Australian Government
Australian Renewable Energy Agency

ARENA

Overcoming the Fundamental Performance Limitations of Commercial Solar Cells

Final report: results and lessons learned

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Executive Summary

The ARENA 1-082 proposal, formulated in 2009, ambitiously targeted the development of a new solar cell that would overcome the fundamental performance limitations of most commercial solar cells, while simultaneously aiming to set new performance records for commercial grade p-type silicon wafers (the types most commonly used) at both cell and module level. These aims were successfully achieved in conjunction with industry partner Suntech This project has accordingly been credited with the achievement of the world's first multicrystalline silicon module of over 16% efficiency and then subsequently the first to exceed 17% efficiency, with the latest milestone achieved in early 2015 now successfully reaching 18% efficiency. To emphasize the impact and importance of these achievements, at the time of project commencement, the world record module efficiency was only 15.5% and had been held unchallenged for 15 years by Sandia National Laboratories in the USA.

At cell level, the ARENA 1-082 project targeted the achievement of the long-term industry target, set by international experts, of achieving the world's first 20% efficient p-type CZ cell fabricated using commercial equipment. This was achieved in late 2011, almost ten years ahead of the timing predicted by the international experts. The above cell and module technologies were successfully transferred to industry and the corresponding manufacturing environment. This was demonstrated by the fact that all the record performance cells and modules were either manufactured or duplicated by the industry partner using their own facilities.

Importantly, the new developments were also achieved while being accompanied by large cost reductions with the new technology being shown to successfully surpass the industry's long-term cost target of $1/Wp at module level, a cost that would allow photovoltaics to compete with fossil fuel generated electricity at retail level in most locations around the world.

Project Overview

Project summary

From the outset, this project hoped to develop new areas of solar cell technology that when used in conjunction with each other would overcome the fundamental limitations of conventional solar cell technology for standard p-type commercial grade silicon wafers. In so doing, it has been the intention to set new performance records with such silicon wafers, both at cell level and with encapsulated modules. In parallel, aims for the technological advances also included developing ways to significantly bring down the costs of manufacturing to help photovoltaics reach grid parity where the cost of electricity from photovoltaics can directly compete with fossil fuel generated electricity, at least at retail level. All of these hopes and aims have been successfully achieved.

The main areas of focus include:

1. Improvements to the front surface of the solar cell
2. Improvements to the rear surface of the solar cell
3. Improvements of bulk minority carrier lifetimes
4. Design, development, construction and evaluation of required manufacturing tools

1. Improvements to the front surface of the solar cell

The achievements of the first year of the project were well ahead of those ever achieved previously world-wide for multicrystalline silicon pv modules, necessitating not only significant improvements in the device technology to minimise losses, but also the establishment of a new world-record module performance. As indicated in the grant application, at the time of writing the proposal, the highest efficiency ever achieved for a multicrystalline silicon module was 15.5%. This had been achieved by Sandia National Laboratories more than a decade earlier and was achieved as an aperture area measurement on a hand-crafted module fabricated from small area cells made by hand in the laboratory. In comparison, in achieving the independently confirmed new world record of 16% efficiency, UNSW and industry partner Suntech were able to achieve these results using full-sized commercial cells fabricated on a new high throughput commercial production line. The independently confirmed measurements corresponding to this result were provided in the corresponding milestone report.

Improvements to the front surface were achieved by moving from the conventional screen-printed (SP) solar cell structure shown in Figure 1 (over 80% of product world-wide uses this structure) to the improved solar cell structure shown in Figure 2.

