# ARENA-Funded Cutting Edge Research in Photovoltaics

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ARENA

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## EXECUTIVE SUMMARY

The Australian Renewable Energy Agency (ARENA) is aiming to reduce the cost of photovoltaic (PV) deployment through the third round of funding under its Research and Development (R&D) Program.

In 2017, $29.2 million in funding was awarded to 20 projects, which sought to achieve at least one of the following outcomes:

- increased efficiency and reliability of solar cells including perovskite cells and tandem cells
- more reliable and durable solar PV cells/modules
- new solar PV materials with potential to unlock new applications of solar PV and/or integration of solar PV with other processes and uses
- translation and commercialisation of Australian R&D into manufacturing supply chains through collaborations.

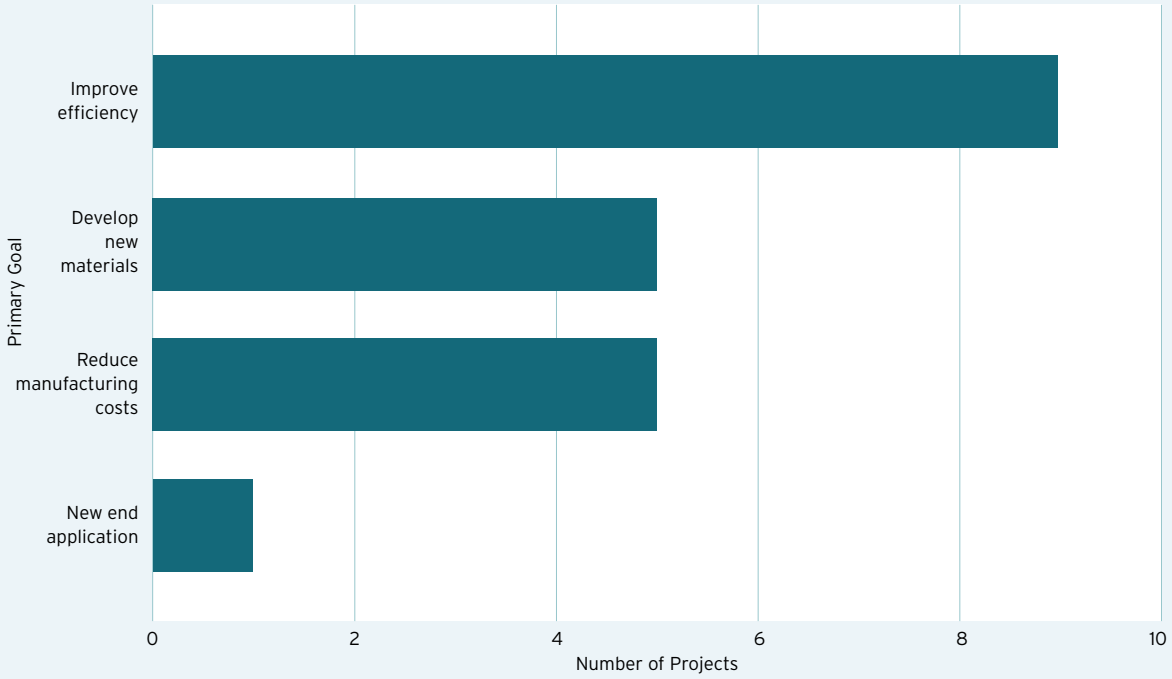


**Figure 1: Solar R&D number of projects by primary goal**

Nine projects focused on improving the efficiency of the existing silicon (Si) solar cells by either: improving the quality of the Si wafers; developing innovative passivating techniques to reduce charge recombination; increasing optical efficiency; or developing tools to detect the defects effectively. Five projects focussed on reducing the costs associated with manufacturing the module by demonstrating novel designs or processes. These research activities included the use of metallised encapsulants, forming monolithic tandem cell with perovskite on commercially available Si cell or forming passivated contacts.

Five grant recipients focused on the development of novel materials for different intended purposes. Most of the novel materials included electrode materials such as stacked metal electrode or carbon electrode, which are cheaper alternatives. Other new materials included polymers that imparted robustness and stability to organic solar cells. One project with a primary goal of being a new end application includes integration of perovskite solar cells in building windows. It aims to harness the solar power through large glass windows of buildings.

This report provides a snapshot of the projects that received ARENA funding. The projects are now eighteen months into their three year duration, and the early results of the projects are innovative and promising. Through world-leading expertise and skills in Si technology and innovation, Australian researchers continue to make ground breaking impacts in this technology, as well as other PV technologies such as perovskite, polymer or III-V semiconductor-based PV. Fig. 2 provides a snapshot of the technologies being pursued by the funding recipients and the innovation that contributed to the respective efficiencies. In addition to improvement in efficiencies, there are other outcomes such as development of processes for depositing passivating layers, development of computer modelling and characterisation techniques, which are not the scope of Fig. 2.

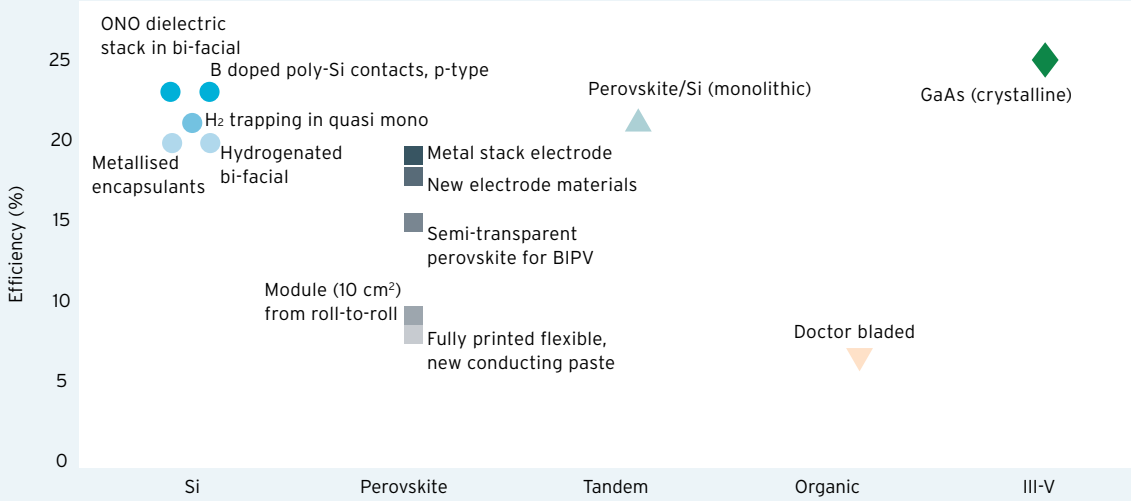


**Figure 2: Summary of research outcomes from ARENA funded projects in improving efficiencies in the dominating PV technologies.**

## INTRODUCTION

In 2017, ARENA provided $29.2 million for 20 research projects to accelerate PV innovation in Australia and internationally. ARENA's third round of R&D funding was targeted towards innovation in the following research areas:[1]

- improved cell and module efficiency, including in Si cells, perovskite cells and tandem cells with Si as a base material
- low cost and robust module design
- improved encapsulation techniques to address degradation issues for emerging photovoltaic (PV) technologies such as perovskite cells
- new tools and processes to identify and address defects to further improve device performance
- low cost and robust mounting designs and improved manufacturing processes
- reduced lifetime cost in wiring, switches, and inverters
- improved operational and maintenance tools and software
- improved solar forecasting
- solar PV end-of-life management and lifecycle assessment
- development of solar PV into new products for flexible, transparent or other specialised applications
- integration of solar PV into new market areas
- researcher-manufacturer collaboration to integrate new ideas, processes and tools into manufacturing operations.

As the current commercial PV market is dominated by Si technologies, most of the funded projects are focused on improving the efficiency of Si solar cells. The other nine projects are researching the next generation technologies such as perovskites, III-V semiconductors, adamantine and organic photovoltaics (Fig. 3).

