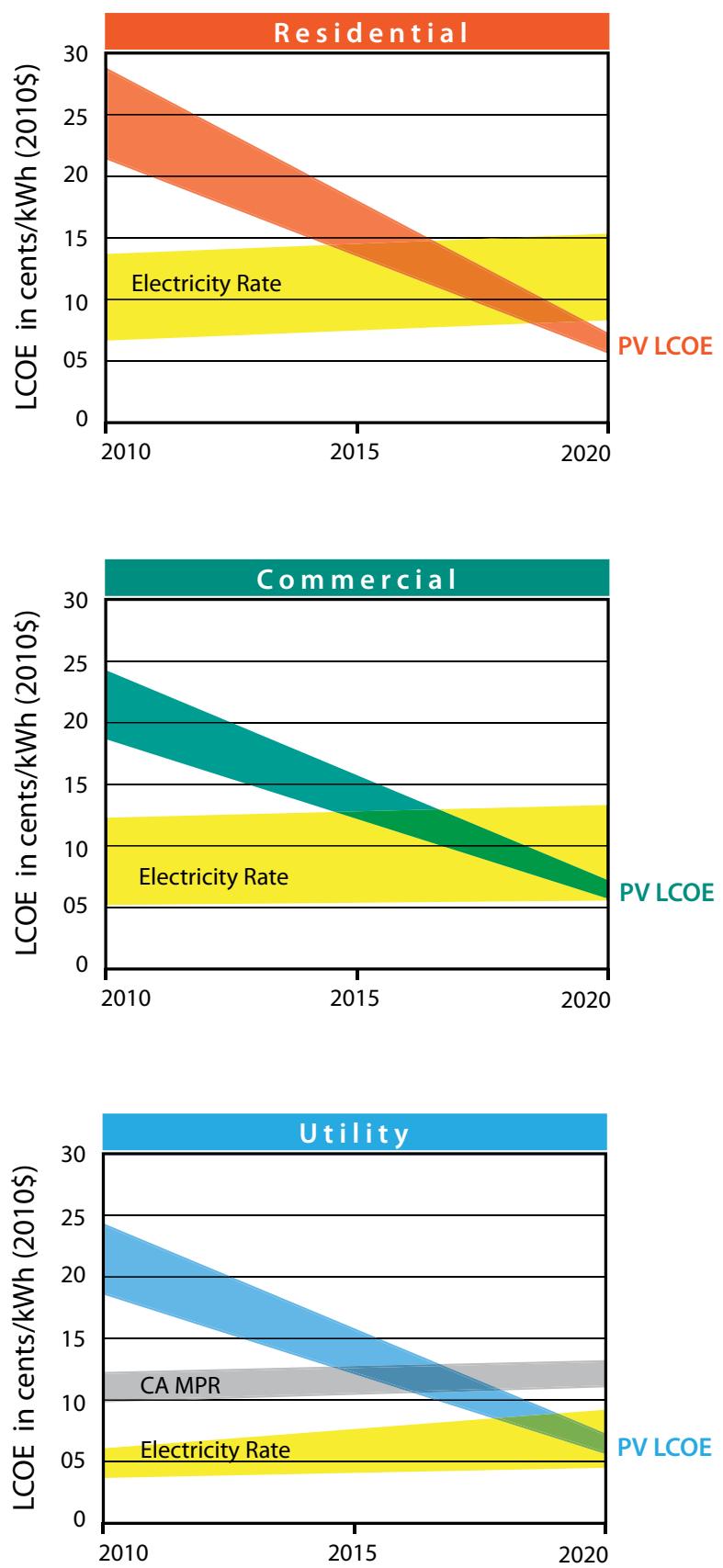


Figure PP4.1: Benchmark 2010 and Sunshot 2020 Targets for LCOE for various PV Markets [PP4.1.1].



5. RESEARCH REPORTS

PROGRAM PACKAGE 5: Education, Training and Outreach

Overview

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 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 call for submissions, visits by policy developers

and their advisors, information papers prepared and presentations to both policy developers and their advisors.

Other activities are directed at improving photovoltaic education programs, already rated as amongst the best in the world, as a contribution to improving the competitiveness of renewable energy technologies in the Australian context.



Figure PP5.1.1: (a,b) The first very successful ACAP Research conference was held at the Tyree Energy Technologies Building, UNSW on 28-29 November 2013. Additional images are available at <http://www.acap.net.au/events/acap-conference>.

PP5.1a: Annual ACAP Conference

Research Team

Academic/ Post-Doctoral (only presenters listed here):

Oral presenters: Prof. Martin Green (ACAP), Ms Veronica Heard (ARENA), Prof. Andrew Blakers (ANU), Prof. Paul Meredith/Prof. Paul Burn (UQ), Dr Gerry Wilson (CSIRO), Dr David Jones (UoM), Dr Udo Bach (Monash), Prof. Martin Green (UNSW), Dr Fiacre Rougier (ANU), A Prof. Thorsten Trupke (UNSW), Dr John Kumar (Monash), Dr Dani Lyons (UQ), Dr Fiona Scholes (UQ), Dr Evan Franklin (ANU), Dr Noel Clark (CSIRO)

Research Students:

Oral presenters: Mr Alex Pascoe (Monash), Mr Jonathan Dore (UNSW), Mr Muhammad Kalim Kashif (Monash), Mr James Banal, Mr Ardalan Armin (UQ)

Poster Authors:

UNSW: Allen Barnett, Susan Bengtson, S.P. Bremner, J.A. Carlin, Mark Carroll, Kah Chan, Jian Chen, Simon Chung, Gavin Conibeer, Jie Cui, Hongtao Cui, Michael Curtin, Xi Dai, Claire Disney, Matthew Edwards, Rhett Evans, Cho Fai, Yu Feng, Andrew Gerger, T.J. Grassman, Martin Green, Neeti Gupta, A. Haas, Jianshu Han, Xiaojing Hao, Xiaojing Hao, Jai Hashim, Anita Ho-Baillie, Shujuan Huang, Thilini Ishwara, Jingjia Ji, Xuguang Jia, Yajie Jiang, Craig Johnson, Siva Karuturi, Mark Keevers, Linda Koschier, Jonathan Lau, Alison Lennon, Alison Lennon, Hongzhao Li, Yang Li, Zhongtian Li, Wei Li, Yuanxun Liao, Dong Lin, Ziyun Lin, Shu Lin, Rui Lin, Xiaolei Liu, Fangyang Liu, Anthony Lochtefeld, Pei-Hsuan Lu, Zhong Lu, I. Al Mansouri, H. Mehrvarz, Robert Opila, Robert Patterson, Ivan Perez-Wurfl, Supriya Pillai, Binesh Puthen-Veettil, Fred Qi, S.A. Ringel, Rui Sheng, Santosh Shrestha, Suntrana Smyth, Thomas Söderström, Ning Song, Donald Stryker, Adeline Sugianto, Nathan Tam, Murad Tayebjee, Ashraf Uddin, Lu Wang, Xi Wang, Pei Wang, Xiaoming Wen, Stuart Wenham, Sanghun Woo, Matthew Wright, Lingfeng Wu, Hongze Xia, Chang Yan, Yang Yang, Chien-Jen Yang, Xiaohan Yang, Yu Yao, Tian Zhang, Haixiang Zhang, Pengfei Zhang

ANU: Chog Barugkin, Kylie Catchpole, Andres Cuevas, V.A. Everitt, Stuart Hargreaves, N.N. Lal, Siew Lim, Daniel Macdonald, M. Stocks, Yimao Wan, Vincent Wensheng, T.P. White, Xinyu Zhang, Ngwe-Soe Zin

UoM: Ognjen Belic, David Jones, Kyra N. Schwarz

UQ: Andrew Clulow, Yuan Fang, Hui (Hellen) Jin, Wei Jiang, Martin Stolterfoht

CSIRO: Regine Chantler, Chris Fell, Doojin Vak, Scott Watkins

Monash: Yu Han, Jiangjing He, Fuzhi Huang, Wanchun Xiang, Manda Xiao

Funding Support:

ACAP, UNSW

Background

ACAP intends to hold an annual research conference near the end of each year to inform ARENA, and its National Steering Committee, to exchange research results, to enhance collaboration and to 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 Director and oral and poster presentations of technical progress from staff and student researchers.

The 2013 conference was held at the Tyree Energy Technologies Building at UNSW on 28-29 November 2013. Participants were welcomed by the Director, Prof Martin Green, who introduced ARENA representative, Ms Veronica Heard and invited her to deliver the Keynote Address. This was followed by a series of summaries of nodes' progress and plans by each Director and an afternoon poster session, with 31 presentations. The second day comprised two technical presentations on projects based at each of the six nodes and wrap-up by Prof. Green. The Third ACAP Management Committee Meeting was held on the afternoon of the first day of the conference.

The next conference will be held in association with the First Asia-Pacific Solar Research Conference (see PP5.1b below).

PP5.1b: Annual APVI Conference

Research Team

Academic/ Post-Doctoral:

Staff and students of all nodes:

Funding Support:

ACAP and sponsors of APVI

Background

The Australian Photovoltaics Institute (<http://apvi.org.au>) was formed in late 2013 as an evolution of the Australian Photovoltaics Association (APVA). At its formation meeting in Sydney on 25 November 2013, attended by ACAP representative Dr Richard Corkish, it was decided to set up a new academic solar research conference. The First Asia-Pacific Solar Research Conference (<http://apvi.org.au/solar-research-conference>) will be held 8-10 December 2014 at UNSW and future conferences are to be located in other Australian cities. Representatives of three ACAP nodes, UNSW, Monash and ANU are involved in organization and volunteer staff and students from the nodes will participate in academic review committees, etc.

As a result of ACAP-APVA discussions through 2013, the Second Annual ACAP conference (see PP5.1a above) will be held in association with the First Asia-Pacific Solar Research Conference, at the same venue and it is planned to hold them in association similarly in future years.

PP5.1c: APVA/APVI Engagement

Research Team

Academic/ Post-Doctoral:

UNSW: Dr Muriel Watt, Dr Richard Corkish,
Prof. Deo Prasad, Mr Hua Fan

Monash: Prof. Yi-Bing Cheng

ANU: Prof. Andrew Blakers

CSIRO: Dr Scott Watkins

APVI: Muriel Watt

ASTRI: Dr Manuel Blanco

AUSTELA: Dr Andrew Want

SE Transformation: Dr Ken Guthrie

Funding Support:

ACAP and sponsors

Background

ACAP will become a founding “Large Organization” member of the Australian Photovoltaics Institute (APVI) in January 2014. The Australian Photovoltaics Association (APVA), forerunner of APVI has been one of the more effective vehicles for Australian policy development and ACAP partners have been active institutional members of APVA throughout 2013. ACAP collaborators contributed to and participated in several APVA workshops and policy considerations and provided information to support its policy development.

PP5.1d: Photovoltaics Industry Precinct

Research Team

Academic/ Post-Doctoral:

APVA: Dr Muriel Watt

UNSW: Dr Muriel Watt, Dr Richard Corkish

UQ: Prof. Paul Meredith

ANU: Prof. Andrew Blakers

Suntech: Dr Renate Egan

CSIRO: Dr Chris Fell

Funding Support:

Not yet approved

Background

ACAP collaborators participated in and supported the application for the proposed Photovoltaics Industry Precinct as an important policy advice and analysis instrument. The program was promoted under the Industry Innovation Precincts Program of the Australian Department of Industry.

A letter from Department of Industry to APVA dated 8 November 2013 expressed thanks for the submission but gave no date for when a decision would be made. Progress, currently on hold, will critically depend on this decision.

PP5.1e: Renewing the Sustainable Energy Curriculum

Research Team

Academic/ Post-Doctoral:

Murdoch Univ.: A Prof. Chris Lund, Prof. Philip Jennings, A Prof. Trevor Pryor, Dr Amanda Woods-McConney

UNSW: Dr Richard Corkish, A Prof. Santosh Shrestha

ANU: Dr Kim Blackmore

QUT: Dr Wendy Miller

UniSA: Prof. Wasim Saman

Funding Support:

Office of Learning and Teaching (www.olt.gov.au/project-renewing-sustainable-energy-curriculum-21st-century-providing-internationally-relevant-skills-0).

Background

Two nodes, ANU and UNSW, participated fully in and supported the major review, led by Murdoch University and funded by the Office of Learning and Teaching (OLT), of the Australian sustainable energy curriculum. The project, called “Renewing the Sustainable Energy Curriculum – Providing Internationally Relevant Skills for a Carbon Constrained Economy”, is described on the project website, www.murdoch.edu.au/School-of-Engineering-and-Information-Technology/Research/Renewing-the-Sustainable-Energy-Curriculum/. As stated on that website, “This project aims 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.”

The project generated a catalogue of sustainable energy skills, knowledge and generic attributes from related reports and existing sustainable energy curricula, programs and courses in order to determine the skills and knowledge required and gaps already identified; surveyed graduates and employers (including employer representative bodies) to determine their views of the skills and knowledge areas and generic attributes required by professionals in this field and how to most effectively deliver them; surveyed and interviewed key staff from international institutions with highly regarded sustainable energy programs 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.

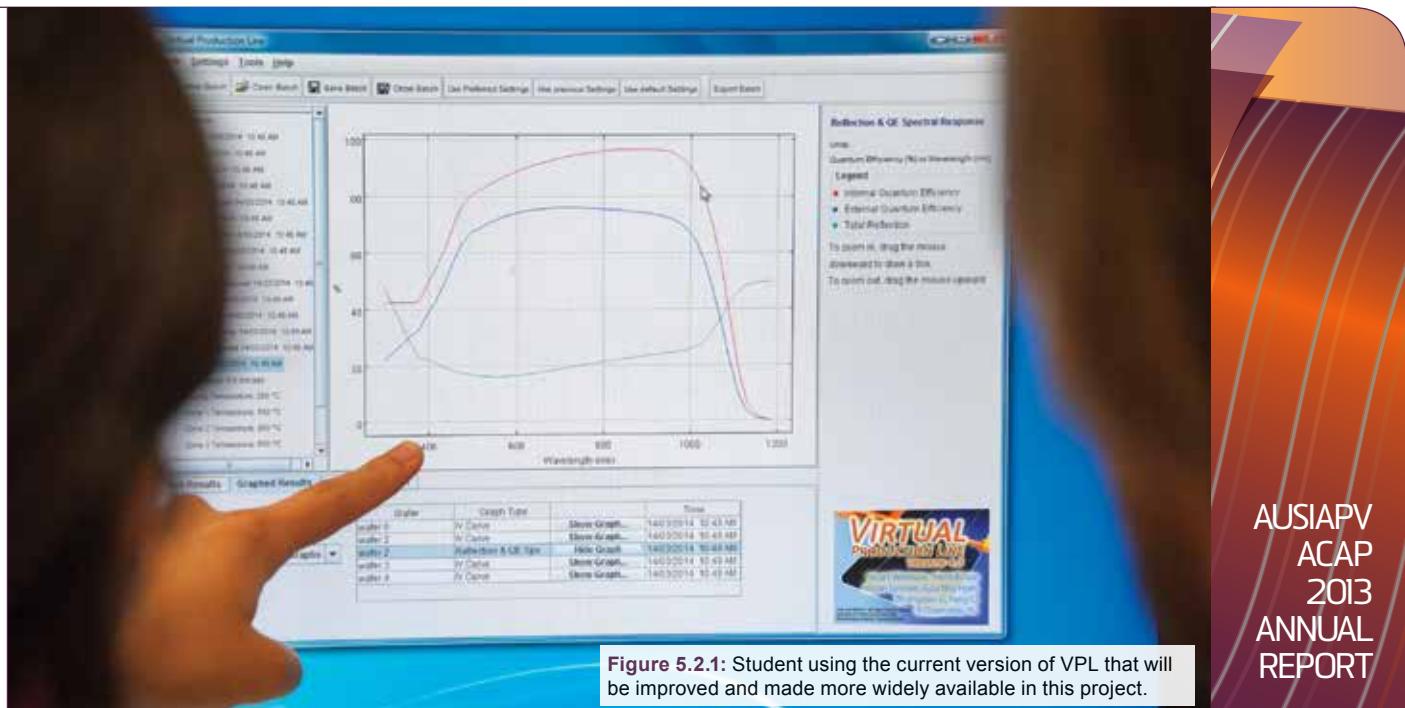


Figure 5.2.1: Student using the current version of VPL that will be improved and made more widely available in this project.