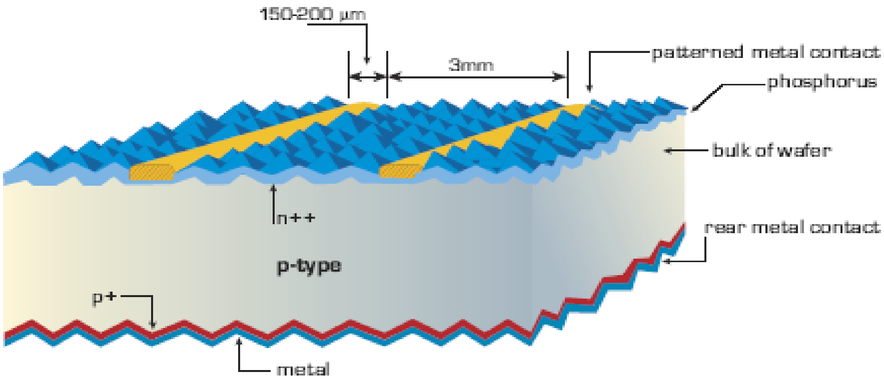


Figure 1: Conventional screen-printed solar cell

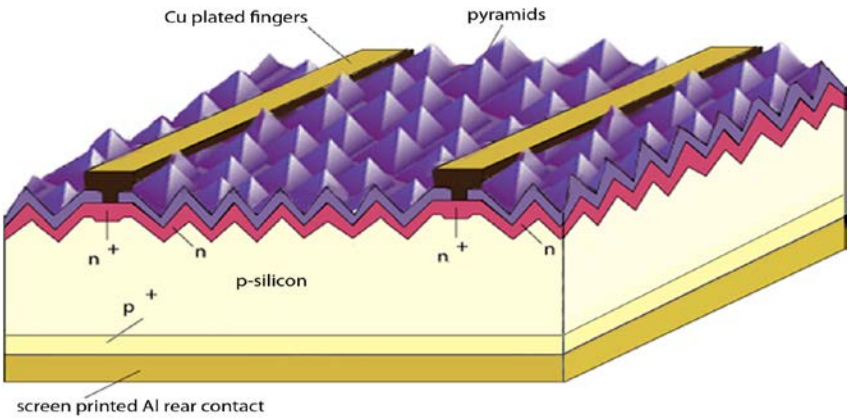


Figure 2: Cross-section of the Pluto cell at the commencement of the ASI 1-082 project, used for implementation of technology improvements.

Table 1 shows the improvement in performance gained from the cell design of Figure 2 compared to that of Figure 1. Cells of both types were fabricated using the same wafers at the same time on juxtaposed production lines.

Table 1: Direct comparison of a standard SP cell and Pluto solar cell

	Jsc mA/cm^2	Voc mV	FF %	Efficiency %
Standard Screen-printed cell	33.4	614	78.0	16.00
17% Efficient Pluto cell	35.4	625	77.3	17.09

At the time of writing the grant application for this project in mid-2009, the highest efficiency ever achieved for a multicrystalline silicon module was 15.5%. To achieve the 16% efficiency milestone and beat the record held by Sandia National Laboratories, a 72-cell module using cells of the type and efficiency indicated in Table 1 was fabricated by Suntech-Power using their standard commercial tools. The performance of the module fabricated during this project was independently verified by the Fraunhoffer Institute in Germany to be 16.5%.

Through the project, ongoing improvements to the Pluto cell depicted in Figure 2 were made, particularly in the areas of improved dielectric patterning, light induced plating (LIP) for the front metal contact and hydrogenation to improve the wafer quality.   These improvements resulted in improved cell performance as outlined in Table 2.

Table 2: Direct comparison of a typical Pluto solar cell from early in the 1-082 project and a subsequent higher performance one incorporating the improvements from the project in plating, dielectric patterning and hydrogen passivation

	Jsc mA/cm^2	Voc mV	FF %	Efficiency %
Standard Screen-printed cell	33.4	614	78.0	16.00
17% Efficient Pluto cell	35.4	625	77.3	17.09
18% Efficient Pluto cell	36.0	631	79.3	18.03

A new Pluto module was fabricated by Suntech using 72 cells typical of the 18% efficient cells from Table 3. In combination, these produced a large multicrystalline silicon module with independently confirmed record aperture area efficiency of 17.0%, which was used as partial fulfilment of milestone 2 for the project.

2. Improvements to the rear surface of the solar cell

Following the improvements in cell design and processing that lead to the achievement of 18-18.5% efficiency multi cells, the front surface of the Pluto cells was considered near optimal. Subsequent work was therefore able to focus on improving the rear surface design to that shown in the schematic of Figure 3. These improvements with rear contacting and rear surface passivation were shown through modelling and device analysis to have the potential to take commercial multi-cell efficiencies to record levels in the 19-20% range and therefore make it feasible to ultimately achieve multi module efficiencies as high as 18% to satisfy future milestone requirements..