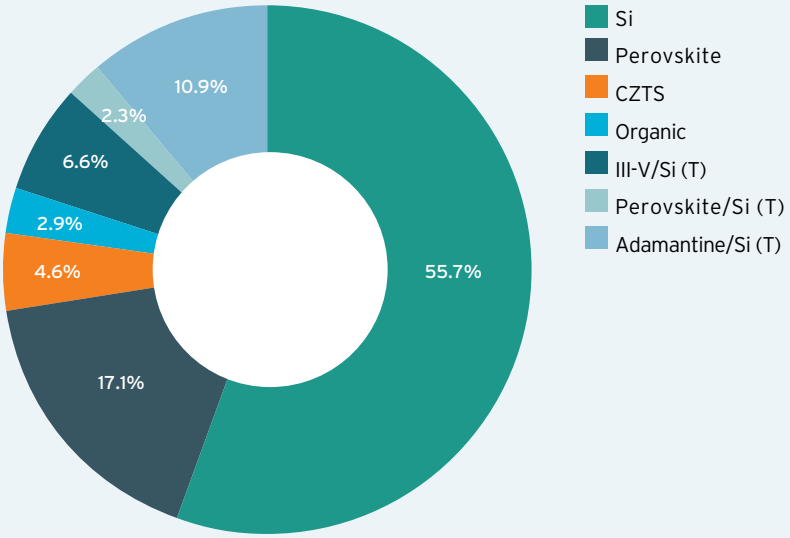


**Figure 3: Breakdown of funds based on PV technology. (T: tandem)**

This report summarises information contained in each of the project's Year Two Knowledge Sharing Reports to provide a snapshot of the research activities being pursued by the projects. The projects made remarkable progress over the past two years, demonstrating innovation and world leading research.

Appendix A provides the details of each of the projects and contains links to most of the Year Two Knowledge Sharing Reports. A Technical Glossary is also included at the back of this report for reference.

1 "Innovating energy ARENA's investment plan – Australian ..." https://arena.gov.au/assets/2017/05/AU21397_ARENA_IP_Document_FA_Single_Pages_LORES.pdf.

## OUTCOMES OF ARENA FUNDED PROJECTS

The projects are developing new technologies and tools to reduce installed costs of PV systems, improve system reliability and longevity, and develop materials for new markets or applications. The projects' outcomes provide opportunities to help Australian industry translate these ideas into PV manufacturing supply chains. The research outcomes from the ARENA-funded projects are described below, and categorised by their primary outcome.

### 1. Improve efficiency

a. **Project Title:** Improving World-Record Commercial High-Efficiency n-type Solar Cells through Recombination Analysis and Innovative Passivation
**ARENA ID:** 2017/RND003
**Lead Researcher:** Professor Chee Mun Chong
**University:** University of New South Wales
**Partners:** Trina Solar, Energy Research Centre of Netherlands (ECN), Jinko Solar, SunPower, The Australian National University
**ARENA Funding:** $1,785,000

Professor Chee Mun Chong and his team aim to further improve the existing n-type Si solar cell efficiency through the identification and rectification of defects or modes of degradation via hydrogenation.

The team observed that there is very little awareness in the Si PV community about the degradation of the n-type Si cell. Degradation of the n-type Si cell is induced by light and heat, which is similar to the degradation of the p-type Si solar cell.

The project concluded that the light-induced degradation (LID) can be addressed by carefully tuning the hydrogen atoms to reduce defects,[2,3] which in turn would improve efficiencies. Important processing parameters in these investigations included the Si response to temperature, wavelength of illumination, power of illumination intensity, cooling rates etc. In Fig. 4(b), the photoluminescence images of the Si wafer demonstrate improvement in the quality of the n-type Si wafer after hydrogen treatment.

Professor Chong's next plan is to adapt the successful techniques demonstrated in the laboratory to an industrial setting to manufacture commercial solar cells.

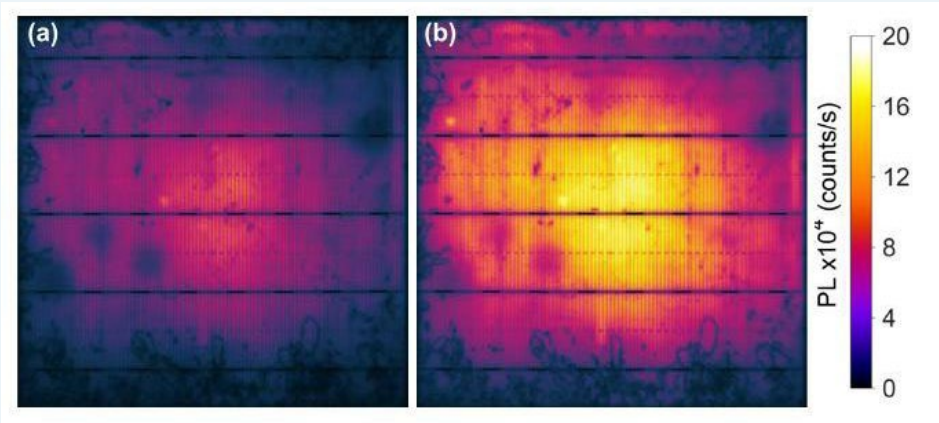


**Figure 4: Photoluminescence images of before (a) and after (b) hydrogen treated n-type Si wafer. Brighter spots show areas of fewer defects.[4]**

2 "Laser Enhanced Hydrogen Passivation of Si Wafers – Hindawi." 13 Mar. 2015, https://www.hindawi.com/journals/ijp/2015/193892/.

3 "Hydrogen Passivation in Si Solar Cells – CSIRO PUBLISHING ..." https://www.publish.csiro.au/ch/fulltext/CH18271.

4 "Improving World-Record Commercial High-Efficiency n-type ..." 28 Aug. 2019, https://arena.gov.au/assets/2018/01/world-record-commercial-high-efficiency-n-type-solar-cells.pdf.

b. **Project Title:** Development of novel hydrogen trapping techniques for breakthrough Si casting and wafering technologies
**ARENA ID:** 2017/RND010
Lead Researchers: Dr. Catherine Chan and Dr. Alison Ciesla
**University:** University of New South Wales
**Partners:** Tongwei Solar, Jinko Solar, The Australian National University
**ARENA Funding:** $1,968,000

Dr. Catherine Chan and Dr. Alison Ciesla, as co-leaders of the project, along with their team, aim to improve efficiencies of low cost Si wafers by adopting hydrogen trapping processes, which are applicable to a broad range of defects and Si types.

Lower cost Si wafers typically have a high number of defects that reduce performance. Hydrogenation is a widely accepted tool to passivate the defects in a low-quality Si wafer, however Dr. Chan and Dr. Ciesla and their team demonstrated novel hydrogen trapping techniques that enhanced the quality of quasi mono Si wafers by 70 per cent more than what standard hydrogenation processes could do alone. Quasi-mono Si wafers are cheap but have a high density of defects that form during Si growth.

The team also observed that excess hydrogen could cause degradation in wafer quality under light and heat, or increase electrical resistance at the metal contacts of the solar cells. Due to these defects and degradations, the cell performance is impaired.

Hydrogen trapping processes applied to a full-size commercial quasi-mono cell have already achieved over 21 per cent stable efficiency by the team that is comparable to commercial cells produced on more expensive, higher quality wafer types. However, they observed that some localised types of grown-in defects like dislocations did not respond to hydrogen trapping.

With continued optimisation and development, the project team aims to transfer the hydrogen controlling process to industry enabling the cheaper wafers to be used in the commercial manufacturing of high efficiency solar cells.

c. **Project Title:** Hydrogenated and Hybrid Heterojunction p-type Si PV Cells
**ARENA ID:** 2017/RND005
**Lead Researcher:** Dr. Brett Hallam
**University:** University of New South Wales
**Partners:** Apollon Solar, Arizona State University, LONGi Solar, Meyer Burger, The Australian National University
**ARENA Funding:** $1,735,000

Dr. Brett Hallam and his team aim to improve efficiency by investigating the benefits of gettering and hydrogenation in the manufacture of heterojunction solar cells using low quality p-type Si wafers.[5]

The p-type Si solar cells are known for their inferior quality and require conscientious efforts to reduce defects to be competitive with more expensive n-type solar cells. The team performed high temperature gettering and injection of hydrogen before the formation of heterojunction structures followed by low temperature hydrogen activation process to avoid LID. The resulting p-type Si solar cell exhibited higher efficiency with open circuit voltages over 700 millivolts, which is higher than the current mass-produced PERC solar cells (which are p-type in nature).