The project work was completed in late 2013 and Survey results and draft curriculum frameworks were presented with the frameworks progressing at a project workshop at UNSW on 17 Dec 2013, prior to report finalisation in January 2014. A final curriculum frameworks document and report of the project findings was produced and distributed to all relevant stakeholders, and the final report and other results were delivered to OLT in early 2014. The report is currently awaiting formal acceptance. The outcomes of the research will be presented both in journal articles and at key national and international conferences.

PP5.2a: Virtual Production Environment

Research Team

Academic/ Post-Doctoral:

UNSW: Dr Alison Lennon

Academic Partners:

QESST (USA)

Industry Partners:

PV Lighthouse

Funding Support:

ACAP, UNSW, PV Lighthouse

Background

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 Prof. 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). This simulation has been 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. Students can access the simulation from UNSW computers or download it to their laptops and participate in a number of tutorials that teach

However, since the simulation was first developed there have been many changes in the manufacturing process and, although teaching staff at UNSW have tried to maintain the currency of the simulation, major changes are now desirable. Improved methods of modeling solar cells have evolved, presenting new opportunities to improve the accuracy of the simulation. New paradigms for managing and accessing software simulations provide opportunities to make using the simulation a more engaging and effective learning experience.

This project involves the engagement of the Australian company PV Lighthouse to re-design and re-deploy the VPL simulation. In 2011, PV Lighthouse launched a website to assist PV researchers by providing simulation programs and experimental data. The website now receives 1500 visits per week and is widely 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 is ideally placed to take the VPL to the next level.

The redeployment of the VPL will occur within an exciting new simulation framework called the Virtual Production Environment (VPE). Although initially just hosting the VPL simulation, the VPE will enable other education institutions, researchers, and manufacturing companies to develop their own simulations and to make these available. Thus, the VPL that was conceived and fostered in the UNSW classroom will be delivered to a vast population of PV researchers and enthusiasts around the globe.

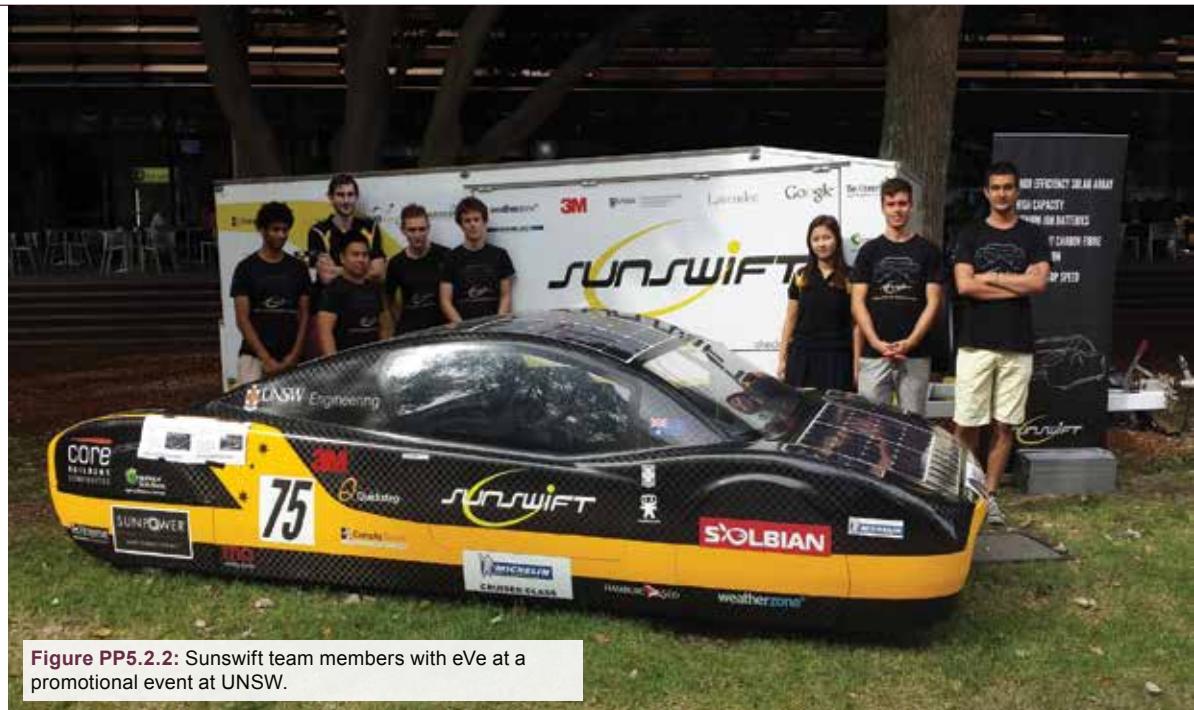


Figure PP5.2.2: Sunswift team members with eVe at a promotional event at UNSW.

The VPE, with the beta version of the VPL, is scheduled to be available as a UNSW teaching resource in the second semester of 2014. Researchers at ASU will integrate the educational resources of PVEducation.org into the VPL, thereby providing up-to-date process descriptions and video links to manufacturing. After this initial trial, it is anticipated that the VPE will be made more widely available and be used in the photovoltaic engineering teaching programs at both ANU and ASU.

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

Research Team

Academic/ Post-Doctoral:

UNSW: Mr Robert Largent, Dr Richard Corkish

Students:

UNSW: Ibraheem Al-Mansouri, Dun Li, Fangyang Liu, Ziheng Liu, Rui Sheng, Ning Song, Lu Wang, Sanghun Woo

Academic Partners:

Sunswift Team, participating secondary and primary schools

Industry Partners:

World Solar Challenge,

Funding Support:

ACAP, Sunswift's sponsors (http://sunswift.com/?page_id=47), UNSW (Faculty of Engineering, Faculty of Science, School of Photovoltaic and Renewable Energy Engineering)

Background

The UNSW student-led solar race car team, Sunswift, built, tested and raced a new car, named eVe, in 2013. For the first time, the team entered the "Solar Cruiser" class – with two seated occupants.

The team achieved line honours in the world solar challenge race from Darwin to Adelaide in October 2013. They achieved the fastest time and average

speed ever for a Sunswift team. In the overall points the team came a very close third place, behind international teams with far bigger budgets.

Throughout the preceding year the team members were ambassadors for solar energy, carrying out 15 outreach events across a wide range of social and demographic groups, garnering an estimated \$611,000 worth of media coverage. By February 2014, they had 4000 combined social media followers.

Events leading up to the October race included:

- eVe concept launch at UNSW
- Renewable Energy Day at Canberra with 230-270 visitors
- UNSW Orientation week with 5846 viewers on Facebook and over 70 students stopping to talk
- CSIRO Easter Eggstravaganza at CSIRO Discovery Centre - 3300 viewers on Facebook and nearly 100 stopping by
- •Pozible campaign media launch at UNSW for 50-60 people
- Pozible crowd funding campaign reaching 3396 Facebook users (<http://www.pozible.com/eVe>)
- eVe Unveiling Launch for 300 (<http://www.youtube.com/watch?v=0m2j8v8rE3E>)
- Solar car outreach workshops
- NSW Transport Working Group Seminar
- Media Day for around 20 journalists from large international organisations (BBC, Reuters, SMH, etc)
- Farwell Parade with about 2000 university students and staff.
- Following the race, three more outreach events were undertaken before the end of the year:
 - Public display in Leichardt with about 300 attendees
 - CSIRO Discovery Day with UWS Solar Car for around 200 people
 - Crowdfunding Track Day at St Ives for around 20 people



Figure PP5.2.3: Sunswift team entered the “Cruiser” class for the first time in 2013 (image courtesy of Sunswift).

The SunSprint Solar Challenge is a collection of age appropriate solar races designed for K-12 school students. The event comprises 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 Model Solar Car Challenge is a photovoltaics project-based learning event designed for high school students. In the event, solar cars are designed and built according to 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 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, which can be built in an evening by means of soldering, gluing and taping as part of its assembly.

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 shape of solar cells and motors. The challenge is to get the boat to float right-side up and to move through the water successfully in competition with others.



Figure PP5.2.4: Sunswift outreach event (image courtesy of Sunswift).



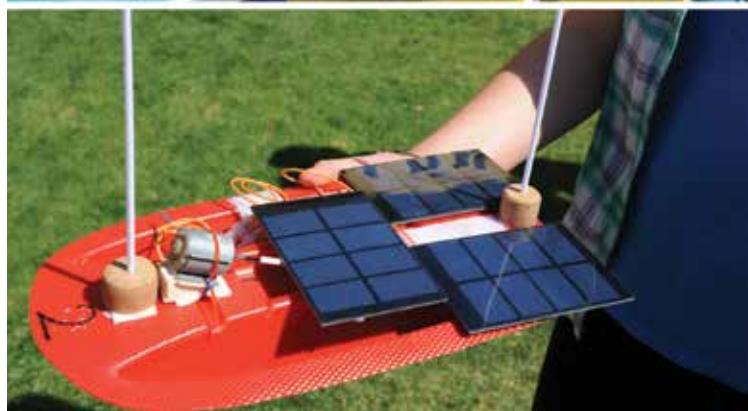
Figures 5.2.5,6,&7: SunSprint on an 80 metre figure 8 track.



Figure PP5.2.8 MiniSprint – on a 20 metre straight track.



Figures 5.2.9&10:
Model Solar Boats.



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

Research Team

Academic/ Post-Doctoral:

UNSW: Prof. Martin Green, Mr Robert Largent

Academic Partners:

Arizona State University (USA), National University of Singapore

Industry Partners:

Asian Photovoltaic Industry Association (APVIA)

Funding Support:

APVIA, UNSW, ASU, NUS

Background

During 2013 the Asian Photovoltaic Industry Association 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 solar industry is poised for unprecedented growth and needs leaders who have a good understanding of the most current technical and business concerns in the field, in order to facilitate the rapid advancements in the solar industry. The programs, to be delivered by UNSW, Arizona State University and National University of Singapore, are designed to help participants meet employers' demands for sophisticated professionals that can address science, policy and high-level business issues.

UNSW will initially offer an Applied Photovoltaics Online Course (www.engineering.unsw.edu.au/energy-engineering/applied-photovoltaics-online-course) that provides students with familiarization with practical properties of solar cells and modules and concentrates on photovoltaic applications ranging from small stand-alone systems to large grid-connected installations.

For more information, see the APSI website at <http://www.apvia.org/about.aspx?gid=0ad2d52b-7029-4b7c-ad69-cbee795f8e96&i=1&id=118> and the home page for the Applied Photovoltaics Online Course at <http://www.engineering.unsw.edu.au/energy-engineering/applied-photovoltaics-online-course>.

This UNSW course will be complemented by the Solar Energy Engineering & Commercialization Certification Program offered by ASU and Characterisation of PV cells and modules offered by the Solar Energy Research Institute of Singapore (SERIS) at NUS.

PP5.2d: International Student Engagement

Research Team

Academic/ Post-Doctoral:

UNSW: Dr Richard Corkish, Prof. Martin Green (UNSW), Prof. Gavin Conibeer, Prof. Darren Bagnall, Prof. Graham Davies

Academic Partners:

Arizona State University (USA)

Funding Support:

UNSW

Background

UNSW staff visited and/or hosted visits from several potential or actual international university partners with a view to developing or extending research and education collaborations. In 2013 these included Arizona State University (AUSIAPV partner), Stanford University (AUSIAPV partner), Huazhong University of Science and Technology, University of Science and Technology China, Shanghai Jiaotong University, Wuhan University, Wuhan University of Technology and IIT Bombay. Detailed discussions are now underway regarding student exchange agreements with Arizona State University and another of the listed universities.

UNSW PhD student, Phil Hamer, spent a year in Cambodia with Engineers Without Borders. His work included translation and transfer of UNSW photovoltaics course materials to the Royal University of Phnom Penh. He presented a seminar (see PP5.2f) in March 2014.

The UNSW education programs are listed with IRELP to publicise their availability to the global student community (<http://irelp.irena.org/courses/index.aspx?cc=true&PriMenuID=6&mnu=Pri>).

PP5.2e: National Centre for PV Research and Education (NCPRE), Mumbai

Research Team

Academic/ Post-Doctoral:

UNSW: Dr Richard Corkish

Academic Partners:

NREL: Dr William Tumas

IIT Bombay: Professor Juzer Vasi (NCPRE Co-Convenor) and staff of NCPRE ([www.ncpre.iitb.ac.in/pages/faculty.html](http://ncpre.iitb.ac.in/pages/faculty.html))

Funding Support:

NCPRE, UNSW, NREL



Figure PP5.2.11: Low cost photovoltaics spectral response tool designed and developed for NCPRE by the University of Mumbai and IIT Bombay.

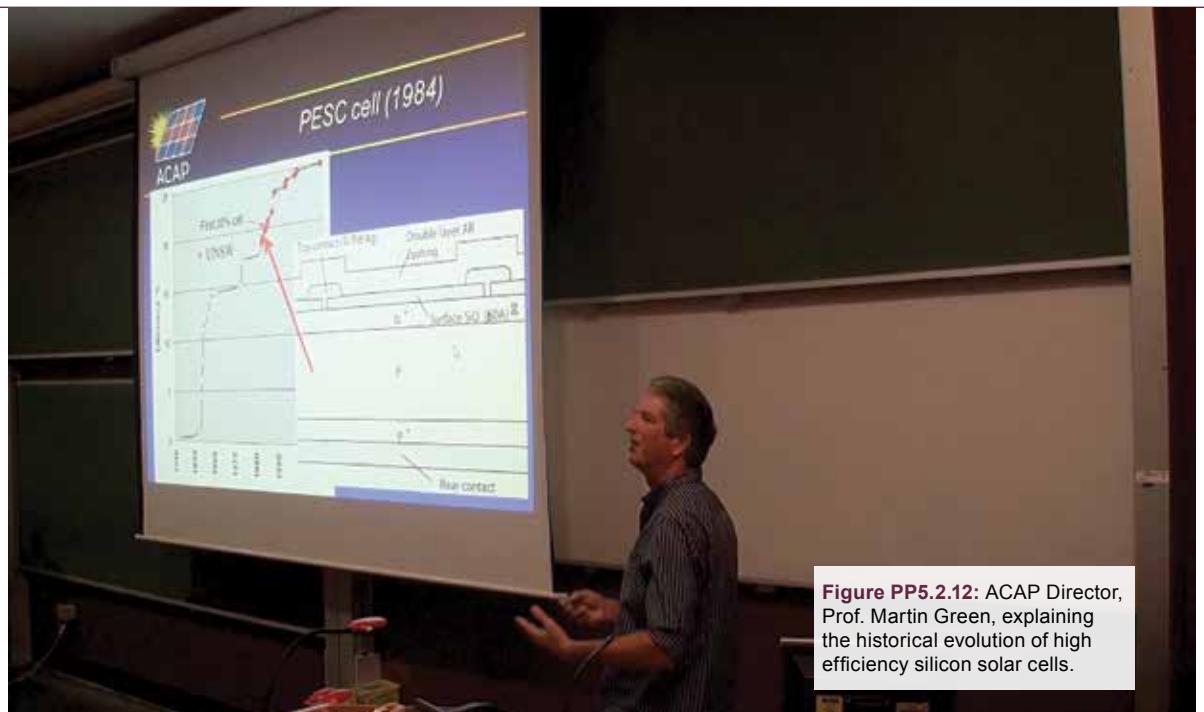


Figure PP5.2.12: ACAP Director, Prof. Martin Green, explaining the historical evolution of high efficiency silicon solar cells.