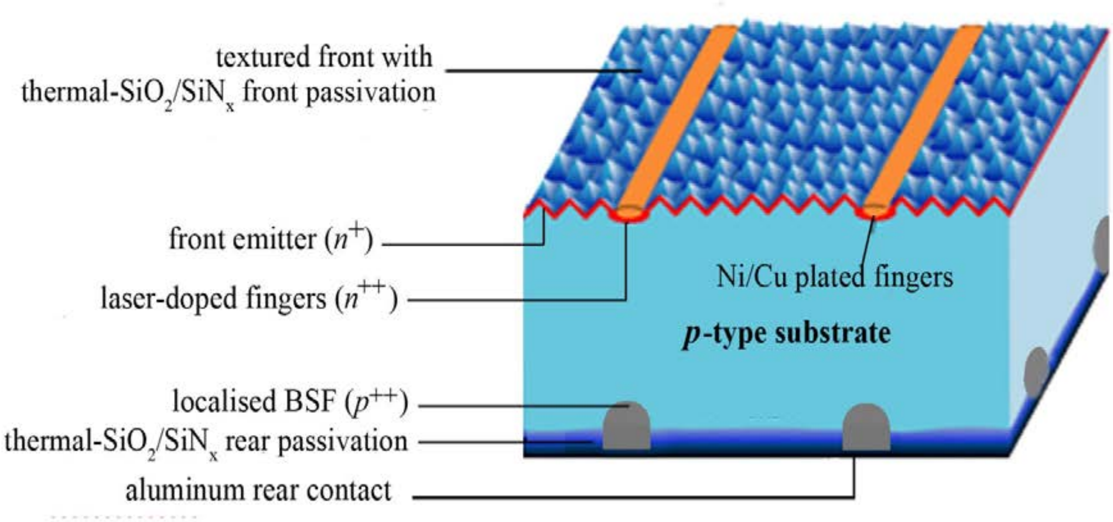


Figure 3: Schematic of the new generation of Pluto cells incorporating rear surface passivation and localised low area metal contacts. These improvements are believed necessary to take multi cell efficiencies to 19-20% range.

This same rear surface passivation approach was incorporated into the monocrystalline silicon CZ wafers with the aim of achieving the world's first 20% efficient solar cell using these wafers. This has been achieved with the corresponding world-record being claimed by UNSW/Suntech in a press-release and journal publication. It is likely that this result along with the commercial success of the Pluto technology, lead to Professors Wenham and Green (CI's of this project) in conjunction with Suntech receiving the 2012 Australian Collaborative Innovation Award from the Premier of South Australia.

Figure 4 depicts the evolution of Pluto technology during the research and development work associated with this project. The next generation Pluto technology developed during the project underwent two stages of development in device structure. The first stage employed the design concept of Passivated Emitter and Rear Cell (PERC), whereby the localized rear openings were left undoped prior to rear surface metallization (Figure 4b). In the second stage, a heavy p^{++} diffusion was introduced into the rear silicon openings to produce a localized BSF, similar to that of PERL cell structure (Figure 4c).