5 "The role of hydrogenation and gettering in enhancing the ... – UNSWorks," 8 Jun. 2017, http://unsworks.unsw.edu.au/fapi/datastream/unsworks:46795/bin2db1e892-e4aa-41a4-a49a-14c195e63031?view=true.

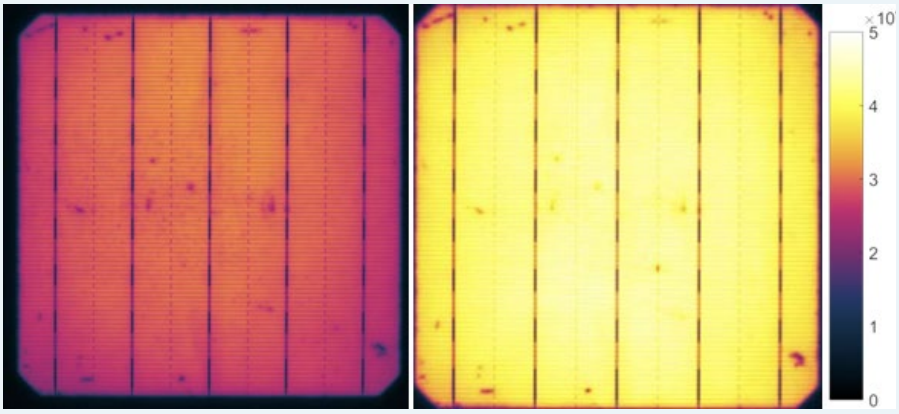


**Figure 5: Industrial heterojunction n-type solar cell's response to photoluminescence, (left) before and (right) after the post-fabrication process. The brighter image indicates improvement in device voltage which is attributed to improved quality.**[6]

Following from the lessons learnt from the application of post-fabrication processes of p-type Si solar cells, the team also identified a rapid post fabrication process (patent pending) for industrial n-type heterojunction solar cells (Fig. 5). This process improves the performance of the n-type Si solar cells by 0.7 per cent absolute due to the improvement in surface passivation and transport of electrons within the device. This outcome has gained significant interest for commercial heterojunction solar cell manufacturers as a way to potentially reduce fabrication cost. Dr. Hallam is targeting translating these improved material qualities to improved efficiencies.

d. **Project Title:** Integrating industrial black Si with high efficiency multicrystalline solar cells
**ARENA ID:** 2017/RND009
**Lead Researcher:** Dr Malcolm Abbott
**University:** University of New South Wales
**Partners:** Canadian Solar, 1366 Technologies Texturing Division, Macquarie University, Danish Technical University (DTU), Oxford University (QU) and AMOLF
**ARENA Funding:** $500,000

Dr. Malcom Abbott and his team aim to improve the efficiency of multicrystalline solar cells by integrating black Si.

Black Si describes a variety of texturing techniques that reduce reflection losses at the front side of a solar cell. Though the less aggressive forms of black Si have been implemented into production lines, the more promising aggressive texturing approaches are not yet integrated into commercial cells. This is due to process complexity or lack of knowledge on the specifications and correlation of their opto-electronic properties with device performance.

Dr. Abbott's team is addressing this problem from two sides, firstly by working closely with industrial black Si manufacturing to make improvements to the production process. Secondly by working with various forms of extreme black Si (i.e. the ideal case in terms of optical performance) and developing techniques to integrate these extreme surface features with production compatible processing equipment.

The team has developed several advanced characterisation techniques that include measuring texture uniformity, accurate extraction of surface features, location of electrical junctions and detailed optical scattering including the angular dependence. The project has also developed a number of rapid simulation techniques that enable computer modelling programs for precise and rapid analysis of a wide range of black Si. This analysis enables the performance of different textures to be assessed not just on a cell level but also in terms of energy production when deployed in a field.

6 "Hydrogenated and Hybrid Heterojunction p-type Silicon PV ..." 4 Sep. 2019, https://arena.gov.au/knowledge-bank/hydrogenated-and-hybrid-heterojunction-p-type-silicon-pv-cells/.

In the second half of the project, the team will focus on the integration of extreme texture features into solar cells including the development of advanced surface passivation, doping and metal contact approaches, which are in line with the expertise at UNSW SPREE.

e. **Project Title:** Driving Increased Efficiency and Reliability in Si Photovoltaics – From Ingots to Modules
   **ARENA ID:** 2017/RND017
   **Lead Researcher:** Professor Daniel Macdonald
   **University:** The Australian National University
   **Partners:** National Renewable Energy Laboratory (NREL), Jinko Solar, BT Imaging, University of New South Wales
   **ARENA Funding:** $2,399,392

Professor Daniel Macdonald and his team aim to improve efficiency and reliability in Si PV, by reducing defects and degradation mechanisms. In order to achieve these objectives, it is necessary to detect and quantify the defects accurately.

Professor Macdonald's team developed and demonstrated a range of new or improved methods, based on advanced luminescence technology, to identify loss and degradation mechanisms in Si solar cells at numerous points along the production chain. Advanced luminescence-based methods allow rapid, contactless, and high resolution imaging of the relevant properties. The team is also testing the commercial viability of these methods through their collaborators.

f. **Project Title:** Next generation Si sub-cells for high efficiency III-V/Si multi-junction solar cells
   **ARENA ID:** 2017/RND008
   **Lead Researcher:** Associate Professor Stephen Bremner
   **University:** University of New South Wales
   **Partners:** The Ohio State University
   **ARENA Funding:** $1,144,628

Associate Professor Stephen Bremner and his team aim to develop high efficiency III-V/Si multijunction solar cells. The goal of this project is to enable a novel approach to deposit III-V (gallium phosphide/gallium arsenide phosphide) materials on Si using thinner Si substrates, reduce material usage, and to simplify processing by including a heterojunction type rear surface.

The team observed that nickel oxide has demonstrated promising results as a carrier selective contact material for use on the rear surface of the Si cell. The carrier selective contact type of approach will enable use of thinner Si substrates thereby, reducing material usage and reducing fabrication costs. In order to address the limitations of thin Si devices, they explored and observed that by an additive textured (poly-di-methyl-siloxane) PDMS layer, the monolithic device performance was significantly improved. They intend to further investigate this effect. The incorporation of a room temperature metal contacting technique, that uses electric breakdown of an insulating layer on the rear of the Si has also been applied to III-V on Si devices.

Lessons learnt include identification of defects that degrade Si during deposition of III-V materials, which inhibit attainment of high efficiencies. Their proven solution involves high temperature anneal of the Si substrate prior to the III-V deposition process and use of a Si nitride (SiN) layer on the rear of the Si.

The next steps for this project are significantly increasing the efforts in metal oxide layers at the Si rear which will be enabled by the acquisition of an (atomic layer deposition) ALD deposition tool to give excellent control over the oxide properties.

g. **Project Title:** Tandem PV Micro-Concentrator
**ARENA ID:** 2017/RND020
**Lead Researcher:** Professor Andrew Blakers
**University:** The Australian National University
**Partners:** National Renewable Energy Laboratory (NREL)
**ARENA Funding:** $788,515

Professor Andrew Blakers and his team aim to improve the efficiency while reducing the fabrication costs of III-V/Si tandem solar cells by using a tandem PV micro concentrator.

His team applied the Sliver technique[7] to gallium arsenide (GaAs) in order to increase the surface area for enhanced absorption of light. Dicing and Inductively Coupled Plasma Reactive Ion Etching (ICP/RIE) were investigated and the latter was found to be the most efficient in acquiring 100 micrometer deep and 23 micrometer wide GaAs microstructures thereby proving the technical viability of the Sliver technique for GaAs material. The team also demonstrated that all of the components of the tandem PV micro concentrator (micro concentrator, GaAs cell and Si cell) can function together effectively, which upon further optimisation can be employed with existing PV tracking systems.