Background

ACAP partner, UNSW, through Dr Richard Corkish, and AUSIPV member, NREL, through Dr William Tumas, are actively supporting the photovoltaics research community in India. They are both members of the NCPRE Advisory Committee that meets annually in Mumbai to review progress and plans. This supportive contact between developing and developed world laboratories is mutually beneficial and can potentially accelerate the mass adoption of photovoltaics for the Indian population.

PP5.2f: Lunchtime public seminar series

Research Team

Academic/ Post-Doctoral:

UNSW: Dr Alison Lennon, Dr Ivan Prez-Wurfl, Dr Linda Koschier

Funding Support:

UNSW

Background

In 2012 the UNSW School of Photovoltaic and Renewable Energy Engineering instituted a series of lunchtime seminars with visitors and local researchers. Many of the speakers consented to audio/video recording of their sessions and subsequent web access, thus creating a significant persistent education and outreach resource. The suite of recordings from 2013 is available on SPREE's website: www.engineering.unsw.edu.au/energy-engineering/video-research-seminars-2013-0.

PP5.2g: Pollinate Energy

Research Team

Academic/ Post-Doctoral:

UNSW: Dr Richard Corkish

Industry Partners:

Cundall, RAWImpact

Funding Support:

ACAP, Cundall, RAWImpact, crowd funding, individual students

Background

During 2013 ACAP UNSW node agreed to partial support of travel costs for four students of the UNSW School of Photovoltaic and Renewable Energy Engineering who were selected by Pollinate Energy as fellows. Two of them, Anna Nadolny and Jiefei Wang, travelled to India to help set up solar PV lighting micro-businesses in Bangalore during 2013, following two previous SPREE students, Jacqui Mills and Sanika Waghulde, who had participated earlier in 2013 without ACAP support. An additional two students, Ashwin Thomas and Mikaila Thwaites, won Fellowships and ACAP support in 2013 and travelled to Bangalore in early 2014.

Pollinate's Mission Statement:

- Improve the lives of India's urban poor by giving them access to sustainable products that make their lives better.
- Empower local Indian entrepreneurs to be a positive force for change in India's urban poor communities.
- Make social business mainstream by raising awareness about the communities we work with and supporting the next generation of social entrepreneurs

In Anna Nadolny's own words: "The work Pollinate Energy does in India is extremely important, not only locally for these people who are unconnected to modern infrastructure, but also globally, as the cook fires and kerosene used for light produces large amount of black carbon, which is a bad GHG. I am grateful to ACAP for helping with the costs and I would strongly recommend that any student, regardless of the apparent relevance of their degree, work on this program, as the skills and experiences that one can take from this social business are unique, and the people that you will meet are unforgettable."



Figure 5.2.13: Cooking and lighting have both been provided from smoky indoor fires. (Image courtesy of M. Thwaites).



Figure 5.2.14: PV bringing light to one of the dwellings (Image courtesy of M. Thwaites).

Figure 5.2.15: Demonstrating the lamp (Image courtesy of M. Thwaites).



In Mikaila Thwaites own words: "For the past month I have been in India undertaking the Pollinate Energy Fellowship, where my key role was helping to train Shashi, a new "Pollinator" at Pollinate Energy, to sell solar lights and clean cook stoves to slum communities in South Bangalore. It was an incredibly eye-opening month for me. I learned a lot about energy poverty, about India, about social business and about myself. Thanks to Pollinate and to ACAP for allowing me the chance."

UNSW student Jiefei Wang created a photo-essay to document his experience:

<http://pollinateenergy.org/blog/photo-essay-jiefei-wang/>.

In 2014 Pollinate will expand to work in Chennai and the UNSW ACAP node intends to continue to support the involvement of SPREE students in this outreach activity.

PP5.2h: Collaborative Future Cambodia

Research Team

Academic/ Post-Doctoral:

UNSW: Dr Anna Bruce

Cundall: Alistair Coulstock

Raw Impact: Troy Roberts

Undergraduate Students:

UNSW: Class of undergraduate course SOLA3010.

SPREE students who travelled to Cambodia:
Thomas Henry, Emma Hollo, Martin Kolocsay

Funding Support:

ACAP UNSW Node, Cundall, RawImpact, crowd funding

Background

Collaborative Future is a project in which UNSW students join members of the construction industry to design houses for rural families in Cambodia.

From July 2013, three students from the UNSW course SOLA3010, Low Energy Buildings and PV, teamed up with professional Sydney architects and other UNSW students. These teams, supported by professional engineers in Australia and Cambodia were challenged to design a house using local materials and a budget of \$2,000 for Cambodian families in the village of Chom Trach. The houses had to use local materials, respond to the local environmental, cultural and spatial considerations and meet the needs of the local people.

A shortlist of designs was decided on by a judging panel of representatives from the construction industry, UNSW, the Royal University of Phnom Penh and RawImpact.

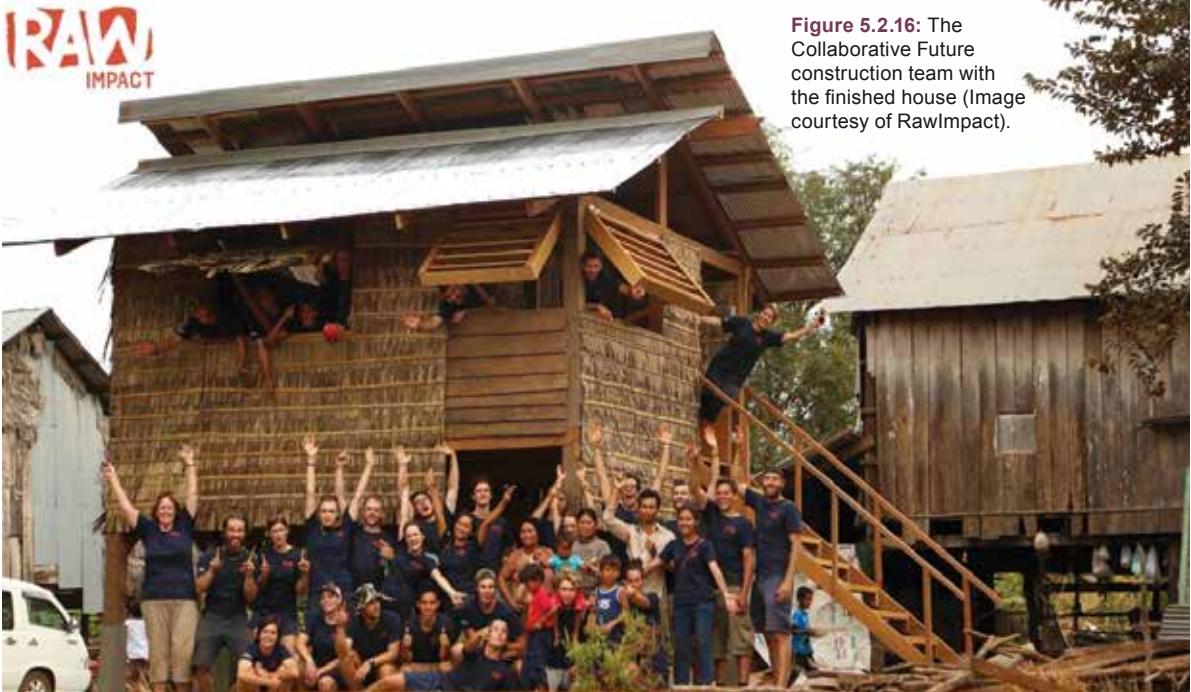


Figure 5.2.16: The Collaborative Future construction team with the finished house (Image courtesy of RawImpact).

The shortlist design winners then had the opportunity to join Troy Roberts of Raw Impact and his local team to help build their designs on the ground in Chom Trach.

The team headed to Cambodia in the first week of January 2014, including UNSW SPREE students Thomas Henry, Emma Hollo, Martin Kolocsay. Two houses were constructed for the most disadvantaged in Chom Trach, who are now living off the ground, out of the rain and free from cooking smoke.

PP5.2i: Program stream revisions

Research Team

Academic/ Post-Doctoral:

UNSW: A Prof. Santosh Shrestha, Dr Alison Lennon, Dr Stephen Bremner, Assoc. Prof. Alistair Sproul, Dr Anna Bruce.

Academic Partners:

Arizona State University

Funding Support:

UNSW

Background

Through 2013 the photovoltaics devices education stream of the undergraduate Photovoltaics & Solar Energy Program (www.engineering.unsw.edu.au/energy-engineering/be-in-photovoltaics-solar-energy-engineering-3642) and of the SPREE postgraduate programs (www.engineering.unsw.edu.au/energy-engineering/coursework-programs) were internally reviewed and revised to identify and remove unnecessary overlaps and repetitions and to replace less relevant material with current and future technology. The results, informed by the external review led by Murdoch University, Renewing the Sustainable Energy Curriculum (see PP5.1e, above) and the Virtual Production Line development (see PP5.2a, above), will be implemented in 2014 and 2015.

PP5.2j: Share PV manufacturing course

Research Team

Academic/ Post-Doctoral:

UNSW: Dr Alison Lennon.

Academic Partners:

Arizona State University (USA): Adj. Prof. Jeff Cotter

Universidad Tecnológica Nacional (UTN, Argentina): Prof. Julio Bragagnolo

Instituto Tecnológico Buenos Aires (ITBA, Argentina): Prof. Julio Bragagnolo

Funding Support:

UNSW, ASU, Universidad de Buenos Aires

Background

UNSW's PV manufacturing course, SOLA3020 (<https://www.handbook.unsw.edu.au/undergraduate/courses/2014/SOLA3020.html>), based on the Virtual Production Line teaching tool, was transferred in 2013 for delivery at ASU. This will broaden and expand the reach of this pioneering course.

The first delivery at ASU (EEE498/591) began on 17 March 2014, with 22 enrollees, hailing from across the world.

Preparations are also underway to transfer the course to Universidad Tecnológica Nacional (<http://www.utn.edu.ar/subsecretarias/posgrado/proyectos.utn>) and Instituto Tecnológico Buenos Aires (see <http://www.itba.edu.ar/maestria-energia/>) in Argentina.

PP5.2k: Deliver ASU's Advanced PV Manufacturing course to UNSW

Research Team

Academic/ Post-Doctoral:

UNSW: Dr Alison Lennon

Academic Partners:

Arizona State University: Adj. Prof. Jeff Cotter

Funding Support:

UNSW, ASU

Background

Agreement was reached during 2013 for the transfer from ASU to UNSW of ASU's course, "Manufacturing Science of Solar Cells" (<http://pv.asu.edu/node/77>). In this course, first taught at ASU in 2012, students will 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, PP5.2j in this report). The new course will be delivered initially in UNSW's Summer Session 2014/2105.

PP5.2l: AQF Level 9 specialisation of The Master of Engineering Science

Research Team

Academic/ Post-Doctoral:

UNSW: Assoc. Prof. Santosh Shrestha, Dr Anna Bruce, Assoc. Prof. Alistair Sproul; Prof. Darren Bagnall, Dr Stuart Upton

Funding Support:

UNSW

Background

During 2013 the UNSW School of Photovoltaic and Renewable Energy Engineering began revision of its two postgraduate coursework streams to ensure compliance with Australian Quality Framework Level 9 program criteria.

The new program structure will have 96 Units of Credit (UoC) delivered over two years full time or equivalent, consisting of:

- 72 UoC specialisation courses (18-30 UoC of disciplinary knowledge courses, 18-30 UoC of advanced disciplinary courses, 18-30 UoC of enquiry-based courses including 12-24 UoC project); and
- 24 UoC elective courses, including at least 6 UoC of Engineering and Technology Management courses.

The new programs will be presented to the 4 April 2014 Faculty Education Committee meeting for discussion and potential approval for forwarding to additional checking/approval stages. The new streams are intended for first delivery in 2015.

PP5.2m: WCPEC-6

Research Team

Academic/ Post-Doctoral:

UNSW: Prof. Martin Green, Dr Richard Corkish

Academic Partners:

NREL: Dr David Ginley, Dr Larry Kazmerski, Dr Qi Wang

Stanford University: Prof. John Benner

University of Tokyo: Prof. Y. Okada

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

Industry Partners:

A wide range of industry partners is represented on the committees

Funding Support:

UNSW, sponsors of WCPEC-6

Background

Planning for the 6th World Conference on Photovoltaic Energy Conversion (WCPEC-6), to be held from Sunday 23rd November to Thursday 27th November, 2014, at the Kyoto International Conference Center in Kyoto, Japan, proceeded throughout 2013. This is a joint conference of the 24th Asia/Pacific PVSEC (PVSEC-24), the 41st IEEE PVSC and the 30th European PVSEC and covers the full scope of photovoltaic science and engineering. Three ACAP/AUSIAPV member organisations have representatives on the organizing committees for this important summit, including two participants from UNSW.

PP5.2n: WIRE

Research Team

Academic/ Post-Doctoral:

UNSW: Dr Richard Corkish, Prof. Darren Bagnall, Ms Naomi Stringer

Funding Support:

ACAP, UNSW

Background

Women in Renewable Energy (WIRE) was an initiative of female students at the UNSW School of Photovoltaic and Renewable Energy Engineering and is intended to grow to encompass like-minded students throughout UNSW. It is active in mutual support for women students and engaging with industry mentors, especially female alumni. Its web profile is low (<https://orgsync.com/81213/chapter>) although it has an active Facebook presence (<https://www.facebook.com/groups/WIRE.UNSW/>).

The UNSW node of ACAP is working with and supporting WIRE in 2013 to increase its web profile in 2014.

PP5.3 ANU-led activities

PP5.3a: New Course on Smart Grids

Research Team

Academic/ Post-Doctoral:

ANU: Evan Franklin, Tom White

Academic Partners:

NICTA: Optimization Research Group.

Funding Support:

ANU

Background

A course outline developed during 2013 for a new Masters-level course on renewable energy grid integration and smart grid technology, to be finalized by mid-2014. This will be an integral part of the ANU Master of Engineering Specialization in Solar Energy Technologies.

Detailed curriculum development will proceed in the second half of 2014, with the first offering as an advanced topic course in semester 1, 2015.

providing a snapshot of international energy trends. The Energy Update series provides an authoritative annual update on energy matters for key decision makers and interested members of the general public.