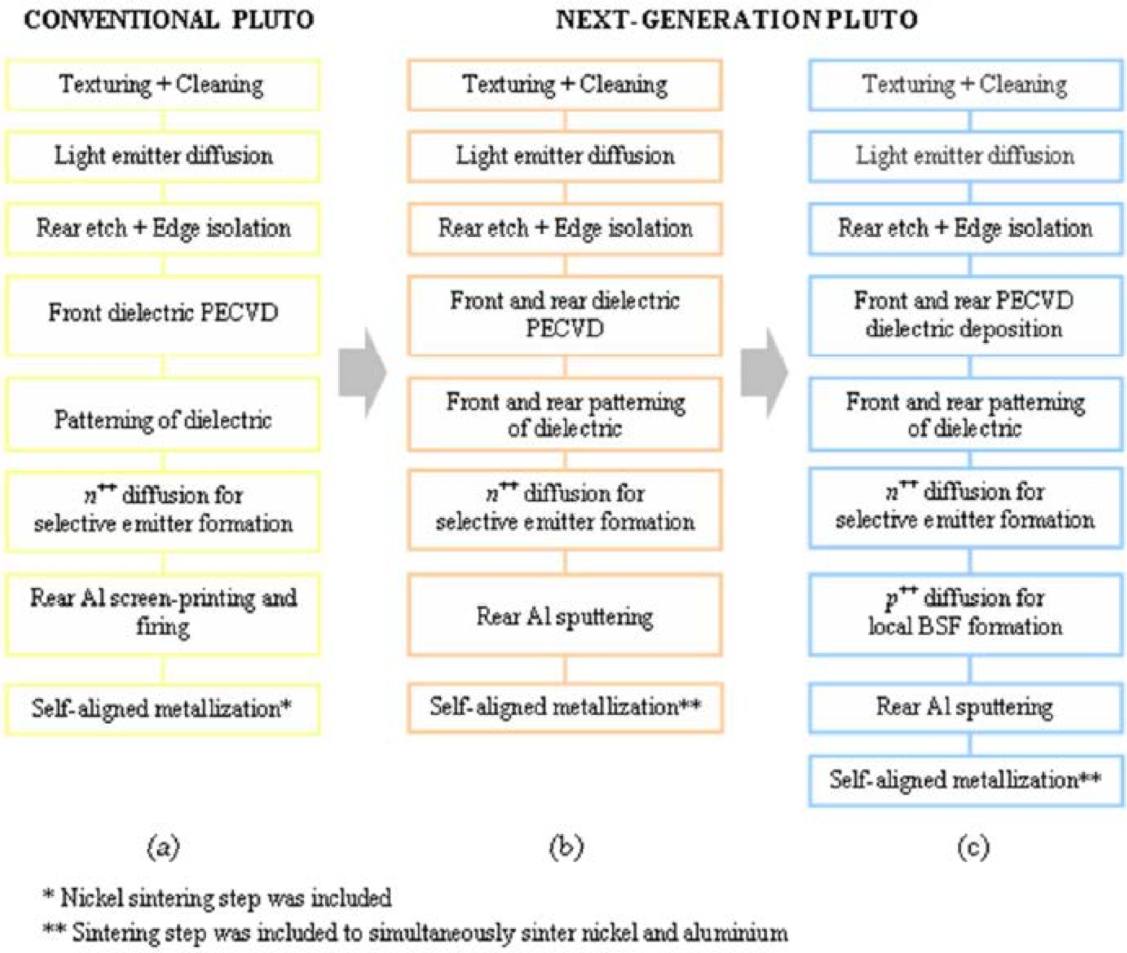


Figure 4. Process flow diagram for (a) first-generation of Pluto cell; (b) next-generation Pluto cell based on PERC rear surface design (Pluto-PERC); (c) next-generation Pluto cell based on PERL rear surface design (Pluto-PERL).

The Pluto cells in this work utilised 155 cm^2 *p*-type commercial-grade CZ wafers, with bulk resistivity of 1-3 Ω.cm and wafer thickness of 180 µm after texturing. As seen in Table 3, the next-generation Pluto, despite its early stage of development, is already producing average cell efficiencies of more than 1% absolute above those achieved by the conventional Pluto technology. The best conventional Pluto cell was independently confirmed to be 19.6% in efficiency, which at the time represented a record efficiency for standard commercial p-type wafers. Since then a new record of 19.7% was independently confirmed by the Solar Energy Research Institute of Singapore (SERIS) for a Pluto cell using the Pluto-PERC cell structure and the same commercial p-type wafers. More recently and also as part of this project, an efficiency of 20.3% has been independently confirmed by SERIS on similar commercial-grade wafers, this time using the Pluto-PERL structure. Again this represented a world record efficiency using such commercial wafers.

Table 3: Light J-V and average Suns-Voc data of next generation Pluto cells. Data for conventional Pluto cells was extracted from other published material for comparison

	Light J-V measurement				**Suns-V_{oc} measurement**			
	V_{oc} (mV)	**J_{sc} (mA/cm^2)**	**FF (%)**	**Eff (%)**	**pFF (%)**	***n* at 1-Sun**	**J_{01} (pA/cm^2)**	**J_{02} (nA/cm^2)**
Pluto [11,14]								
Best cell*	**636**	**38.6**	**79.7**	**19.6**	**-**	**-**	**-**	**-**
Average	632	38.2	78.8	19.0	82.8	1.02	0.72	8.25
Pluto-PERC								
Best cell*	**674**	**39.3**	**73.9**	**19.7**	-	-	-	-
Highest V_{oc}	683	39.3	72.1	19.4	-	-	-	-
Average	674	39.0	73.6	19.3	81.1	1.12	0.148	24.0
Pluto-PERL								
Best cell*	**665**	**40.9**	**74.4**	**20.3**	**-**	**-**	**-**	**-**
Highest V_{oc}	668	40.5	73.3	19.9	-	-	-	-
Average	662	40.7	74.3	20.2	83.3	1.06	0.151	21.2