Under concentration, the single-junction crystalline GaAs cells exhibited 25 per cent efficiency which the researchers are confident will increase by subsequent optimisation steps and characterisation. Upon successfully achieving the milestones, Professor Blakers plans to develop a prototype cost-competitive tandem micro concentrator system, which will be ready for the next stage of commercialisation.

h. **Project Title:** Accelerating industrial solar cells efficiency by development of plasma-enhanced chemical vapour deposition (PECVD) – based metal oxides
**ARENA ID:** 2017/RND001
**Lead Researcher:** Dr. Ziv Hameiri
**University:** University of New South Wales
**Partners:** Meyer Burger, Shamash Australia, Sunrise Global Solar Energy, The Australian National University
**ARENA Funding:** $503,389

Dr. Ziv Hameiri and his team aim to improve the efficiency of Si PV by depositing transition metal oxides (TMOs) using common industrial techniques. The TMOs deposited between the Si and metal contacts suppresses energy losses from recombination of charges and facilitate transportation of current. Poor cell designs affect the performance of the cell and it has been shown that energy loses at the metallic contacts limit the efficiency of most of industrial solar cells. An improved design with the appropriate materials will boost device performance by reducing losses, without increasing the fabrication costs.

Dr. Hameiri is leading the project of developing PECVD processes, which offer several advantages over other deposition methods of metal oxides as PECVD offers more flexibility regarding the processing parameters than the other conventional methods.

In order to deliver the research outcomes, the team concentrated their efforts in modifying their deposition tool and have successfully deposited TiOx. The project aims to implement the PECVD deposited metal oxides in PV production line and assess the material and device performance relationship. Further lessons learnt include the effect of the work function of various metals on the recombination at the surface of passivated Si wafers.

7 "Metal Assisted Chemical Etching of Silvers," https://arena.gov.au/assets/2019/01/metal-assisted-chemical-etching-of-silvers.pdf.

i. **Project Title:** Next Generation Industrial Bifacial Si Solar cells
**ARENA ID:** 2017/RND015
**Lead Researcher:** Dr. Kean Chern Fong
**University:** The Australian National University
**Partners:** Wavelabs
**ARENA Funding:** $1,977,845

Dr. Kean Chern Fong and his team aim to improve the efficiency of laboratory and industrial bifacial Si solar cells by investigating and incorporating state-of-the-art laboratory technology.

There is rising demand for bifacial Si solar cells in the global PV market as they demonstrate improved power generation owing to rear light absorption, and significant reduction in rear metal paste consumption resulting in lower production costs.

For the fabrication of bifacial solar cells, Dr. Fong identified the following technologies as most promising:

- oxide-nitride-oxide (ONO) dielectric stack with a dual functionality of excellent passivation quality and anti-reflection qualities. This technology can be applied to both n and p type of bifacial solar cells
- low-pressure chemical vapor deposition (LPCVD) of polySi-oxide contact to reduce charge recombination at the contacts
- laser doping processes for n-type bifacial cells to form localised selective contacts underneath metal contacts. This technology reduces the number of required high-temperature processing steps while reducing carrier recombination and resistivity at the contacts.

Dr. Fong successfully demonstrated 23.1 per cent efficiency with 97 per cent bifacial factor using ONO on both the front and rear surfaces of n-type bifacial solar cell (Fig. 6). For p-type bifacial solar cell, he successfully demonstrated 23.2 per cent efficiency with 94 per cent bifacial factor. An interesting feature of this project is the project management approach taken which involved a stage-gate process providing a methodological approach towards a highly complex multi-tiered technology development. The other technologies such as laser doping and passivating contacts are currently in the pipeline.

At the final stage, the successful technologies will be integrated into industrial-size (6-inch) bifacial cells on industry partner's pilot line. The researcher is confident that by the end of the project, Australian research institutes can become or continue to be research hubs in the future for bifacial technology development and commercialisation endeavours.

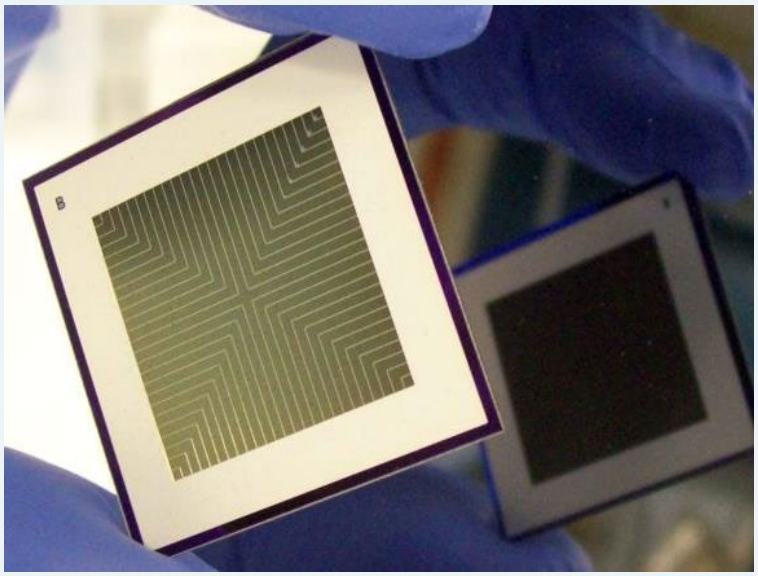

**Figure 6: Laboratory scale bifacial cell fabricated at ANU (Source: ANU)**

## 2. Reduce manufacturing costs

a. **Project Title:** Investigate Metallised Encapsulant for Si PV Modules: A Path to Reduced LCOE for PV
**ARENA ID:** 2017/RND002
**Lead Researcher:** Associate Professor Alison Lennon
**University:** University of New South Wales
**Partners:** DSM Advanced Surfaces B. V., Energy Research Centre of the Netherlands, LONGi Solar, Sizhou PV Tech, The Australian National University
**ARENA Funding:** $1,160,000

Associate Professor Alison Lennon and her team aim to reduce the costs associated with module fabrication
by using metallised encapsulants for Si PV modules.

In Fig. 6, the project team demonstrated that the costs associated with module fabrication are increasing considerably over time. Prof. Lennon's team proposed metallised encapsulants (metal conductors in polymers) that provide additional benefits such as:

1. increasing cell efficiency through reduced carrier recombination at the metal contacts resulting in a voltage increase
2. reduced silver usage resulting in lower manufacturing costs
3. provision for optimising the design which contributes to lower thermomechanical stress in Si wafers. Lowering thermomechanical stress is critical for the next generation thinner Si substrates. The design also contributes to higher electricity yield at all incident angles arising from improved optical performance
4. increased flexibility in module fabrication with the potential to purchase pre-fabricated metallised encapsulant for module fabrication.

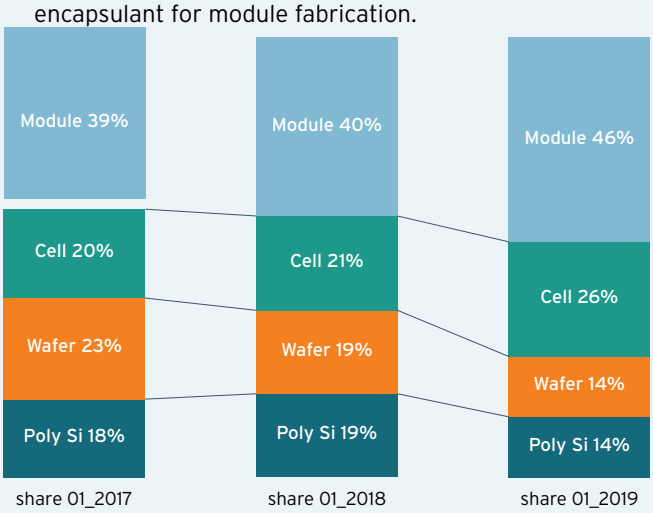


**Figure 6: Depiction of different elements of the module contributing to the module manufacturing cost.**[8]

In order to meet their project objectives, the team directed their research activities towards developing processes for directly forming metal conductors in polymers. They are also developing characterisation techniques and simulations to evaluate stress and optical performance in Si PV modules, which would benefit solar farms in predicting electricity yield accurately. Though the project is in the initial stages of R&D, the researchers demonstrated a cell-area-based PERC module efficiency of 19.95 per cent on two cell module laminates, which is comparable to the efficiencies of the state-of-the-art soldered five bus bar (5 BB) PERC module (see Fig. 7).