PP5.3c: Solar Oration

Research Team

Academic/ Post-Doctoral:

ANU: Andrew Blakers

Funding Support:

ANU

Background

In 2013 the orator was Giles Parkinson, and the event was well attended, with an audience of about 150. The Solar Oration series provides relevant lectures by prominent individuals in November each year.

PP5.3d: Outreach events

Research Team

Academic/ Post-Doctoral:

ANU: Andrew Blakers, Kylie Catchpole, Andres Cuevas, Evan Franklin, Dan Macdonald, Matt Stocks, Klaus Weber, Tom White

Funding Support:

ANU

Background

ANU undertook a wide variety of outreach activities in 2013, including seminars, public lectures, media events, VIP visits; procuring items in radio, TV, newspapers, popular print and internet magazines and trade magazines.

PP5.3b: Energy update

Research Team

Academic/ Post-Doctoral:

ANU: Ken Baldwin, Andrew Blakers

Funding Support:

ANU

Background

On 5 December 2013, 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 2013 (WEO 2013). Ian Cronshaw presented the IEA perspective on the WEO 2013 (published on November 12th),

PP5.4 UQ-led activities

PP5.4a: Undergraduate course in Nanoscience: Synthesis

Research Team

Academic/Post-Doctoral:

UQ: School of Chemistry and Molecular Biosciences staff

Funding Support:

UQ

Background

Preparations for this course were made in 2013 and early 2014, with 14 students enrolled in late March 2014. It is anticipated that around 30 will be enrolled before the commencement of the course in the second semester of 2014.

PP5.5 UoM-led activities

PP5.5a: Public lecture and Panel Discussion: Energy Future: the developments in materials to meet alternative energy challenges (held on the 30th January 2014)

Research Team

Dr David Jones, A/Prof. Ray Dagastine,
Prof. Paul Mulvaney

Panel Members:

UoM: Prof. Andrew Holmes (President elect Australian Academy of Science)

Grattan Institute: Tony Wood

Greens MP: Adam Bandt

Academic Partners:

Argonne National Laboratories: Dr Eric Isaacs,

Industry Partners:

Public Lecture

Funding Support:

ACAP, UoM, CSIRO, Realtek, Melbourne Centre for Nanofabrication (MCN), Australian Nanotechnology Network (ANN).

Background

Dr Eric Isaacs will give a public lecture, followed by a panel discussion featuring Australian Academy of Science President elect Andrew Holmes, the Grattan Institute's Tony Wood, and Greens MP Adam Bandt. The discussion was moderated by Dr Shane Huntington, host of RRR radio's science program, Einstein A Go-Go.

PP5.5b: Workshop: Advanced Nanomaterials for Energy (held 31st January 2014)

Research Team

Dr David Jones, A/Prof. Ray Dagastine, Paul Mulvaney

Speakers:

Argonne National Laboratories & University of Chicago, USA: Eric Isaacs, Materials Science in the National Interest: Discovery, Innovation and Energy

Australian National University: Klaus Weber, Silicon PV Research at ANU

Swinburne University: Baohua Jia, Nanomaterials for advanced light management in nanophotonics solar cells

Argonne National Laboratory, USA: Peter Littlewood, Energy storage from first principles

University of Melbourne: David Jones, Excitonic bulk heterojunction organic solar cells

University of Newcastle: Paul Dastoor, Solar Paint: A New Paradigm in Organic Photovoltaics

Monash University: Udo Bach, Sensitized Mesoscopic Solar Cells

CSIRO: Jacek Jasieniak, Solution Processed Nanocrystalline Solar Cells

Monash University: Michael Fuhrer, Graphene optoelectronics: sensitive photothermoelectric detectors, and the ultimate transparent conductors

Massachusetts Institute of Technology, USA: Michael Strano, Merging synthetic nanomaterials with the biological world: molecular recognition, sensor implants and plant nanobionics

Frei University of Berlin, Germany: Michael Giersig, Metallic nanostructures for transparent and conductive electrodes for the possible application in photovoltaics

Bayreuth University, Germany: Andreas Fery, Tailoring Plasmonic Absorption Characteristics by Surface Assembly of Metal Nanoparticles

Industry Partners:

Over 100 research and industry participants.

Funding Support:

ACAP, UoM, CSIRO, Realtek, Melbourne Centre for Nanofabrication (MCN), Australian Nanotechnology Network (ANN).

Background

This workshop brings leading researchers together with Australian experts to discuss the future trends in the development of nanoscale materials. In particular, the workshop will explore completely new ideas for the way nanomaterials can be used to help solve the number one scientific challenge in the world – creating a sustainable energy future.

PP5.5c: New masters Course: Organic electronic Materials (Semester 1 2014)

Research Team

Dr David Jones, Dr Wallace Wong,
Prof. Kenneth Khiggino

Academic / Post Doctoral:

UoM: Dr David Jones, Dr Wallace Wong,
Prof. Kenneth Ghiggino.

CSIRO MSE: Dr Birendra Singh

Academic Partners:

UoM, CSIRO

Funding Support:

ACAP, UoM, CSIRO

Background

The University of Melbourne approved a new Masters Course, to be taught for the first time in Semester 1, 2014. The course covers aspects of the development of organic electronic materials, from materials design, synthesis, characterization through to device architecture and assembly. There is a focus on OPV materials in the course, which is designed to allow guest lectures to be delivered from visiting AUSIAPV partners.

PP5.6 Monash-led activities

PP5.6a: John Monash Science School

Research Team

Academic/ Post-Doctoral:

Monash: Dr Simon Thompson, Prof. Yi-Bing Cheng

Funding Support:

Monash

Activity:

John Monash Science School is a selective government school associated with Monash University. Students in the school have particular interests in science and engineering. As a Science Fair project of the School, a team of students was involved in preparation of dye-sensitised solar cells using raspberry juice and titanium dioxide coated conducting glass substrates in July 2013. Dr Simon Thompson, a postdoctoral research fellow, interacted with the student team in a visit to the Monash solar cell lab, where techniques for the construction of the solar cell devices were demonstrated. In a following up meeting, Prof. Yi-Bing Cheng and Dr Thompson met with Ms Barbara McKinnon, a Science teacher at the school, and the team of students. They answered students' questions and discussed the future development of solar cell technologies.

PP5.6b: DSC-OPV9 conference

Research Team

Academic/ Post-Doctoral:

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

Funding Support:

Monash

Activity:

The 2014 Aseanian Conference on Dye-Sensitised and Organic Solar Cells (DSC-OPV9) will be held in Sydney on 8-10 Dec. This is the first time that this annual series conference is being held outside Asia. The conference will be run together with the APVI and ACAP meetings as a joint Solar Research Conference. The Conference Organisation Committee was formed in 2013, after which conference organization proceeded, with a conference website set up in early 2014 (<http://apvi.org.au/solar-research-conference/>).

PP5.6c: Visits by local companies

Research Team

Academic/ Post-Doctoral:

Monash: Prof. Yi-Bing Cheng, Dr. Yong Peng, Dr. Simon Thompson

Funding Support:

Monash

Activity:

To promote awareness of the large-scale solar cell printing facility at the Renewable Energy Laboratory of Monash University and engage with local industry, the Monash team was involved in the Open Day for Industry organized by Monash University. On 17 December 2013, two groups of visitors from local industrial companies visited the Monash Solar Cell lab, where they were introduced to recently developed technology for printing of solar cells, with a demonstration of the automatic machine constructed for printing of cells at Monash.

PP5.7 CSIRO-led activities

PP5.7a: Inquiry Oriented Learning

Research Team

Academic/Post-doctoral:

CSIRO: Dr Scott Watkins, Dr Hasitha Weerasinghe, Dr Noel Clarke, Dr Doojin Vak

UTS: Prof. Les Kirkup

Students:

Monash: Mr Shannon Bonke

Academic Partners:

UTS

Background

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 trialed with a large proportion of first year students at UTS and is an important component of their broader Inquiry Oriented Learning

effort. CSIRO supplied 50 printed OPV modules from the VICOSC consortium for use in a first year physics class at UTS. Dr Scott Watkins gave two lectures to classes, one in each semester. The first was by video link, the second in person in Sydney.

UTS produced a video that described the collaboration:

<http://www.youtube.com/watch?v=ZBdTDoAuX2Q&feature=share&list=PLDJaBzsPdPGxBvpap0INBi5sEb0T4o3jM&index=6>

PP5.7b: STELR

Research Team

Academic/Post-doctoral:

CSIRO: Dr Scott Watkins, Dr Gerry Wilson

Background

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. It is a national secondary school science education initiative of the Australian Academy of Technological Sciences and Engineering (ATSE). The aim is to have third generation thin film solar cells (and their manufacture) included in the STELR curriculum. In 2013 discussions were initiated with STELR and their Program and Education manager, Dr Peter Pentland visited to plan interactions for 2014.

PP5.7c: Pollinate Energy

Research Team

Academic/Post-doctoral:

CSIRO: Dr Scott Watkins

Background

Continue outreach to India working with Pollinate Energy (see also PP5.2g).

Dr Scott Watkins has been accepted into the Pollinate Energy Fellowship program for April 2014. CSIRO is supporting Dr Watkin's travel with ACAP funds and an in-kind contribution of his time. Dr Watkin ran a successful crowd-funding campaign (www.pozible.com/scott) to raise the remainder of the funds. While in India, he will also visit Barefoot College to build further links with potential end-users of the technology.

PP5.7d: International Researcher Engagement

Research Team

Academic/Post-doctoral:

CSIRO: Dr Scott Watkins

University of Washington: Prof. Forrest Michael

Academic Partners:

University of Washington

Background

A key aim of AUSIAPV is to establish new relationships and consolidate existing relationships with existing

and potential partner institutions and businesses for an exchange of knowledge and sharing 'best practice' about materials and manufacturing processes. To this end, CSIRO negotiated a new partnership with the University of Washington, whereby one of their staff members, Prof. Forrest Michael, arranged to spend 6 months on secondment to CSIRO.

PP5.7e: Media Releases/Outreach

Research Team

Academic/Post-doctoral:

CSIRO: Dr Scott Watkins, Dr Gerry Wilson

Background

The aim of these activities is to promote and disseminate the work and achievements of CSIRO and to engage in public debate about the nexus between Energy, Manufacturing (Employment) and Climate. CSIRO's major effort in this area was a press release in May 2013 that highlighted the work of the VICOSC partners on printed solar cells.

<http://www.csiro.au/Portals/Media/Printing-Australias-largest-solar-cells.aspx>

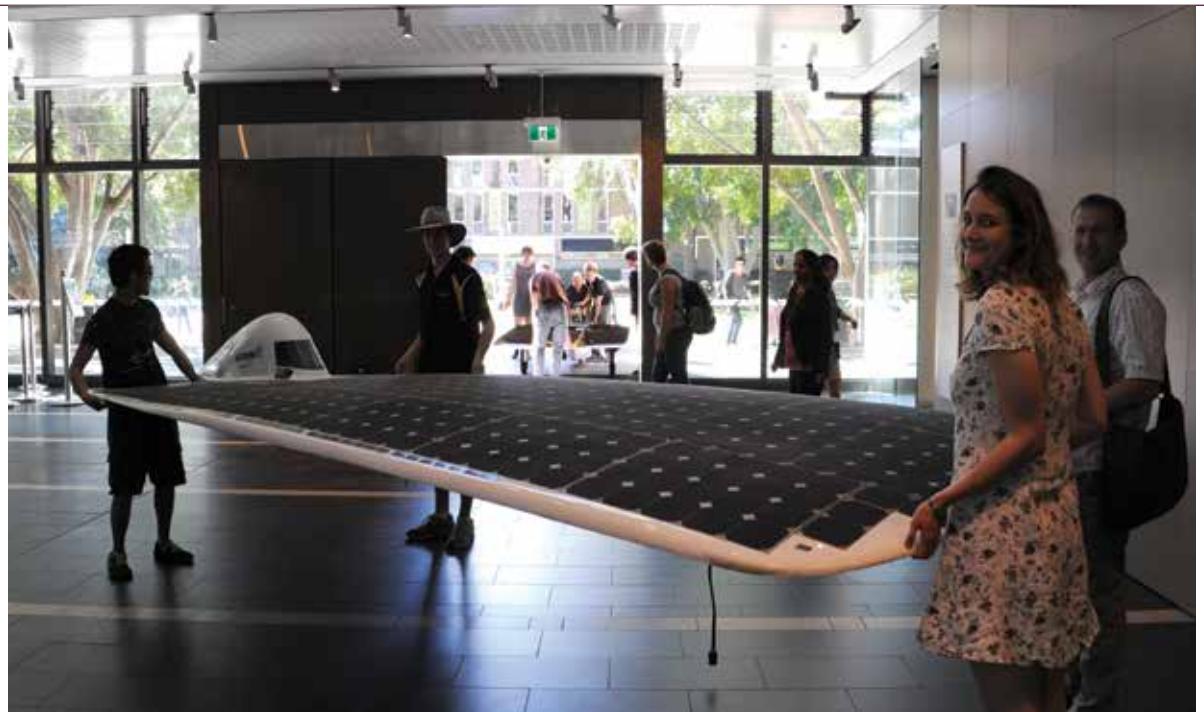
This release initiated a large number of follow-up interviews, blogs and lecture requests. The social media articles around the release were CSIRO's most popular posts for a science story ever. For example, the story reached over 4,000,000 twitter accounts, the YouTube video has been viewed over 44,000 times and one of the blogs that reported the story, Mashable.com, was shared over 9,000 times.

Podcasts

CSIRO: <http://www.csiro.au/Portals/Multimedia/CSIROpod/Printing-solar-power-like-money.aspx>

University of Melbourne: <http://upclose.unimelb.edu.au/episode/252-watts-fit-print-developing-flexible-organic-solar-cells>

Talking Technology: <http://itunesu.its.rmit.edu.au/node/1031>



Videos

- CSIRO: <http://www.csiro.au/Portals/Media/Printing-Australias-largest-solar-cells.aspx>
- University of Melbourne: <http://visions.unimelb.edu.au/episode/ctrlp-australias-largest-solar-cells>
- Museum Victoria: <http://museumvictoria.com.au/scienceworks/whatson/current-exhibitions/think-ahead/videos/sustainable-cities---scott-watkins/>
- SPIE: <http://spie.org/x104737.xml>

Interviews

- Radio Australia: <http://www.radioaustralia.net.au/international/radio/program/innovations/printing-flexible-solar-panels/1138442>
- 2TM: <http://youtu.be/wWICumEXLD4>
- Lectures**
- Beyond Zero Emissions: <http://bze.org.au/events/discussion/5-august-dr-scott-watkins>
- Georgia Institute of Technology: <http://www.youtube.com/watch?v=eKTE2zR8xSo>



6 AUSIAPV INTERNATIONAL ACTIVITIES

6.1 40% efficient 'Power Cube' power tower receiver

Researchers

Australia

UNSW: Dr Mark Keevers, Prof. Martin Green, Jonathan Cho Fai Lau, Nathan Tam, Jai Hashim

Raygen: Ian Thomas, John Lasich

USA

Spectrolab: Dr Richard King

NREL: Dr Keith Emery

Project support:

ASI/ARENA, AUSIAPV, NREL, Spectrolab (USA),

Raygen (Australia), UNSW

Introduction

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 percent. 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 main deliverable of the Power Cube project is to design, fabricate and test a proof-of-concept, prototype spectrum splitting CPV module demonstrating an independently confirmed efficiency above 40%. The independent testing will be performed by NREL within the AUSIAPV program. Two years into the project, we have fabricated and tested a substantive mock-up of the prototype module following several iterations of the design.