3. Improvement of bulk minority carrier lifetimes

The efficiency boost demonstrated by the next-generation Pluto is primarily attributed to the improved rear surface design that leads to up to 6% higher V_{oc} and J_{sc}. As listed in Table 4, the next-generation Pluto cells demonstrated a significant reduction in rear surface recombination velocity (SRV), approximately by four orders of magnitude, which indicates the effectiveness of the rear dielectric layer in passivating the *p*-type surface while restricting the metal/silicon interface area to less than 2%. The reduction in rear SRV is also accompanied by reduced bulk recombination to help maximise the voltage increase. The next-generation Pluto cells were shown to exhibit improved bulk lifetime over conventional Pluto cells. As both conventional Pluto and next-generation Pluto use similar quality, resistivity and thickness of CZ wafers, the significant increase in bulk lifetime is made possible by improved hydrogenation of the bulk materials with low-temperature metallization processes. Of key importance in achieving these improved bulk lifetimes is the use of a PECVD hydrogenation process at 400^{o}C that capitalises on charge-state control of the hydrogen atoms (in accordance with the patent applied for as part of this project) and the subsequent avoidance of temperatures above 400^{o}C when forming the metal contacts. In this process, it is believed that the hydrogen atoms bond to defects and contaminants within the silicon, nullifying their negative impact on cell performance that would otherwise result. Attempts to introduce similar hydrogenation processes into the screen-printed cells of Table 2 were unsuccessful with bulk minority carrier lifetimes falling by more than an order of magnitude from almost 1ms to less than 100 µs during the firing of the screen-printed contacts. This highlights the potential importance of the new hydrogen passivation techniques, but also the challenges associated with incorporating the new techniques into some solar cell technologies.

In addition to rear surface and bulk recombination, other sources of recombination such as the n^{+} emitter and front SRV were investigated and improved upon. All of the abovementioned improvements resulted in a total of 30 – 40 mV increase in V_{oc}, with a large proportion of the increase being attributed to improved rear surface passivation and bulk lifetime. Device V_{oc}'s as high as 683 mV (Table 3) have been demonstrated, record values for these commercial grade wafers.

Table 4. Simulated light J-V data and relevant device parameters for Pluto cells in Figure 3, based on fitting to the measured IQE curve and light J-V data.

	Pluto	Pluto-PERC	Pluto-PERL
Device parameters			
Emitter sheet resistance (Ω/squ)	100	140	140
Bulk lifetime (microsec)	100	500	500
Front SRV (cm/s)	1000	1000	1000
Rear SRV (cm/s)	1×10^{6}	180	100
Rear series resistance (Ω.cm^2)	1×10^{-6}	1.4	1.1
Simulated J-V results			
V_{oc} (mV)	636	670	666
J_{sc} (mA/cm2)	38.6	39.7	40.6
FF (%)	79.8	73.6	74.3
Efficiency (%)	19.6	19.6	20.1

4. Design, development, construction and evaluation of required manufacturing tools

To expedite commercialisation of the new technologies developed in this project, attention has also been given to the design, development, construction and evaluation of additional manufacturing tools needed for the implementation of large-scale manufacturing of the newly developed solar cell technologies. In particular, the lack of commercially available large-scale plating tools has restricted the commercialisation of any cell technologies such as Pluto that require plated contacts.

The International Technology Roadmap for Photovoltaics (ITRPV) produced by an international team of experts, predicts that plated cell metalisation will eventually displace the use of screen-printed contacts. This transition however is expected to take as long as 5-10 years (2014 ITRPV), due in part to this lack of suitable commercial plating tools for large-scale manufacturing. To accelerate Pluto's implementation into large-scale manufacturing, this project included as a milestone, the fabrication, installation and evaluation of plating baths, based on the UNSW developed plating technology, that are suitable for large-scale manufacturing. These baths were designed by Dr Ji, a world expert in plating technology and now an academic at UNSW, and have been constructed in China by the company Kuttler.