8 "Investigate Metallised Encapsulant for Silicon PV Modules ..." 4 Sep. 2019, https://arena.gov.au/knowledge-bank/investigate-metallised-encapsulant-for-silicon-pv-modules/.

**Figure 7: Photo of a 2 by 2-cell module laminate with an ME module (with silver-coated structured ribbon conductors) on the left and a reference 5 BB soldered module on the right. Module laminate fabricated by C. Roemer (UNSW)[8].**

With further refinement of this technology, the team is confident in advancing commercial prospects in conjunction with its partnership with LONGi Solar and Sizhuo PV Tech.

b. **Project Title:** Advanced high-efficiency Si solar cells employing innovative atomic scale engineered surface and contact passivation layers
**ARENA ID:** 2017/RND007
**Lead Researcher:** Associate Professor Bram Hoex
**University:** University of New South Wales
**Partners:** Jiangsu Leadmicro Nano-Equipment Technology, The Australian National University
**ARENA Funding:** $2,019,456

Associate Professor Bram Hoex and his team aims to reduce manufacturing costs and complexity involved in manufacturing PERC solar cells.

Ultrathin films at the rear of the PERC cells are the main contributors to the PERC cells' high efficiency. In the PERC solar cell, a thin film stack consisting of aluminium oxide and Si nitride is used to reduce electronic losses at the rear side of the solar cell. Further improvements in efficiency can be achieved by the use of thin, novel films to simultaneously reduce electronic losses and extract the solar-generated electricity via the so-called passivating contacts. The properties of thin films need to be controlled at the atomic level and this is best achieved by atomic layer deposition (ALD).

Professor Hoex proposes bifacial atomic layer deposition of aluminium oxide in PERC as a solution to reduction in manufacturing costs and complexity. As shown in Fig. 8, PERC solar cells with a bifacial ALD aluminium oxide have higher efficiency (> 21.5 per cent) than the other existing technologies. It can clearly be seen that the solar cells with the bifacial aluminium oxide layer show a better performance compared to the monofacial aluminium oxide layer while the production costs of the bifacial aluminium oxide are significantly lower. An additional aluminium oxide layer on the front of a PERC solar cell improves its performance by lowering the contact resistance between the silver front metal grid and the emitter after contact firing. This process reduces complexity for the ALD process and increases its throughput, thus decreasing the costs of the PERC production.

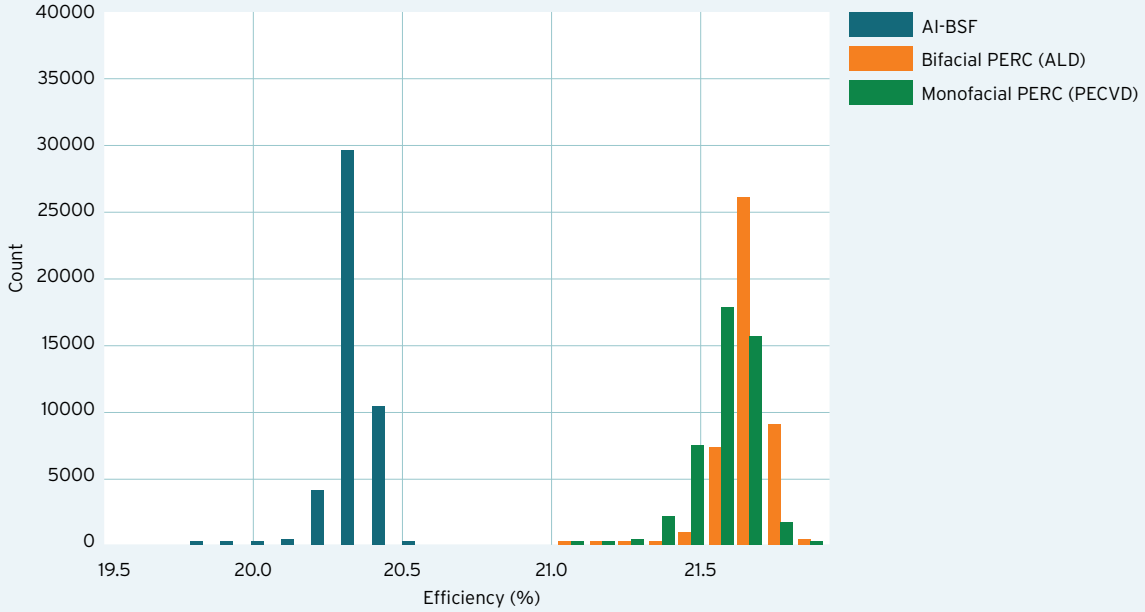


**Figure 8: High-volume production data for the incumbent aluminum Back Surface Field (Al-BSF) technology and PERC solar cells with a monofacial and bifacial aluminium oxide layer.**[9]

The team will also receive a pilot scale ALD reactor which will propel their collaborative work with industry and universities to an international level. Based on preliminary promising results, the team will further investigate other doped metal oxides (including tertiary compounds) that could lead to a further reduction in manufacturing costs.

c. **Project Title:** Advanced Si Solar Cells by DESIJN (Deposited Si Junctions)
**ARENA ID:** 2017/RND016
**Lead Researcher:** Professor Daniel Macdonald
**University:** The Australian National University
**Partners:** Jinko Solar
**ARENA Funding:** $1,116,142

Professor Daniel Macdonald and his team aim to ease Si PV fabrication process by the use of poly-Si contacts.

The poly-Si layers enable electrical contact to be made to the solar cell with low resistive losses as well as block charge carriers within the solar cell from reaching the defective surfaces where they could otherwise be lost.

The project findings include the fabrication of 23 per cent efficient p-type cell incorporating a heavily boron-doped poly-Si layer on the rear surface of the cell. The layer was deposited using a low cost sputtering method with in-situ doping. This approach has distinct cost and safety advantages over the standard methods for creating poly-Si contacts and has the potential to be transferred to the production lines of Jinko Solar.

9 "Advanced High Efficiency Silicon Solar Cells Employing ..." 4 Sep. 2019, https://arena.gov.au/knowledge-bank/advanced-high-efficiency-silicon-solar-cells-employing-innovative-atomic-scale-engineered-surface-and-contact-passivation-layers/.

d. **Project Title:** Monolithic perovskite – Si tandem cells: towards commercial reality
**ARENA ID:** 2017/RND018
**Lead Researcher:** Professor Kylie Catchpole
**University:** The Australian National University
**Partners:** Jinko Solar
**ARENA Funding:** $672,841

The researchers at ANU, led by Professor Kylie Catchpole, aim to reduce the manufacturing cost of high efficiency solar cells comprising of perovskite solar cells deposited atop commercially available Si solar cells forming a monolithic tandem cell.

The ANU team demonstrated excellent cell performance of about 21 per cent efficiency through optimising the deposition of good quality perovskite films over a larger area (4 cm2) using vacuum flash technique. In vacuum flash technique the perovskite precursor film is exposed to a low vacuum, together with nitrogen gas flowing over the surface. The team also investigated the impact of cheaper hole transporting alternatives such as nickel oxide, on their device performance.

This project is also a testimony to the achievement of common goals through collaboration between ANU and Jinko Solar where the teams collaborated to modify their processes to accommodate novel architectures that are commercially and technically viable. See the lessons learnt report here.

e. **Project Title:** Hydrogenated Bifacial PERL Si PV Cells with Laser Doping and Plated Contacts
**ARENA ID:** 2017/RND004
**Lead Researcher:** Professor Chee Mun Chong
**University:** University of New South Wales
**Partners:** None
**ARENA Funding:** $1,100,000

Professor Chee Mun Chong and his team aim to develop a breakthrough low-cost, high-efficiency PERL cell technology and innovative, high-throughput commercial production processes and equipment.