Prototype design and fabricated mock-up

The prototype design is based on reflective concentration optics, a custom bandpass (spectrum splitting) filter, and two 1-cm² high efficiency commercial CPV cells (Si cell from Sunpower, 26% @ 80x; III-V TJ cell from Spectrolab, 38.5% @ 300x), 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.



Figure 6.1.1: Artist's conception of a CPV power tower system being developed by Raygen Resources Pty Ltd, consisting of a field of heliostats and a CPV receiver atop a mast (image courtesy of Raygen). Insets show a conventional flat receiver consisting of a dense array of TJ cells (top) and a schematic of the proposed spectrum splitting receiver (bottom).

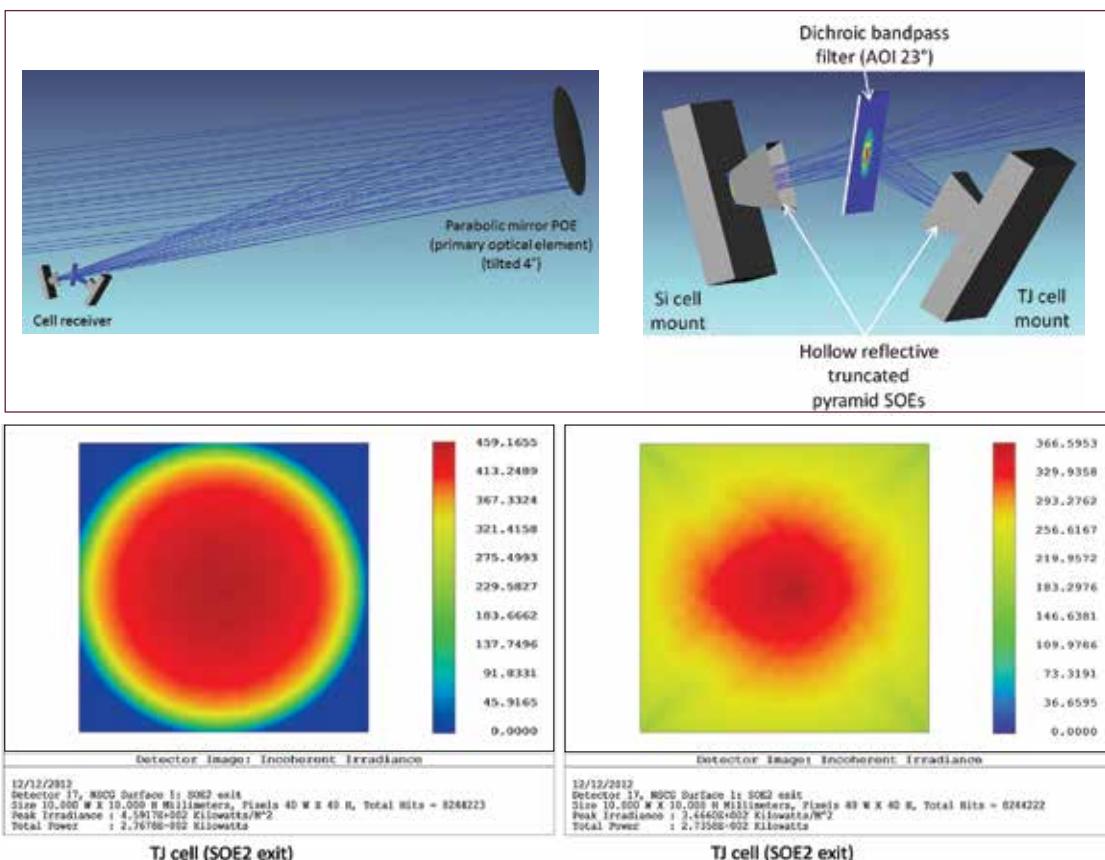
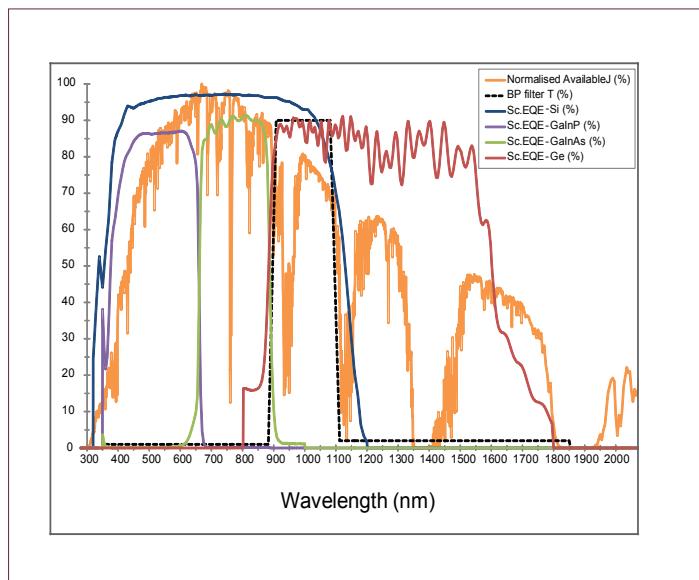


Figure 6.1.2: Ray trace (Zemax) diagram of the spectrum splitting prototype module, showing the overall design (top left) and a close-up of the ‘cell receiver’ (top right). In this example, both the TJ and Si cells are located at the focal point of the parabolic mirror ($FL = 1m$) for full beam capture within the cell active areas. The false-colour plots show the resulting poor irradiance uniformity on the TJ cell (bottom left) and the improved uniformity achieved by moving the cell beyond the focal point to benefit from the homogenising effect of the secondary optic (bottom right).

The optics design achieves the required high optical efficiency (> 95%) using a tilted ‘enhanced silver’ coated parabolic reflector to concentrate the sunlight (geometric concentration 270x), a custom bandpass filter to optimally split the solar spectrum between the TJ and Si solar cells, and reflective secondary optics to optionally improve flux uniformity (Figure. 6.1.2). The critical component of the prototype is the spectrum splitting filter, and it is a significant challenge to manufacture a filter with the desired characteristics across the broad band of solar wavelengths relevant to CPV (350–1850nm). After a wide search, a US company (Omega Filters) has been selected as the preferred vendor to design and fabricate the custom bandpass filter.

An Excel spreadsheet was developed to calculate the optimum filter passband and the combined TJ + Si cell efficiency. Inputs to the calculation are the solar spectrum (ASTM G173-03 AM1.5D), filter transmission and reflection response functions (idealised Omega filter), and TJ subcell and Si cell EQE and I-V parameters (a 38% TJ cell is used to obtain a conservative or lower bound result). The filter cut-on/cut-off wavelengths are adjusted to current match the Ge subcell to the top and middle subcells, giving a maximum contribution to the Si cell, or to provide some excess Ge current as a margin for error and hence a reduced Si output (Figure. 6.1.3 and Table 6.1.1). The spectrum splitting provides a 4.5% absolute (12% relative) efficiency increase over the baseline TJ-alone case (38.0%) to result in a combined cell efficiency of 42.5%. Including the optical efficiency (>95%) of the concentration optics results in a predicted prototype efficiency in excess of the target 40%.

Figure 6.1.3: Transmittance curve for an optimised Omega bandpass filter, the AM1.5D solar spectrum (in terms of photon flux or available J_{sc}) and TJ subcell and Si cell EQEs.



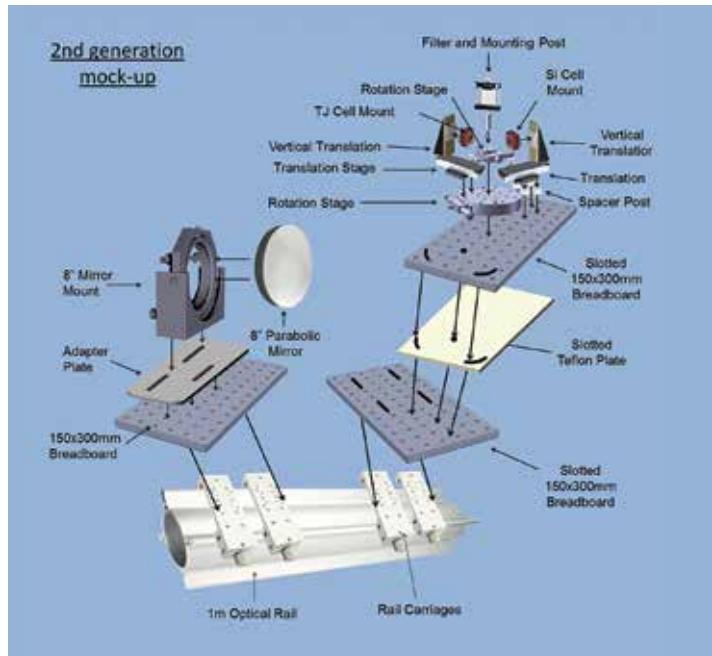


Figure 6.1.4: Exploded view of the structural design of the latest mock-up of the prototype, showing the optomechanical components. This design is lighter, more robust (especially to shear stress experienced during solar tracking), and has a lower centre-of-mass (making it compatible with the tracker) than previous iterations.

Table 6.1.1: Combined TJ + Si cell efficiency calculated using an optimised Omega bandpass filter (geometrical concentration 300x, J_{sc} values are shown at 1-sun for convenience).

Filter	Bandpass (nm)	J_{sc} (top) (mA/cm ²)	J_{sc} (mid) (mA/cm ²)	J_{sc} (Ge) (mA/cm ²)	J_{sc} (Si) (mA/cm ²)	Combined Efficiency (%)
None (baseline case)	-	13.72	14.30	22.57 (8.85 excess)		38.0
Omega (99-90-98%) - Match J_{sc} - 5% Ge margin	874-1113 888-1107	13.59 13.59	13.62 14.01	13.61 14.28	9.67 8.73	42.5 42.5

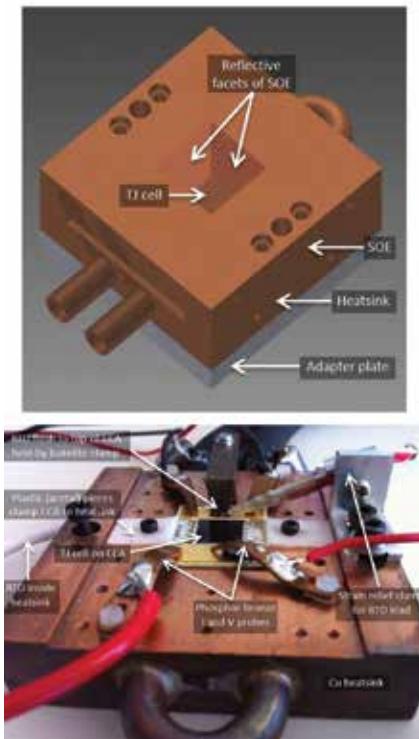


Figure 6.1.5: Top: CAD drawing of complete assembled CPV cell mount, including SOE. Bottom: Photo of TJ CCA on heatsink in the latest mock-up of the prototype, includes 4PP contacting and top RTD to measure the CCA temperature.

After several iterations, the structural or mounting design now provides the necessary robustness and portability, whilst maintaining a fully adjustable structure (Figure. 6.1.4). The latter enables alignment and optimisation about all relevant linear and rotation axes, including the independent adjustment of each cell-primary optical element (POE) distance (full beam capture versus a more uniform illumination of the cell).

The thermal design uses active cell cooling to achieve the standard 25°C cell temperature. This is achieved using a custom designed water-cooled Cu heatsink and suitably positioned temperature sensors (Figure. 6.1.5). To improve thermal contact between the cell and heatsink, the CCA is mounted using a thermal compound. Light I-V measurement uses the 4-point-probe (4PP) method

to avoid parasitic resistance losses from the wiring and contact resistances (Figure. 6.1.5).

The telescope tracker enables the prototype, once aligned, to automatically follow the path of the sun. The pyrheliometer is attached to the prototype to accurately measure the direct normal irradiance (DNI), essential for the calculation of conversion efficiency. The custom light current-voltage (LIV) curve tracer automatically and repeatedly measures the electrical output of each solar cell,

the temperature of each CCA and heatsink, and the DNI, and calculates the conversion efficiency of the prototype. The LIV tracer consists of a National Instruments PXIe system (chassis, controller, DAQs and switch) with customised Labview software and a Toellner 4-quadrant amplifier (Figure. 6.1.6). A temperature controlled bath and resistance temperature detectors (RTDs) provide for active cooling of the cells.

The first on-sun tests of the prototype were performed using individual cells (without the spectrum splitting filter or SOEs), enabling refinement of the prototype and the measurement setup and method. Photographs and results from the most recent tests (10 Dec 2013) are presented below (Figures 6.1.7-6.1.9).

The LIV results show that correct temperature control is important. The temperature coefficients determined in Figure. 6.1.9 are $\Delta V_{oc}/\Delta T = -6.5$ mV/K and $\Delta E_{ff}/\Delta T = -0.049\%(abs)/K$. The CCA is typically 7°C hotter than the heatsink (not shown), which means controlling the CCA (rather than the heatsink) temperature to 25°C increases the TJ cell Eff by 0.34%(abs). The discrepancy between the measured efficiency (31.4%) and the TJ cell efficiency measured by Spectrolab under standard test conditions (37.4%) can be accounted for in equal parts by reflection losses at the primary mirror ($R \sim 93\%$ here, whereas 97% is planned for the final prototype) and spectral mismatch causing the TJ cell to be more top-cell limited (lower blue content here due to late time of day and Sydney air pollution).

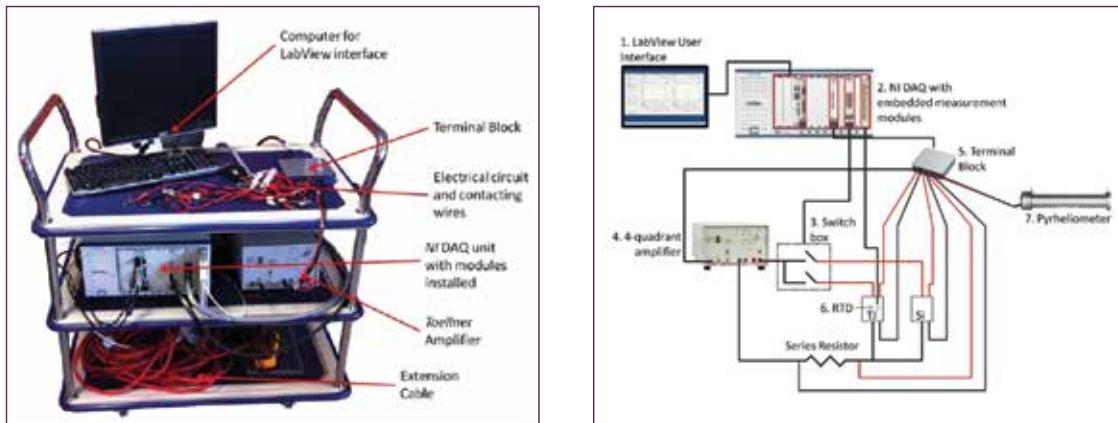


Figure 6.1.6: Custom LIV curve tracer on dedicated trolley (left) and schematic of measurement circuit (right).