Figure 5: Unique metal plating baths using UNSW technology for the plating of solar cell contacts designed by world expert Dr Ji. These have been constructed in China by the company Kuttler and now installed in SIRF at UNSW.

Other project achievements

The final technical achievements of the Project involved taking all the relevant developments of the project, particularly the advanced hydrogenation, the new plating technologies implemented via the new commercial plating baths and the new rear surface passivation approaches with localised metal contacts, and incorporating them into the processing of commercial or solar grade (SG) monocrystalline silicon wafers and multicrystalline silicon wafers. For the former, efficiencies in the range of 20.5-21% were being targeted while for the latter, the aim was to achieve an 18% efficient module. This was seen as an extremely ambitious milestone at the time of writing the grant application given that at that time the long-term industry target set by international experts for such SG p-type mono wafers was only about 20% efficiency while the long-standing world record for such multi modules was only 15.5% and this had not been beaten for well over a decade. Never-the-less, with the help of industry partners Suntech and Sunrise, the respective components of the milestone for both mono and multi p-type wafers were met, culminating in the successful achievement of all project milestones including several new cell and module world records.

Project scope

Explain why you undertook the project.

At the time of proposing this project for funding, typical commercial cell efficiencies were only 16.5-17% with costs of manufactured product being about a factor of five higher than at present. Key challenges of the project were to address the performance limitations of standard cells while trying to make a significant impact in bringing down manufacturing costs such as developing and demonstrating commercially viable approaches for replacing the use of silver with copper and replacing expensive silicon wafers with newer lower cost types without suffering performance loss.

What problems were you trying to solve?

From a technical perspective, at the commencement of this project, the performance limitations of the typical commercial screen-printed (SP) cells that needed to be solved, could be broken down into four main areas. In brief, these related to:

1. the need for SP contacts to evolve into ones capable of much narrower line widths with significantly reduced shading losses and recombination losses from the metal/silicon interface
2. the need for a selective emitter design that could decouple the heavy doping requirements for the metal/silicon interface from the emitter requirements in non-metallised areas through which the light must penetrate
3. the need for greatly improved rear surface passivation and metal contacting
4. the need to improve the silicon wafer quality which was being compromised by the strong push to reduce wafer costs that strongly dominated the cost of making solar cells.

From a cost perspective, at the commencement of this project, the two dominant costs for making typical commercial solar cells that needed to be substantially reduced related to: firstly, the high cost of the silicon wafers; and secondly, the high cost of the silver metallisation for conducting the generated current from the solar cell.

What barrier were you trying to overcome?

A range of technical and cost barriers needed to be overcome. Of particular importance technically were the barriers introduced by the nature of the SP contacts, where the requirement for heavily doped silicon at the interface and the use of narrower lines compromise performance. In particular, for the latter, reliability and performance are compromised due to the challenges in the printing process that cause breaks to occur in metal lines if the width becomes too narrow. The new technology developments aimed at solving these barriers.

Cost barriers primarily focused on the unwillingness of cell manufacturers to use the new lower cost types of silicon wafers in large-scale manufacturing due to concerns relating to stability and performance. The new passivation technology was developed to overcome this barrier.

What knowledge, skills, capability, technical, logistic or commercial advances were you trying to create?

The primary aim was to develop a range of new technologies which when combined, would create a new solar cell technology which could overcome the various performance and cost limitations of existing standard commercial cell technologies while simultaneously addressing the various barriers preventing their widespread use. One aim for this was to give industry partners a commercial advantage over competitors. Achieving such aims required greatly improved understanding of the loss mechanisms associated with standard devices which in turn required the use and development of various analysis and evaluation techniques. Following such improved understanding, solutions could be sought and developed, with corresponding new technology, knowledge, skills, capabilities and patents collectively forming part of a valuable intellectual property portfolio to be made available for technology transfers to industry partners and licensees as well as comprising valuable components in education and training packages developed for wider use such as for use within UNSW’s undergraduate degree in Photovoltaic Engineering.