Professor Chong's team fabricated laser doped PERC and PERL (Passivated Emitter Rear Locally-diffused) devices with plated contacts and passivated using advanced hydrogenation. They incorporated advanced hydrogenation process at different stages of the cell fabrication: before laser doping, after laser doping, after nickel plating and after copper plating. The team effectively demonstrated light induced plating to deposit metal at low temperature for laser doped bifacial PERL cell. The laser doping and self-aligned plating form closely placed narrow fingers with significantly reduced losses caused by shading. Smooth and uniform metal deposition on both the n-type surface and p-type surface was achieved.

Therefore, this method reduces the costs associated with module fabrication by avoiding the use of expensive silver and aluminium screen-print pastes. They observed that hydrogen passivation can successfully passivate laser induced defects and eliminate LID efficiency losses to less than 1.5 per cent relative. The team was successful in achieving a 19.8 per cent efficient solar cell and are optimistic in further enhancing the efficiency through lessons learnt from the project.

## 3. Development of novel materials

a. **Project Title:** Bringing all-polymer solar cells closer to commercialization
**ARENA ID:** 2017/RND014
**Lead Researcher:** Professor Christopher McNeill
**University:** Monash University
**Partners:** Flinders University, Macquarie University, National Renewable Energy Laboratory (NREL)
**ARENA Funding:** $840,000

Professor Christopher McNeill and his group aim to investigate the genesis of poor photochemical stability in organic solar cells and explore materials that are robust and yield better performance. Their focus is to develop processes that are scalable and compatible with industrial methods.

Polymer cells are attractive in portable power electronics or building integrated photovoltaic (BIPV) applications due to their low weight, easy fabrication process and being colorful, flexible and transparent. However, their commercialisation is bottlenecked by their lower cell efficiencies and poor stability.

Blade-coating which can be extended to industrial coating methods owing to its coating and drying conditions being similar to industrial processes, was employed by the group. By using blade-coating technique, the group produced promising data (6.7 per cent efficiency) by conscientiously optimising several process parameters. In Fig. 9, the larger area polymer solar cells on the right were fabricated using blade-coating which exhibited similar efficiencies as that exhibited by laboratory methods for small area deposition. These results are promising and highlight the robust nature of polymer blend which can be used for large scale manufacturing of polymer solar cells.

Another interesting outcome of this research is the "time-resolved microwave conductivity" that uses fast laser pulses along with microwaves to check the capability of a polymer without going through the longer process of making a complete solar cell device, thereby significantly saving time in the development cycle.

In the next half of the project, Prof. McNeil plans to develop and test new materials, assess thermal stability and producing large area (> 1 $cm^2$) cells and certify their efficiency.

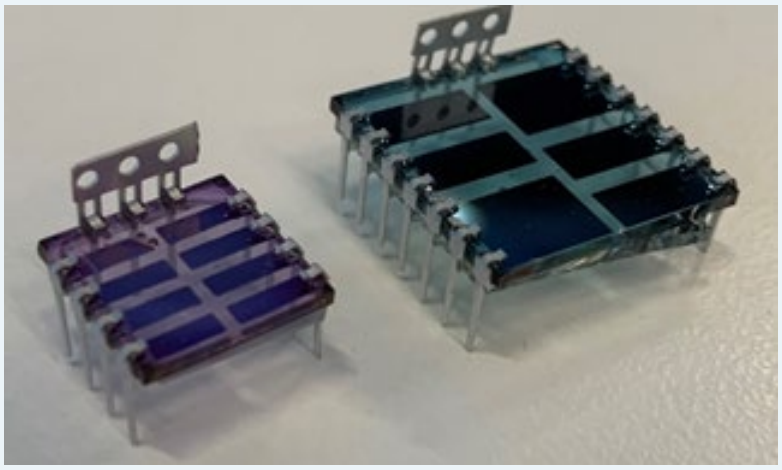

**Figure 9: Images of polymer solar cells. On the left, the geometry comprises of 12 mm by 12 mm substrate, and on the right is their new 19 mm by 19 mm substrate geometry.**[10]

10 "Bringing all-polymer solar cells closer to commercialization ..." 28 Aug. 2019, https://arena.gov.au/assets/2018/05/bringing-all-polymer-solar-cells-closer-to-commercialization.pdf.

b. **Project Title:** Development of Stable Electrodes for Perovskite Solar Cells
**ARENA ID:** 2017/RND019
**Lead Researcher:** Professor Kylie Catchpole
**University:** The Australian National University
**Partners:** Monash University
**ARENA Funding:** $936,732

Professor Kylie Catchpole and her team aim to improve the commercial potential prospects of perovskite solar cells by using electrodes which are cost effective while not affecting the efficiency and stability of the cell adversely.

They are investigating two electrodes: (1) a novel metal stack comprising of a barrier layer (bismuth) and a thick good conductor material such as silver and (2) a carbon electrode. With the metal stack, the team demonstrated 19 per cent efficiency in comparison to the existing 21 per cent efficient perovskite cell comprising of the expensive gold contacts. The cell with the metal stack also demonstrated excellent thermal stability. Early results with the carbon electrode looked promising as well. See their recent report on lessons learnt, here.

Professor Catchpole plans to further test the stability of the solar cell with these new electrodes and investigate the effect of modifications to the electrode structure on cell stability.

c. **Project Title:** Manufacturing of Printed Perovskite PV Modules
**ARENA ID:** 2017/RND012
**Lead Researcher:** Dr. Doojin Vak
**University:** Commonwealth Scientific and Industrial Research Organisation (CSIRO)
**Partners:** Monash University, University of New South WalesWales, University of Cambridge
**ARENA Funding:** $3,310,248

Dr. Doojin Vak's team aims to investigate new materials and new deposition techniques that will impart stability and high performance to perovskite based solar cells while being compatible with the Australian manufacturing sector.

The challenges associated with the lab-scale high efficiency; perovskite technology also includes the viability of low cost manufacturing techniques to deposit high quality perovskite films.

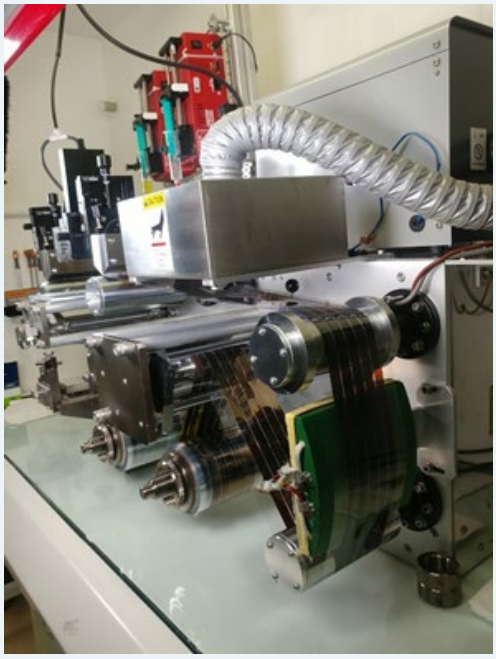

**Figure 10: Roll-to-roll fabrication of flexible perovskite PV module.**[11]

11 "Manufacturing of Printed Perovskite PV Modules – Australian ..." 4 Sep. 2019, https://arena.gov.au/knowledge-bank/manufacturing-of-printed-perovskite-pv-modules/.

The group at CSIRO has demonstrated nine per cent efficiency for (10 cm x 10 cm) perovskite module which was fabricated by roll-to-roll coating technique. To date, the roll-to-roll fabrication of perovskite PV has been reported by only four research groups — Solliance, a cross-border Dutch-Flemish-German thin-film photovoltaics research initiative with a large industry network, the National Renewable Energy Laboratory (NREL) in the US, VTT in Finland and Dr. Vak's team at CSIRO. The project team also developed new materials which yielded 17.8 per cent efficiency for a lab scale cell. With a new conducting paste, the team fabricated 8.2 per cent efficiency on a fully printed flexible cell. This offers low-cost manufacturing by conventional commercial printers. The key knowledge gap addressed in this project is the correlation between environmental conditions (especially humidity), composition of the precursors and the processing/deposition parameters which is critical for adoption by industries. Fig. 10 shows the equipment printing flexible perovskite solar cells.