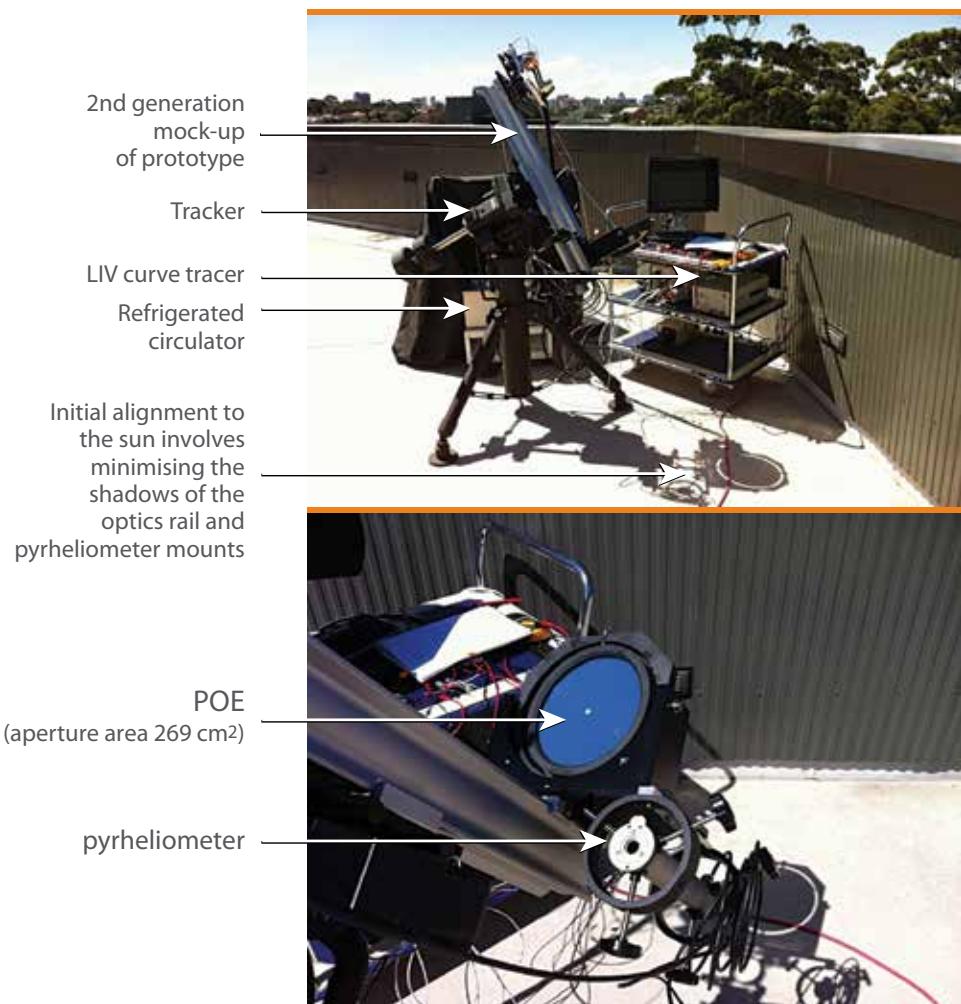
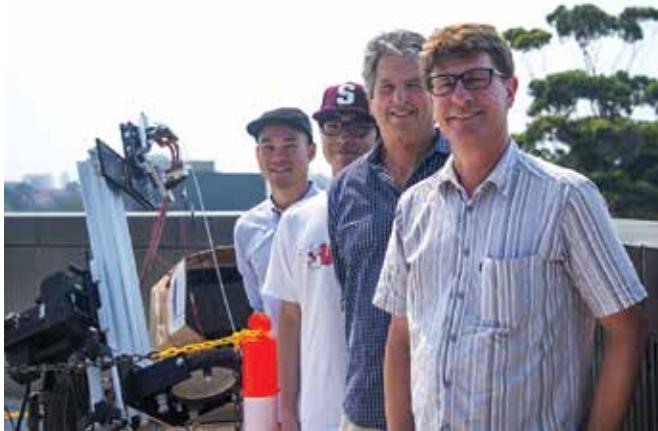


Figure 6.1.7: (top) On-sun LIV testing of a substantive mock-up of the prototype (no spectrum splitting or SOE). (middle) Close-up of the primary mirror and pyrheliometer. (bottom) Team members (from front) Mark Keevers, Martin Green, and undergraduate students Cho Fai Jonathan Lau and Nathan Tam.



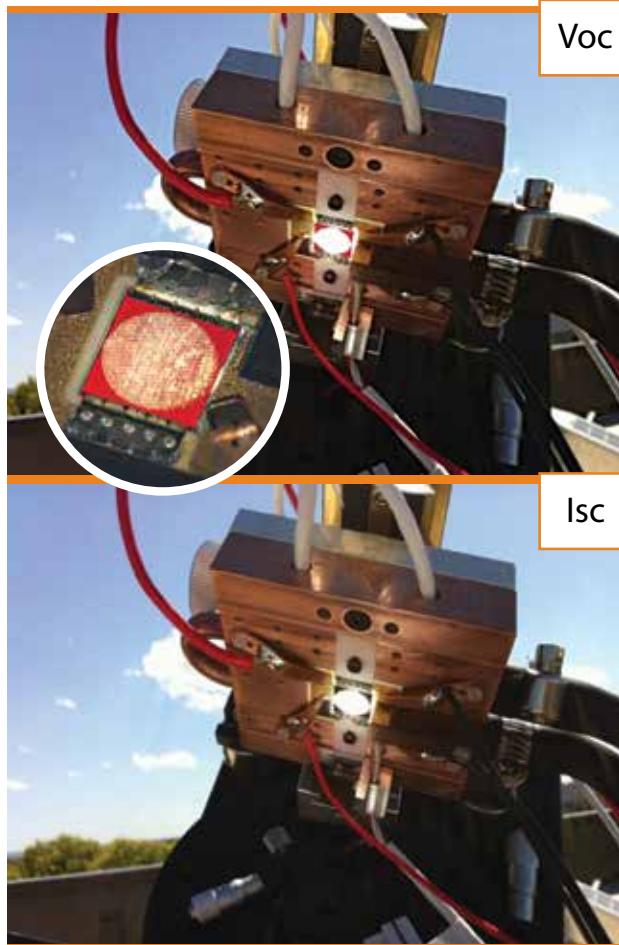


Figure 6.1.8: The TJ cell mounted on the heatsink during on-sun tests, showing full beam capture in the cell active area (cell at focal point of primary mirror). An interesting feature is the bright red (670nm) PL from the top subcell visible at Voc (top) but not at Isc (bottom). Inset shows a close-up of the illuminated TJ cell at Voc.

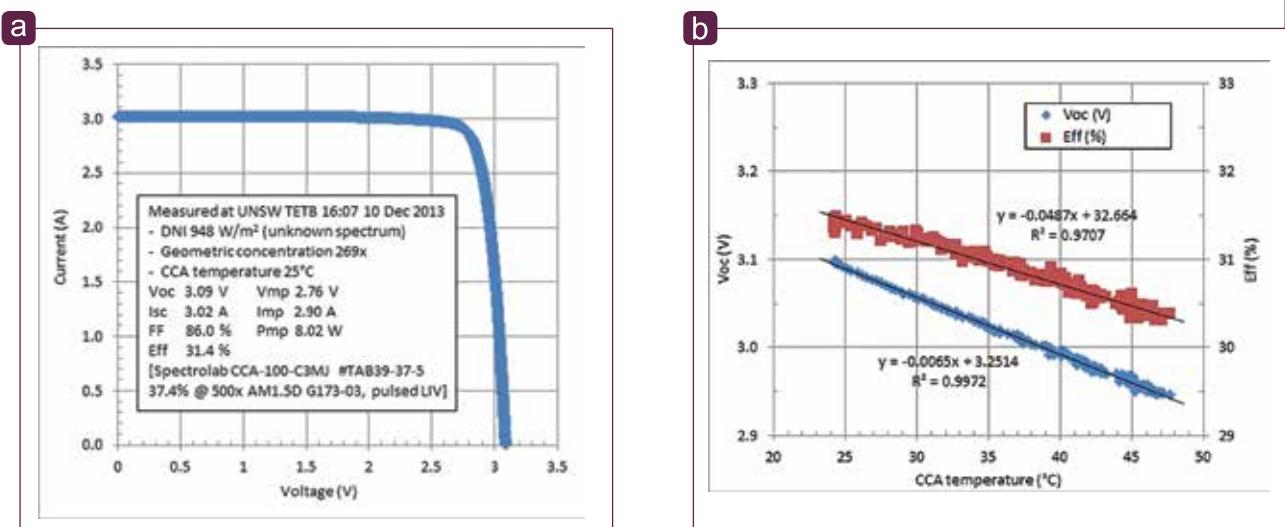


Figure 6.1.9: (a) Measured on-sun LIV for the prototype mock-up (no spectrum splitting or SOE). Standard conditions were closely met for cell temperature (cf 25°C) but not for irradiance or spectrum (cf 1000 W/cm², ASTM G-0173-03 AM1.5 direct). (b) Temperature dependence of Voc and Eff measured during the same session by switching off the water chiller.

Future work

The prototype mock-up fabricated and tested to date provides a substantive basis for the final prototype targeting 40% efficiency. Only incremental changes are required to this mock-up and the measurement setup. In early 2014, after incorporating the spectrum splitting filter, ‘enhanced silver’ coated POE and SOEs and best available Si and TJ solar cells, we will continue on-sun testing to optimise the prototype to maximise

the conversion efficiency. Temperature corrections will be minimised by actively cooling the cells so that the CCA-mounted RTD is at 25°C. Spectral mismatch corrections will be included, aided by a knowledge of the solar spectrum obtained from a spectroradiometer and the solar cell EQEs. Once the anticipated 40% target (standard test conditions) is achieved, the prototype will be taken to NREL in the US for independent testing.

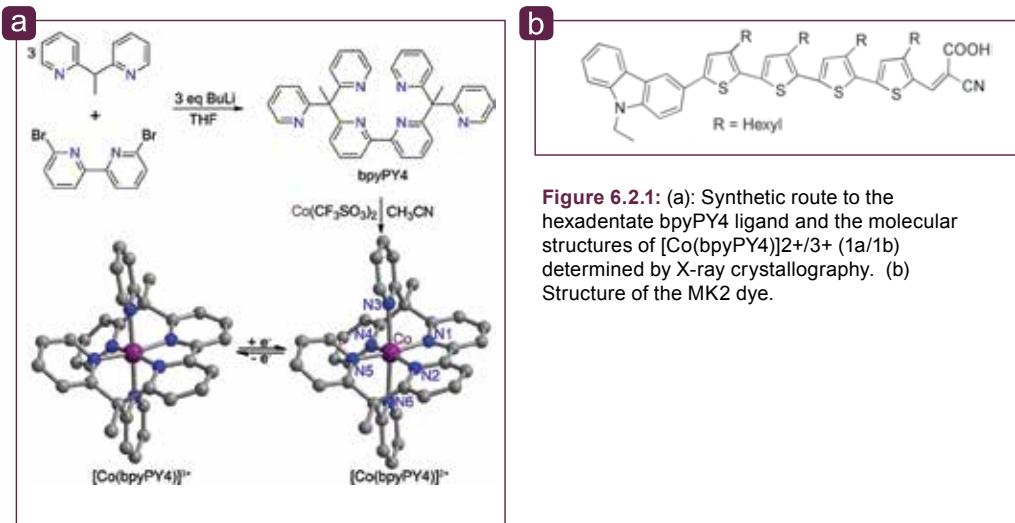


Figure 6.2.1: (a): Synthetic route to the hexadentate bpyPY4 ligand and the molecular structures of $[\text{Co}(\text{bpyPY4})]^{2+/3+}$ (1a/1b) determined by X-ray crystallography. (b) Structure of the MK2 dye.

6.2 Transition Metal Complexes as Redox Active Materials for Dye-Sensitized Solar Cells

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ARENA, AUSIPAV, VICOSC, Monash
University and University of California Berkeley
/Lawrence Berkeley National Laboratories

The application of cobalt-polypyridyl complexes, such as $[\text{Co}(\text{bpy})_3]^{2+/3+}$ ($\text{bpy} = 2,2'$ -bipyridine) as alternative redox mediators has recently resulted in a step-change in DSC research, replacing the commonly used corrosive iodine/iodide electrolytes, while at the same time affording new record energy conversion efficiencies. The ligand environment of the cobalt complexes is highly tunable and in turn affects their geometric structure as well as their electronic and electrochemical properties. In this respect, the denticity of the ligands forming the cobalt coordination shell is of paramount importance. Firstly, it strongly affects the stability constant β of the metal complex through the chelate effect. Complexes of hexadentate ligands, L, exhibit β values $>>10^4$ times higher than comparable ML_3 complexes where L' is a bidentate ligand. For the complexes of the higher denticity ligands the reorganization energies associated with the $\text{Co}^{2+/3+}$

redox reactions are generally lower. This critically affects charge transfer steps, such as dye regeneration following photo-oxidation and charge recombination at the semiconductor-electrolyte interfaces. Lowering the reorganization energy for the reaction of the oxidized dye and the redox mediator is expected to result in faster reaction rates and more efficient dye regeneration.

In this case study, we report for the first time the application of a cobalt redox couple (Figure 6.2.1) based on a hexadentate ligand (bpyPY4) as redox mediator in DSCs and compare the photovoltaic performance and stability of devices constructed with this redox couple with those made with the reference $[\text{Co}(\text{bpy})_3]^{2+/3+}$ mediator (Co-bpy).

Figure 6.2.2a shows the cyclic voltammogram of 1a in MeCN. The reversible current peak centred at -170mV vs Fc/Fc⁺ corresponds to the $[\text{Co}(\text{bpyPY4})]^{2+/3+}$ redox process whereas that centred at -1188mV corresponds to the $[\text{Co}(\text{bpyPY4})]^{1+/2+}$ couple. Peaks in further negative regions are ascribed to ligand-based processes. Thus, the $\text{Co}^{2+/3+}$ redox potential (**1a/1b**) is 465mV versus NHE, whereas that corresponding to Co-bpy is 560mV. The redox potentials (vs NHE) derived for complexes 1a, $[\text{Co}(\text{bpy})_3]^{2+/3+}$, and HOMO LUMO levels of MK2 are compared in Figure 6.2.2b. The redox properties of 1a indicate that this complex is well suited for DSC electrolyte development using dyes with a HOMO level at around 800mV.

The lower open circuit voltage (V_{OC}) realized in the devices made using electrolyte 1a/1b as compared to the devices made using Co-bpy is

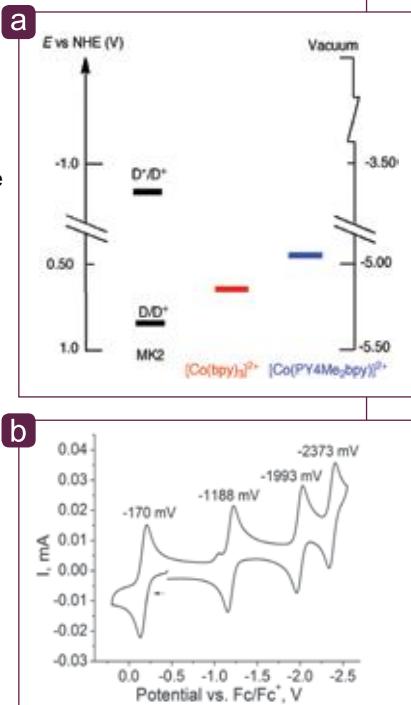


Figure 6.2.2: Cyclic voltammetry and energy level diagram (a) Cyclic voltammogram of 1mM solution of $[\text{Co}(\text{PY4Me}_2,\text{bpy})](\text{OTf})_2$ in MeCN. The measurements were performed using a platinum disk electrode and 100mM $(\text{Bu}_4\text{N})\text{PF}_6$ as supporting electrolyte at a scan rate of 100mV/s. Potentials were internally referenced to the reversible ferrocene/ferrocenium couple. (b) Energy level diagram of DSC components, redox potentials of the redox couples **1a** and **1b**. Data for MK2 dye and cobalt complexes are relative to the normal hydrogen electrode (NHE).

mainly attributed to the lower redox potential of 1a/1b as compared to the Co-bpy complex due to the lower redox potential of the redox couple as shown in Table 6.2.1.