Outcomes

The highest profile outcomes from the ARENA 1-082 project can be summarised as follows:

1. **Boron doping of Al paste for enhanced Hydrogenation**

   Standard screen-printed (SP) solar cells with aluminium alloyed rear surfaces trap hydrogen poorly within the silicon due to the molten Al/Si eutectic region and metal/silicon interfaces that act as a sink for the hydrogen. To significantly increase the amount of hydrogen trapped within the silicon for passivation purposes, it has been shown in this work that the addition of boron to the Al paste acts to block the hydrogen entering the front surface from escaping at the rear.

   While the potential improvements in hydrogen passivation has been demonstrated for standard SP cells through the addition of boron to the Al paste, significantly more work needs to be carried out for this approach to reach its full potential, particularly in relation to optimizing the B concentration, the paste viscosity and the firing conditions including in particular, the cooling regime.

2. **BSF Optimized Firing**
   This work was carried out in conjunction with the work above, focusing on optimizing the Al doped BSF at the rear of the wafers. These areas of work contributed significantly to the new understanding gained in relation to controlling the charge state of hydrogen atoms when in the silicon and the impact this has on both the mobility and reactivity of the hydrogen. This work has therefore contributed in a major way towards the outcomes of this project and in particular, the development of the advanced hydrogen passivation technology and corresponding intellectual property (IP) that is now the major focus of UNSW research due to the enormous potential it has demonstrated for reducing recombination throughout a silicon wafer and corresponding device.

   The initial developments involving improved Al-doped BSF regions have already been incorporated into the Suntech production lines although only gave on average a disappointing 1% (0.2% absolute in efficiency) performance improvement. Significantly increased efficiencies are expected in the future through the full exploitation of the advanced hydrogenation technology which will take place through the new ARENA funded RND068 project.

3. **Independently confirmed 19.7% Pluto Cells – world record efficiency for p-type silicon!**
   Ongoing development of the Pluto technology has taken place through the 1-082 project, leading to numerous world records for commercial cell efficiencies using p-type wafers for both mono and multi wafers. In addition to the various innovative and patented features of the Pluto cell that have contributed to the record performance levels, the improved BSF performance described above allowed a new world record of 19.7% efficiency to be achieved in early 2011. A corresponding Invited Plenary Session paper based on this work was presented in mid 2011 to give more details on this world-leading technology development. In fact this paper was awarded

the most highly sort after and prestigious position in the entire conference, namely the first technical paper of the conference.

4. **15.5% Multi-module world record – 15 year-old record held by Sandia**

In parallel with developing the Pluto technology for p-type CZ wafers, the technology was developed and adapted to also suit multicrystalline silicon wafers as part of this project. This was seen internationally as a major breakthrough in moving towards high performance low cost commercial wafers due to this being the first time that high performance cell technology had ever been able to be successfully applied to the low cost wafers that have significant thermal constraints compared to counterpart mono wafers. The outcome was that Suntech and UNSW, as part of the 1-082 project, were able to achieve a string of world-record efficiencies at both cell and module level for multicrystalline silicon wafers.

Of particular note was industry partner Suntech breaking the 15-year old world record for multi modules of 15.3%, previously held by Sandia National Laboratories in the USA. In fact, following the achievement of the world-record module efficiency of 16.5%, UNSW and Suntech subsequently broke this several times in succession over the course of this project.

5. **17% Multi-module world record**

Through the focused effort and resourcing through the 1-082 project, rapid ongoing improvement in the multi implementation of Pluto has continued, resulting 12 months later in another world-record module efficiency of 17%. The details are as follows in the following Table.

Table: Fraunhoffer independent measurements for the new 17% efficiency Pluto multicrystalline silicon module fabricated in satisfaction of the ASI 1-082 project milestones. Additional details relating to these measurements by Fraunhofer were provided in earlier Milestone reports.