In the next stage of the project, Dr. Vak plans to combine all the above mentioned activities in parallel to create pathway for flexible PV market.

## 4. New end use application

a. **Project Title:** Developing a New Type of High Efficiency Building Integrated PV Cell
**ARENA ID:** 2017/RND013
**Lead Researcher:** Associate Professor Jacek Jasieniak
**University:** Monash University
**Partners:** Commonwealth Scientific and Industrial Research Organisation (CSIRO), CSR Viridian
**ARENA Funding:** $744,661

Associate Professor Jacek Jasieniak and his team aim to harness the unique properties of the perovskites to integrate them into building windows.

Building integrated photovoltaics at a reasonable price point needs to be transparent without compromising on efficiency and stability. To ensure that the solar cells are transparent and are stable for a longer period of time under ambient conditions, researchers are required to optimise photo absorbing material thickness, structure and material of contact electrodes and charge transporting materials.

Professor Jasieniak's team was successful in developing semi-transparent perovskite solar cells (see Fig. 11) with optimal efficiency and improved stability by using a hole transporting layer named N4,N4'-di (naphthalen-1-yl)-N4,N4'-bis (4-vinylphenyl) biphenyl-4,4'-diamine (VNPB) (used in organic light emitting diode technology). These cells had 10 per cent of average visible transmittance and efficiency of 15 per cent.

The researchers are also collaborating with CSR Viridian to test their research outcomes in real-world applications by integrating their solar cell device into one of their commercial partner's window framing systems.


**Figure 11: Semi-transparent perovskite solar cell with a Monash University and CSIRO backdrop.**[12]
**(Source: Jae Choul Yu)**

12 "Developing a New Type of High Efficiency Building Integrated ..." 4 Sep. 2019, https://arena.gov.au/knowledge-bank/developing-a-new-type-of-high-efficiency-building-integrated-pv-cell/.

## CONCLUSION

The researchers are halfway through their three-year projects and already achieving world leading and ground-breaking research outcomes. The researchers are continuing their efforts to address key challenges of the PV industry to maintain Australia's leading position in the sector.

The primary factor reducing the levelised cost of energy for PV modules is through improvements in cell efficiency, meaning the outcomes of these projects are of high value to the sector. Researchers demonstrated novel techniques in identifying defects, rectifying them, and using different materials and architectures to boost cell performance at a commercial scale. Tailoring the solar cell properties to match its application such as semi-transparent perovskite solar cells for BIPV is also a primary objective of one of the ARENA funded projects. Close collaboration between universities and industry facilitated the opportunity to identify problems at the commercial manufacturing scale which lead to targeted research activities for real world applications.

These early results are innovative and promising. Through the application of their expertise in Si technology, Australian researchers continue to make ground-breaking impacts, not only in Si, but in other PV technologies such as perovskite, polymer or III-V semiconductor based PV.

## APPENDIX: A

### Table A: Summary of projects funded in round three of R&D

| GMSID: 2017/RND | Project Title | Lead Researcher | Organisation | ARENA funding ($) | Technology | Link to report |
|---|---|---|---|---|---|---|
| 006 | Development of Beyond 20% Efficiency Kesterite (CZTSSe) Solar Cells: win the PV race with sustainable low-cost, low-toxic and stable materials. | Assoc. Prof. Xiaojing Hao | University of New South Wales | 1,331,098 | Kesterite | Not yet available |
| 014 | Bringing All-Polymer Solar Cells Closer to Commercialization | Prof. Christopher McNeill | Monash University | 840,000 | Organic | Link |
| 012 | Manufacturing of Printed Perovskite PV Modules | Dr. Doojin Vak | Commonwealth Scientific and Industrial Research Organisation (CSIRO) | 3,310,248 | Perovskite | Link |
| 013 | Developing a New Type of High Efficiency Building Integrated PV Cell | Assoc. Prof. Jacek Jasieniak | Monash University | 744,661 | Perovskite | Link |
| 019 | Development of Stable Electrodes for Perovskite Solar Cells | Prof. Kylie Catchpole | The Australian National University | 936,732 | Perovskites | Link |
| 001 | Accelerating industrial solar cells efficiency by development of plasma-enhanced chemical vapour deposition (PECVD) - based metal oxides | Dr. Ziv Hameiri | University of New South Wales | 503,389 | Si | Link |
| 002 | Metallised Encapsulant for Si PV Modules: A Path to Reduced LCOE for PV | Assoc. Prof. Alison Lennon | University of New South Wales | 1,160,000 | Si | Link |
| 003 | Improving World-Record Commercial High-Efficiency n-type Solar Cells through Recombination Analysis and Innovative Passivation | Prof. Chee Mun Chong | University of New South Wales | 1,785,000 | Si | Link |
| 005 | Hydrogenated and Hybrid Heterojunction p-type Si PV Cells | Dr. Brett Hallam | University of New South Wales | 1,735,000 | Si | Link |
| 007 | Advanced high-efficiency Si solar cells employing innovative atomic scale engineered surface and contact passivation layers | Assoc. Prof. Bram Hoex | University of New South Wales | 2,019,456 | Si | Link |
| 009 | Integrating industrial black Si with high efficiency multicrystalline solar cells | Dr. Malcolm Abbott | University of New South Wales | 500,000 | Si | Link |
| 010 | Development of novel hydrogen trapping techniques for breakthrough Si casting and wafering technologies | Dr. Catherine Chan and Dr. Alison Ciesla | University of New South Wales | 1,968,000 | Si | Link |
| 016 | Advanced Si Solar Cells by DESIJN (Deposited Si Junctions) | Prof. Daniel Macdonald | The Australian National University | 1,116,142 | Si | Link |
| 017 | Driving Increased Efficiency and Reliability in Si Photovoltaics - from ingots to modules | Prof. Daniel Macdonald | The Australian National University | 2,399,392 | Si | Link |
| 015 | Next Generation Industrial Bifacial Si Solar Cells | Dr. Kean Chern Fong | The Australian National University | 1,977,845 | Si (Bifacial) | Not yet available |
| 004 | Hydrogenated bifacial PERL Si PV Cells with laser doping and plated contacts | Prof. Chee Mun Chong | University of New South Wales | 1,100,000 | Si (Bifacial) | Link |
| 008 | Next Generation Si sub-cells for high efficiency III-V/Si multi-junction solar cells | Assoc. Prof. Stephen Bremner | University of New South Wales | 1,144,628 | Tandem (III-V/Si) | Link |
| 020 | Tandem PV Micro Concentrator | Prof. Andrew Blakers | The Australian National University | 788,515 | Tandem (III-V/Si) | Link |
| 018 | Monolithic perovskite – Si Tandem Cells: Towards Commercial Reality | Prof. Kylie Catchpole | The Australian National University | 672,841 | Tandem (perovskite/Si) | Link |
| 011 | Efficient Adamantine Thin-Film on Si Tandem Cells: The Next Step in Commercial Cell Evolution | Prof. Martin Green | University of New South Wales | 3,184,166 | Tandem (Thin film adamantine/Si) | Not yet available |

## TECHNICAL GLOSSARY

### Atomic layer deposition (ALD)[13]

Atomic layer deposition enables uniform, conformal and pin free thin film formation. The deposition occurs when gaseous chemical precursors are exposed to a treated surface in a series of pulses. In each pulse, the precursor molecule occupies the reactive sites on the surface thereby forming an atomic layer and the reaction stops once all the reactive sites are occupied. The excess precursor is then removed from the chamber and the surface of the first monolayer of film is then reactivated by exposing the surface to different precursor. Therefore, the thickness and composition of the film can be controlled at the atomic level by repetitive exposures of precursors.