Redox couple ^[b]	1a/1b	Co-bpy
$E_{1/2}(\text{Co}^{2+/\text{3}+})$ (mV) ^[c]	465	560
V_{OC} (mV)	757 ± 2	826 ± 3
J_{SC} (mA cm ⁻²)	14.7 ± 0.2	13.7 ± 0.3
<i>FF</i>	0.75 ± 0.02	0.69 ± 0.01
η (%)	8.3 ± 0.1	7.8 ± 0.2

Table 6.2.1: Photovoltaic performance of DSCs assembled with the two redox couples and MK2 dye, under simulated sunlight (AM 1.5 G, 1000 W/m²)^[a]

[a] Double-layer TiO₂ films (6 μm mesoporous TiO₂ (30 nm) and 4 μm scattering TiO₂ (400 nm)) and a Pt counter electrode were used for DSCs fabrication. The devices were measured immediately and the average performance of at least three devices with standard deviation is provided. [b] The electrolyte consists of 0.20 M CoII complex, 0.10 M of CoI⁺ complex, 0.05 M of LiTFSI and 0.50 M of NMBI in pure acetonitrile (MeCN). [c] Redox potentials of the 1a and Co-bpy are reported vs NHE.

The incident photon-to-electron conversion efficiency (IPCE) spectra of DSCs sensitized with MK2 are shown in Figure 6.2.3. Comparable IPCEs are observed for the devices made using the two electrolyte systems 1a/1b and Co-bpy with a slightly higher IPCE observed for the former, reflected in a slightly higher J_{sc} value.

We also carried out full sun irradiation aging experiments to explore the stability of 1a/1b and Co-bpy redox couples using either NMBI or TFMP as electrolyte additives. Four electrolytes, 1a/1b/NMBI, 1a/1b/TFMP (TFMP = 4-trifluoromethylpyridine), Co-bpy/NMBI and Co-bpy/TFMP were prepared in a MeCN: valeronitrile (V:N, 4:1) solvent mixture to reduce the vapour pressure of the electrolyte. An automated environmental chamber was used to maintain the DSCs under continuous full sun irradiation using Hg-lamp, 45% humidity and at 25–30°C temperatures. Figure 6.2.4 shows the normalized performance of DSCs tested under these conditions over a period of 100h.

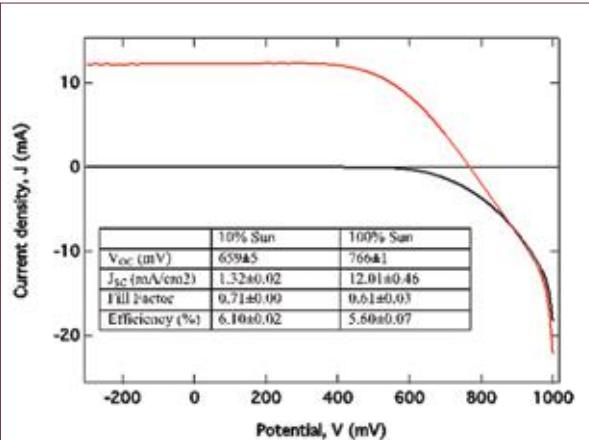


Figure 6.2.3: IV curves showing the DSCs performance for the best devices made using solid state hole conducting material.

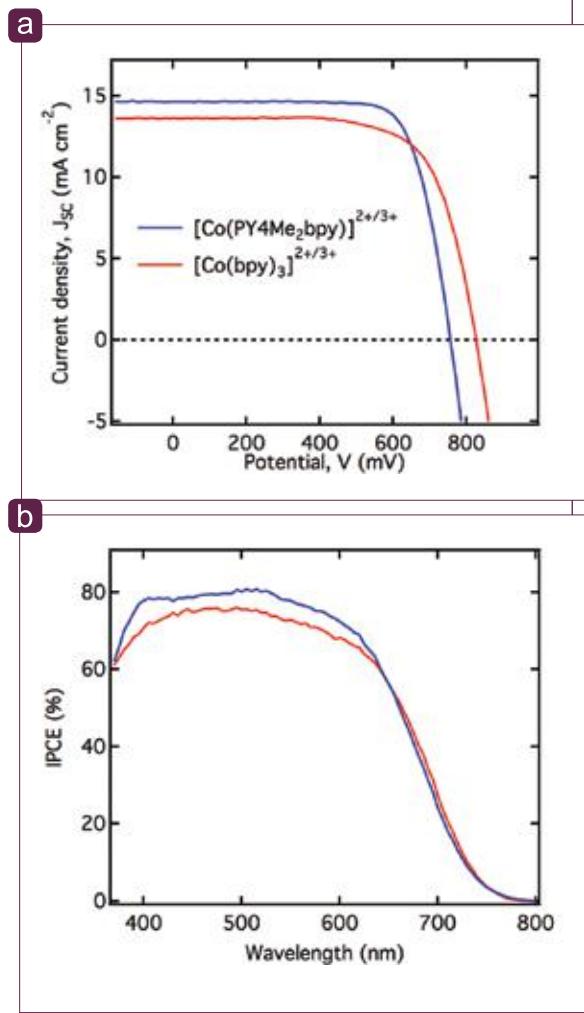


Figure 6.2.4: (a) IV curves showing comparison of the DSCs performance for the best devices made using electrolyte 1a/1b and Co-bpy. Other photovoltaic characteristics and electrolyte components are explained in Table 1. (b) IPCE of the best performing devices is shown.

The devices made with electrolyte 1a/1b/TFMP show an increase in efficiency over first 24h and then become stable for next 80h. The devices made using the 1a/1b/NMBI electrolyte show an increase in efficiency for first 24h, followed by a drop in efficiency for extended periods of light soaking. The devices based on Co-bpy/TFMP show an 80% decrease in efficiency in first 24h. This observation implies that use of TFM leads to the best device stability. Figure 6.2.5 also shows a comparison of normalized efficiencies for the devices made using electrolyte Co-bpy in combination with NMBI. Contrary to the small fall in efficiency observed for the devices made using Co-bpy/TFMP electrolyte, the devices made with Co-bpy/NMBI show greater stability during the irradiation aging experiment. This observation shows the importance of the choice of Lewis base when developing DSC electrolytes based on organometallic complexes.

Solar cells based on thin film technologies are dominating the market due to their ease of fabrication using cheap and abundant materials and mostly using inorganic based components. The very high conductivity shown by polyacetylene opened the field of organic semiconductors. Initially it took some time to flourish, but now a huge interest is being shown in this field. Spiro-MeOTAD is an organic semiconductor and has been used in state-of-the art solid-state dye-

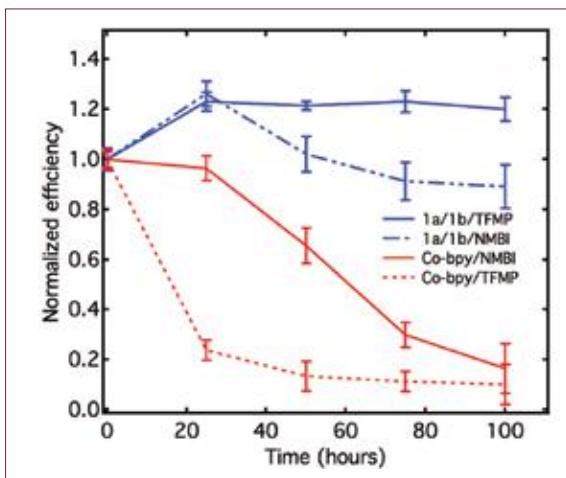


Figure 6.2.5: Normalized efficiency of the devices under full sun irradiation aging experiment is shown with a UV-cut filter. Two Lewis bases; NMBI and TFMP were alternatively used with 1a/1b and Co-bpy. A solvent mixture of MeCN:VN (4:1) was used and otherwise the same composition of electrolyte components as described in Table 6.2.1.

sensitized solar cells as hole conducting material. In the ss-DSCs, hole-conducting material is not only responsible for the dye regeneration but also efficiently transports the charge across counter electrodes.

A very recent revolution in this field came about when the dye component of the DSCs was replaced by methylammonium lead halide perovskite. However, one important component of these solid-state devices is the hole-conducting layer, responsible for the transport of charge across the working electrode and the counter electrode. These simple devices, prepared using room-temperature thin film processing techniques have reached efficiencies above 16% at 100mW cm⁻²

[6.2.1]. This achievement demonstrates the potential of these earth abundant materials to mitigate the challenges presented by world energy crises.

In order to further increase the efficiency and stability of ss-DSC and perovskite mesoscopic solar cells, one major area of interest is the development of new hole conducting materials. In previous studies metal complexes have been used to build transistors based on a single molecule and a number of metal complexes have been used with great success as hole transport materials in light emitting diodes. [6.2.2 – 6.2.7]

In our own research, we have applied a metal complex in ss-DSCs and have achieved efficiencies of 5.6% under AM 1.5 light intensity. One of the key objectives of this project is the identification of new types of solid-state hole conducting materials whose application can be translated to solar cells based on perovskite sensitizers.

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6.3 Carrier Selective Contacts for Boosting Si Solar Cell Efficiency

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California Institute of Technology: Prof. Harry Atwater

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École Polytechnique Fédérale de Lausanne:

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Dr. Stefaan DeWolf

Project Supporters:

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

UNSW will be 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

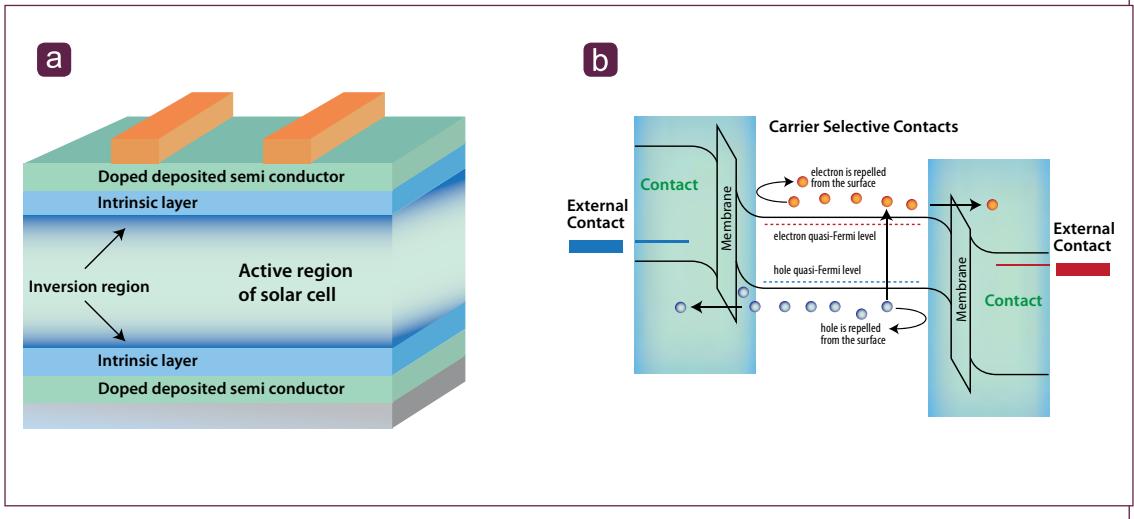


Figure 6.3.1: Schematic of the carrier selective contacts solar cell (a) structure, (b) band diagram based on strong inversion.

listed as a collaborator, along with MIT, Caltech and the Swiss Federal Institute of Technology. UNSW's involvement is coordinated through AUSIAPV.

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 Figure. 6.3.1a), with targeted efficiencies of 29%. UNSW will contribute device modelling (e.g., using Sentaurus TCAD), materials deposition (e.g., via atomic layer deposition), characterisation and integration of selected wide bandgap materials (e.g. GaP) as carrier selective contacts for the novel Si cell structure as part of a collaborative effort.

The motivation for using carrier selective contacts (CSCs) via deposited semiconductor layers that can induce strong inversion in the underlying silicon (see Figure. 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 Figure. 6.3.2a for the methodology). The general concept of the cell structure for the model is shown in Figure. 6.3.2b

and it incorporates the latest Auger and radiative recombination parameters for silicon [6.3.1].

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 Figure. 6.3.3. Open circuit voltage (V_{oc}) and fill factor (FF) as a function of IRV show that, while it is clear the IRV should be kept below 100cm/s to maintain close to ideal V_{oc} and FF, record performance is achievable even for a relatively high IRV of 1000cm/s, due to a lack of minority carriers in the GaP and at the GaP/Si interface.

Further work is ongoing to refine the model, including the possible integration of textured material optical simulation within the current Sentaurus TCAD model, and the development of a GaN/Si structure as a hole CSC, requiring the integration of strong polarization effects in GaN and their impact on the revised structure.

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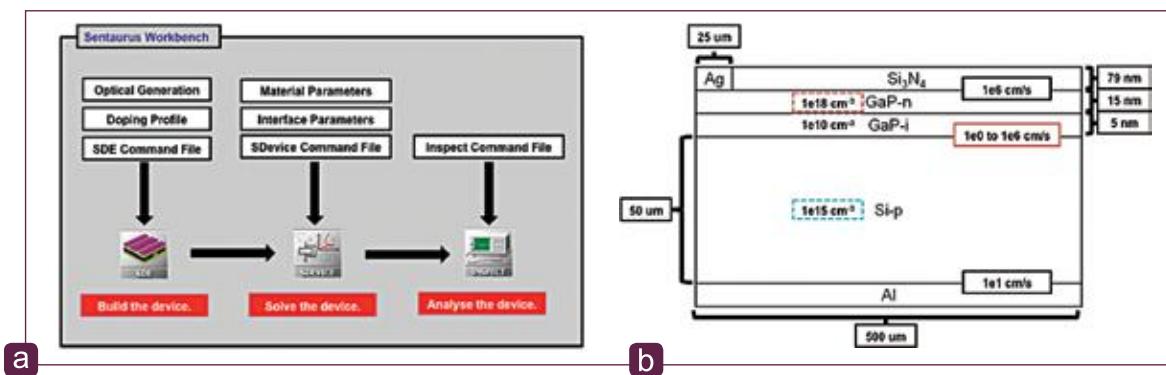


Figure 6.3.2: (a) Methodology and (b) cell structure used in Sentaurus TCAD.

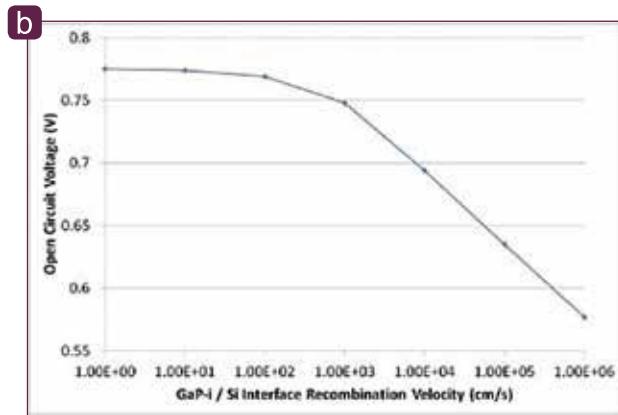
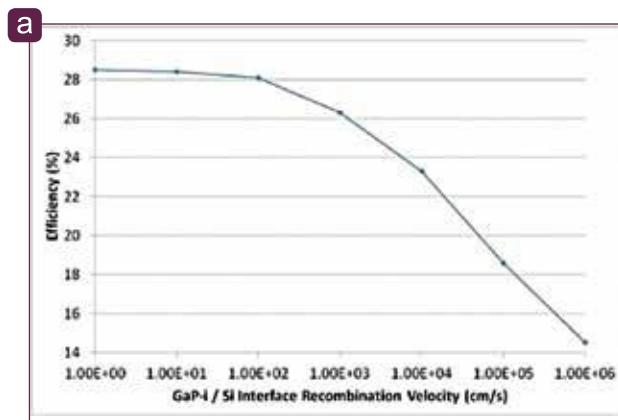
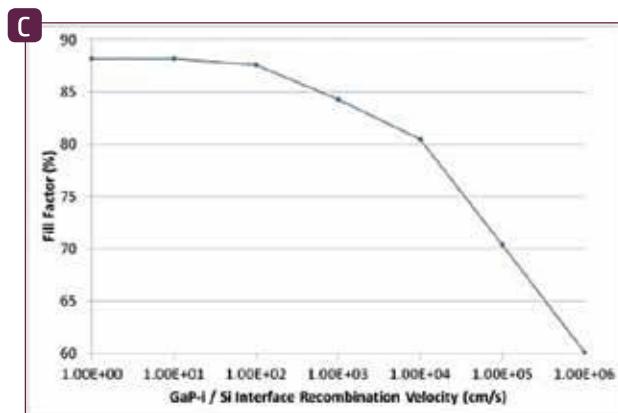


Figure 6.3.3: Simulated cell (a) efficiency
(c) open circuit voltage and (c) fill factor, as a
function of GaP-i/Si interface recombination
velocities (IRV).



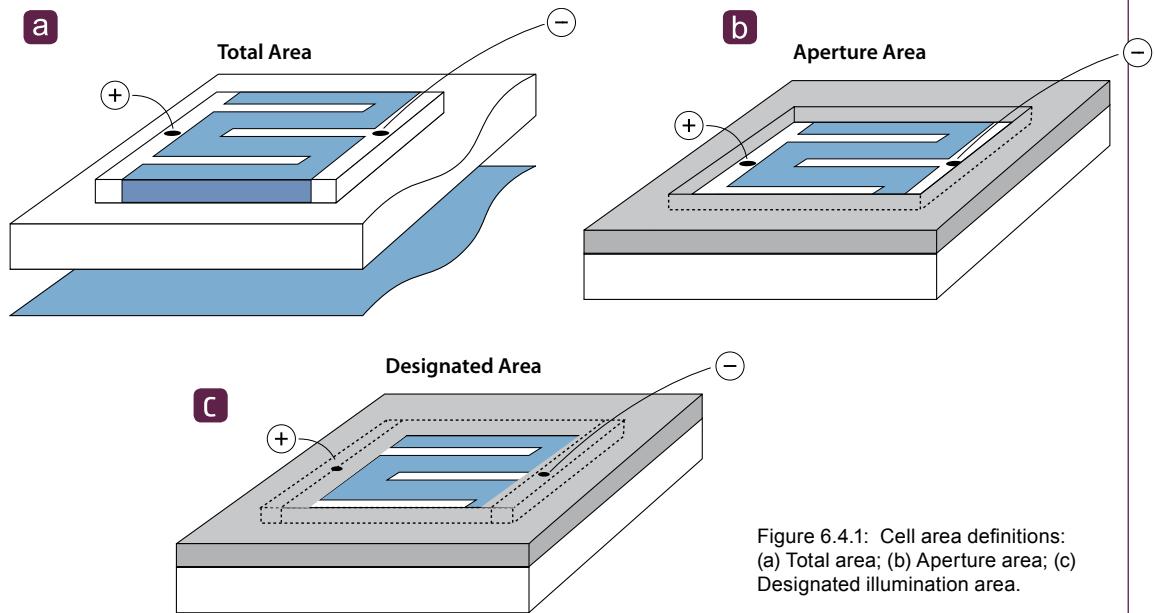


Figure 6.4.1: Cell area definitions:
(a) Total area; (b) Aperture area; (c)
Designated illumination area.

6.4 Solar Cell Performance Documentation

Researchers:

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NREL: Keith Emery

Funding:

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 is being documented by the biannual publication of the "Solar Cell Efficiency Tables" in the Wiley journal, "Progress in Photovoltaics".

By enforcing guidelines for the inclusion of solar cell efficiency results into these Tables, 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 is that results be independently certified at one of an increasing number of "designated test centres", generally of a national facility status, with a certified measurement capability along with involvement in international "round robin" testing.

This rigour has been important, particularly as new device technologies come to the fore and groups, which are relatively inexperienced with cell testing, are suddenly thrust into the limelight.

With its focus on research devices, the Tables often have to deal with issues not related to present standards. One of these has been the definition of cell area. The Tables have developed three area definitions shown in Figure. 6.4.1, between which test centres can choose for the reporting of their results.

The Tables are widely used by the photovoltaic research community. Accordingly to the ISI Web of Knowledge, the two versions prepared in 2013 have been respectively the most cited and the fifteenth most cited papers during 2013 throughout the engineering discipline worldwide.

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.

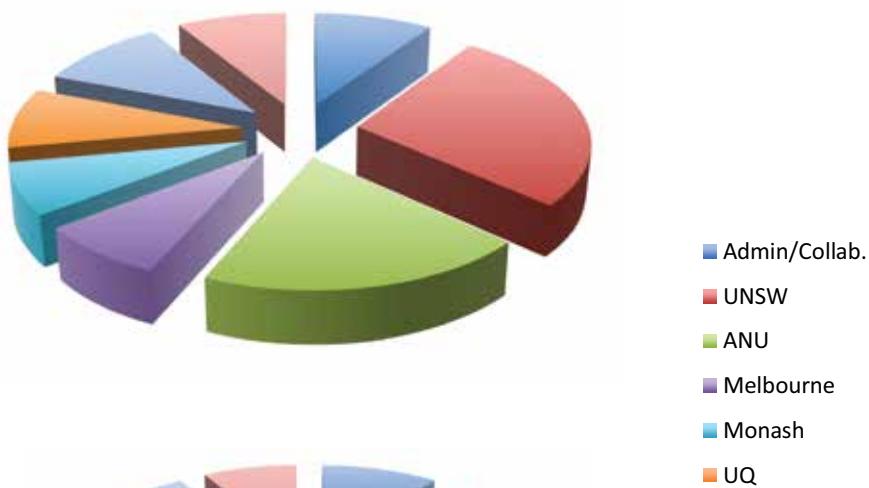
AUSIAPV commenced on 1 February 2013 after the signing of the Head Agreement between ARENA and UNSW on 3 December 2012, and with the receipt of letters of confirmation of participation under the terms of the Head Agreement from the other project participants.

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.

Despite this slower than anticipated start, good progress was made in 2013 in regaining the original project timelines, both in terms of technical progress and budgetary expenditure. All technical milestones for 2013 were achieved. The breakdown by institution of the \$10.2 million total cash and in-kind budget for 2013 is shown in Figure 7.1(a). The total cash and in-kind expenditure as at 31 December 2013 was \$6.6 million as shown in Figure 7.1(b), with additional irrevocable cash commitments carried into 2014.



a



b

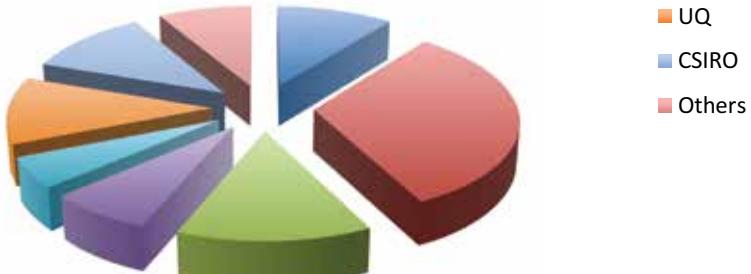


Figure 7.1: (a) Total AUSIAPV/ACAP cash and in-kind budget for 2013 broken down by institution; (b) Actual cash and in-kind expenditure breakdown for 2013.

By carrying over some of the originally planned 2013 expenditure into 2014, it is anticipated that the established favourable technical trajectory can be retained while bringing the project onto its original budgetary timeline by 2015.

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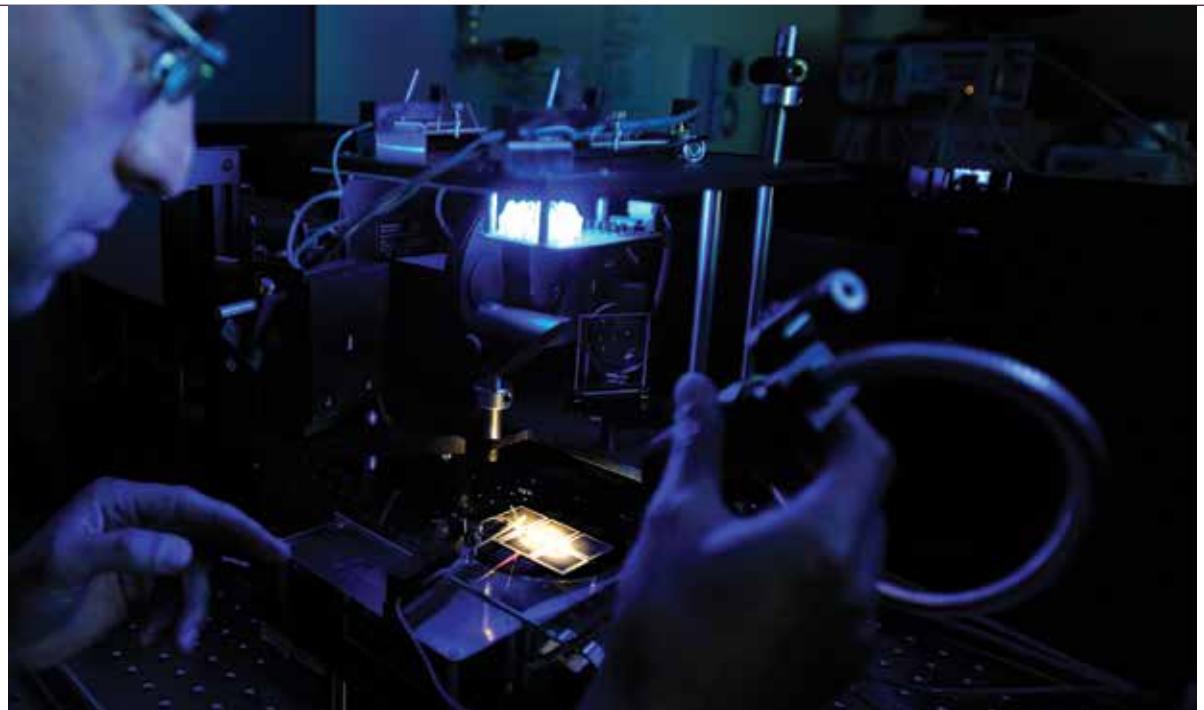
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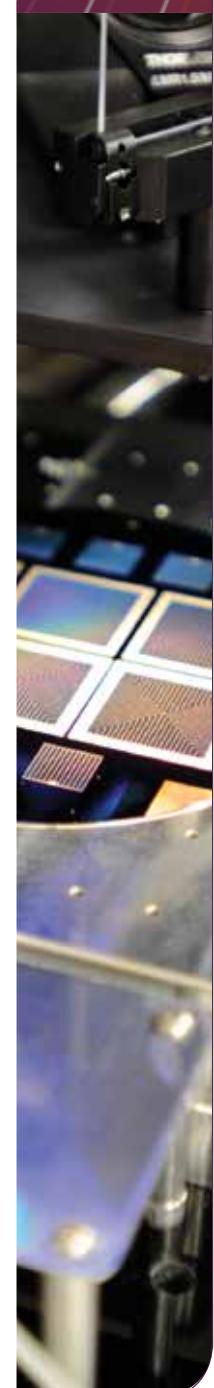


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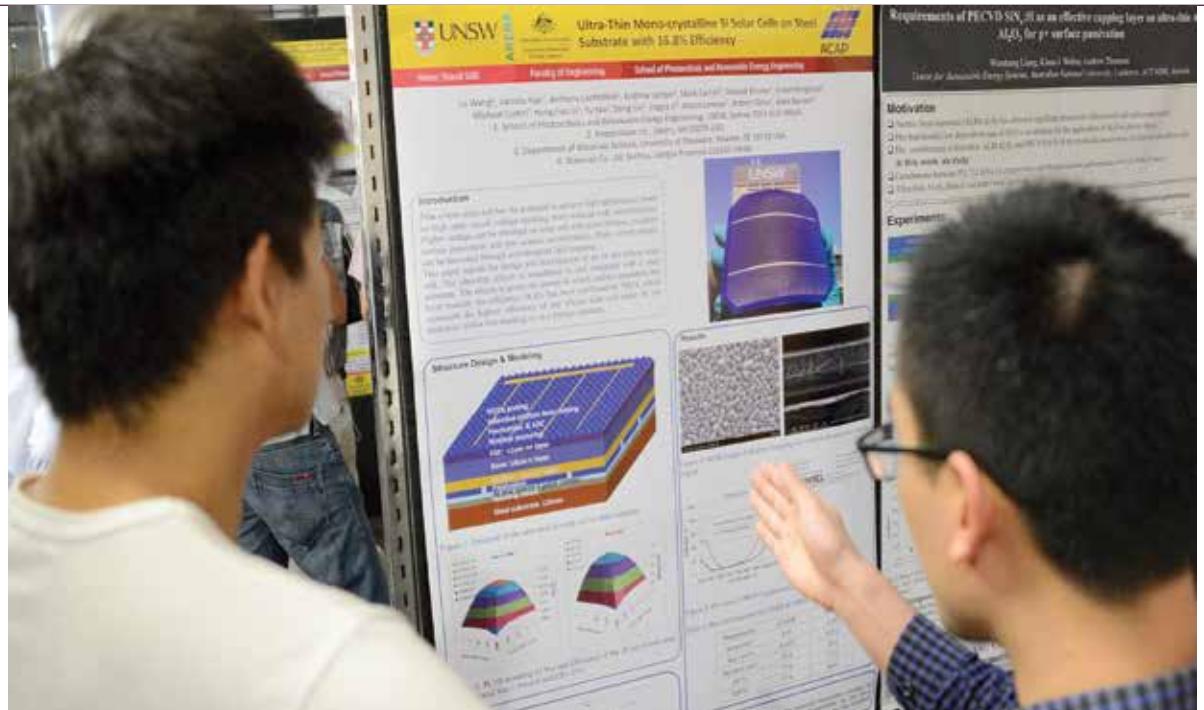
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