### Black Si

Black Si describes a variety of texturing techniques that reduce the reflection losses at the front side of a solar cell, in some cases to zero. Though the less aggressive (low aspect ratio) form of black Si has been implemented into production lines, it does not adequately capture the efficiency entitlements provided by ultra-low reflectance black Si. One example of more aggressive black Si is textured Si having a morphology in the form of very thin upright needles. This type of texturing makes the Si less reflective with a higher absorption coefficient of the visible and infrared light.

### Blade-coating

Blade-coating is a technique that uses a blade (such as a glass slide, Si wafer or knife edge) to coat a layer of solution across a substrate. This technique enables deposition of thin films of thickness in the micrometer range. By tuning the viscosity of the solution, the thickness of the deposited film can be controlled.

### Characteristics of solar cells

The efficiency of a solar cell is the ratio of the output power to the incident simulated solar light (influx of photons) under standard testing conditions. The higher the efficiency, the better the economies associated with solar modules. The theoretical efficiencies are governed by Shockley Queisser limit[14] and several factors determine the practical efficiencies achieved. These factors include quality and band gap of the photoactive layer, chemical stability of the cell, heating of the solar cell when in operation and degradation of the photoactive layer due to ambient conditions.

Efficiency of a solar cell in real world conditions is the product of fill factor (FF), open circuit voltage (Voc) and short-circuit current (Jsc) divided by 100. The FF is an indicator of series resistance and shunt resistance in a solar cell. A "good" FF manifests a "good" solar cell with low series resistance or high shunt resistance. In general, crystalline Si (c-Si) PV has a higher FF than thin film PV and the fall at high light levels will be slower as the series resistance in c-Si tends to be lower than thin films. Shunt resistance results from manufacturing defects and causes substantial power losses. The reduced efficiency in solar cells with low shunt resistance is due to losses in current and reduction in voltage. There are several approaches to enhance the efficiency, stability and reliability of these solar cells which are discussed further in this report.

### Dicing

Dicing is the process of forming grooves by using a dicing saw with a 27 μm-wide blade. Parameters such as spindle speed and cutting speed can be varied in order to obtain the narrowest possible grooves with minimal tapering and chipping.

13 "A brief review of atomic layer deposition: from ... – ScienceDirect.com." https://www.sciencedirect.com/science/article/pii/S1369702114001436.

14 "Detailed Balance Limit of Efficiency of pn Junction Solar Cells – ULB." http://metronu.ulb.ac.be/npauly/art_2014_2015/shockley_1961.pdf.

### Inductively Coupled Plasma Reactive Ion Etching (ICP/RIE)

ICP/RIE is a process of rapid etching of a wide range of materials by using a chemically reactive plasma under low pressure conditions, potentially combined with ion-induced etching. The etching conditions can be controlled by tuning the process parameters such as RF power, pressure, and gas flows. An example of grooves etched using ICP/RIE is shown in Fig. 12. The etch of highly vertical grooves demonstrates good selectivity for the GaAs over the masking material (10 µm-thick $SiO_2$). This is a promising method for the creation of narrow, high quality Sliver grooves in the wafers.

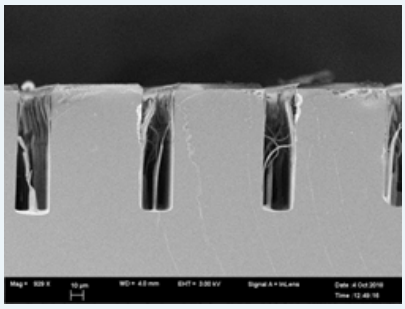

**Figure 12: Grooves etched using ICP/RIE in GaAs. Grooves are 100 µm deep and 23 µm wide.**[15]

### Doping

Doping is the process of adding impurities to semiconductors to change their bandgap and thus their properties such as conductivity. Si is doped with group 5 elements (e.g. phosphorus) to make it n-type (rich in electrons) and with group 3 (e.g. boron) to make it p-type (rich in holes).

### Gettering

Gettering is a process of sucking out as many metallic impurities as possible from the Si. Then hydrogenation is applied to neutralise the residual defects.

### Hydrogenation

Hydrogenation is the process of changing the charge of hydrogen atoms to enable them to move 100,000 times more easily within the Si to find defects and 'passivate' them. This technique is highly valuable in low grade or amorphous Si wafers enabling the production of high quality, high stability, high efficiency and affordable solar cells/modules.

### Hysteresis

Hysteresis is observed when the photocurrent density – voltage (J-V) characteristics of the solar cells are measured by scanning voltage on the solar cell terminal. When the J-V curves of a solar cell do not replicate for a forward scan, which is made from lower to higher voltages and for a reverse scan (from higher to lower voltages), then the hysteresis is more pronounced. The degree of hysteresis is also dependent on the voltage scan rate, voltage scan range, voltage conditioning history, device architecture and composition of the solar cell components. Hysteresis affects the efficiency and stability of the solar cells. Hysteresis in perovskites is more pronounced than in any other PV technology. Researchers debate that the hysteresis in perovskite cells could be due to ion migration or due to electronic defects and the topic is still under investigation.[16]

### Metallised encapsulants

Metallised encapsulants are module encapsulant materials where the conductors are directly electroformed in laser-structured encapsulant surfaces.

15 "Tandem PV Micro Concentrator Project results and lessons ..." 12 Aug. 2019, https://arena.gov.au/assets/2018/01/tandem-pv-micro-concentrator.pdf.

16 "Perovskite solar cells: short lifetime and hysteresis behaviour of ..." 5 Jul. 2019, https://link.springer.com/article/10.1007/s10854-019-01759-2.

### Multi-junction/tandem solar cells

Multi-junction solar cells also known as tandem cells, are comprised of multiple layers of single junction solar cells. The largest bandgap semiconductor material is positioned on the top to absorb high energy photons and allow the low energy photons to pass through which are absorbed through the subsequent lower band gap layers. This architecture is conducive for achieving a high efficiency surpassing the Shockley Queisser limit of an individual solar cell. Currently, the multi-junction solar cells claim the highest efficiencies in the world of about 39.2 per cent without a concentrator.[17]

Semiconductor materials of III-V groups are attractive owing to their direct band gaps and easy engineering of their band gaps for maximum absorption of photons. They are also less degraded by heat and high energy waves. Perovskites whose bandgap can be tuned by varying their composition are also of interest as top cell on Si sub cell. The record efficiency of a monolithic perovskite/Si tandem cell is 28 per cent.[8]

### Passivation

Surface passivation implies rendering the surface resistant or inactive to a reaction (e.g. charge recombination).

### Passivated Emitter and Rear Contact (PERC)

Passivated Emitter and Rear Cell or Passivated Emitter and Rear Contact (PERC) comprises of a dielectric passivation layer on the rear of Si solar cell. The dielectric layer increases the cell efficiency by reducing electron recombination, increasing light pathway by reflecting the unabsorbed light and maintaining the temperature of the cell by reflecting light which causes heat when absorbed.

### Perovskites

Perovskites (name derived from its crystal structure) and organic solar cells offer low cost options for high efficiency solar cells, but their development is bottlenecked by their poor stability and hysteresis. Perovskites generally have ABX3 crystal structure with A being a cation (mainly organic), B being metal (lead or tin) and X being halide (chloride, bromide, iodide). In perovskite solar cells, the perovskite material and in organic solar cell the organic polymer are the light absorbing materials respectively.

### Sputtering

Sputtering is a thin film deposition process by which the target material is bombarded with high energy particles of plasma in a vacuum chamber. Plasma is created by ionizing the inert gas (e.g. argon or xenon) molecules. Ionized gas is gas to which sufficient energy is provided to free electrons from atoms or molecules and to allow both species, ions and electrons to coexist. The target particles then escape due to transfer of momentum, travel and deposit on the substrate to form a thin film. Sputter yield, which is the average number of atoms ejected from the target per incident ion depends on several factors. The angle of collision, the energy of the bombarding particles, mass of the target and the bombarding particles and the surface binding energy of the target are important factors.

17 "Best Research-Cell Efficiency Chart – NREL." 2 Aug. 2019, https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.20190802.pdf.