Fraunhofer ISE

Zusatzinformationen
Additional Information

CalLab PV Modules

Abweichungen zwischen Modul Nenndaten und Messergebnissen
Deviation of module rated values and test results

	Isc [A]	Uoc [V]	Impp [A]	Umpp [V]	Pmax [W]	FF [%]	η [%]
Modul Nenndaten *Rated values*							
Testergebnisse *Test results*	8,58	34,1	8,00	28,3	226,2	77,3	17,0
Differenz *Difference*	-	-	-	-	-	-	-
Abweichung *Deviation*	-%	-%	-%	-%	-%	-%	-%

6. **Advanced Hydrogenation Technology**

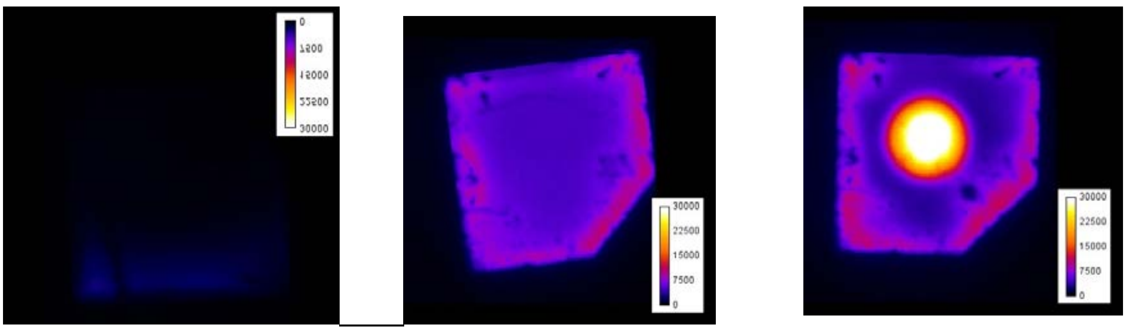
The advanced hydrogen passivation technology developed originally as part of the 1-082 project, and owned by UNSW, has been heralded as one of the major breakthroughs in recent years in silicon photovoltaics. It has been recognized through the awarding of the 2013/14 A F Harvey Engineering Prize, widely regarded as one of the leading Engineering Prizes internationally in any field. A large number of media interviews and articles have been conducted in relation to this technology and the various prizes that have originated as a result.

Importantly, the 1-082 project developed innovative ways for controlling the hydrogen charge state, leading to large and demonstrated improvements in the ability to passivate the silicon and surfaces.   As an example, Figure 6(a) below shows the PL count post silicon nitride deposition on both front and rear surfaces. Figure 6(b) shows the same wafer following the application of standard hydrogenation processes carried out at 700degC. Figure 6(c) again shows the same wafer following localised application of the advanced hydrogen process where localised control of the hydrogen charge states at only 250degC appears to have passivated virtually every defect and contaminant to transform the material into being of similar quality to the highest quality of p-type silicon wafers that are typically more than ten times the price.

Following this important innovation in ARENA 1-082, the new project ARENA RND068 represents the perfect project for the development and integration of this breakthrough into high efficiency cell technology for manufacturing companies.

Figure 6 (below): PL images using the same scale of the same wafer (a) following PECVD deposition (b) following convention hydrogenation at 700degC and (c) following localised application of the advanced hydrogenation at 250degC in the white region

(a) (b) (c)



7. World Record Commercial Cell Efficiency of 20.3%

A new generation of Pluto (Pluto 2) has been developed as part of 1-082. The distinctive difference is rear surface passivation with localized metal contacts. Rear surface dielectrics based on both SiNx and AlOx have been developed, with both demonstrating the potential to facilitate Pluto 2 achieving record open circuit voltages in the vicinity of 700mV, well above the long-term targets predicted as being achievable with p-type wafers by international experts.

In 2011-12, the 1-082 project achieved the world's first 20% efficient commercial solar cell using p-type CZ. Interestingly, until this time, international experts had predicted that 20% efficiency was the upper limit to achievable efficiencies in the long term using p-type CZ as indicated in the International Technology Roadmap for Photovoltaics (ITRPV). However with UNSW and Suntech achieving the new world-record of 20.3% efficiency with Pluto 2, the ITRPV has been revised to raise the long-term target efficiency for p-type CZ to 21.5%, efficiency Pluto 2 should easily surpass in ARENA RND068.

8. Commercial Cell Efficiencies Improved to 20.6% (independently confirmed)

Despite achieving the 20.3% efficient world record described above, significant scope for further optimisation remained in relation to reducing the parasitic resistive losses, particularly the resistive losses associated with the rear localised contacts. Optimisation of this aspect of the cell design allowed efficiencies to be relatively easily increased to the 20.5-21% range as required for the milestone in this project. Independent confirmation by the Fraunhofer Institute of one of the corresponding 20.6% efficient cells is provided in the following Figure 7.

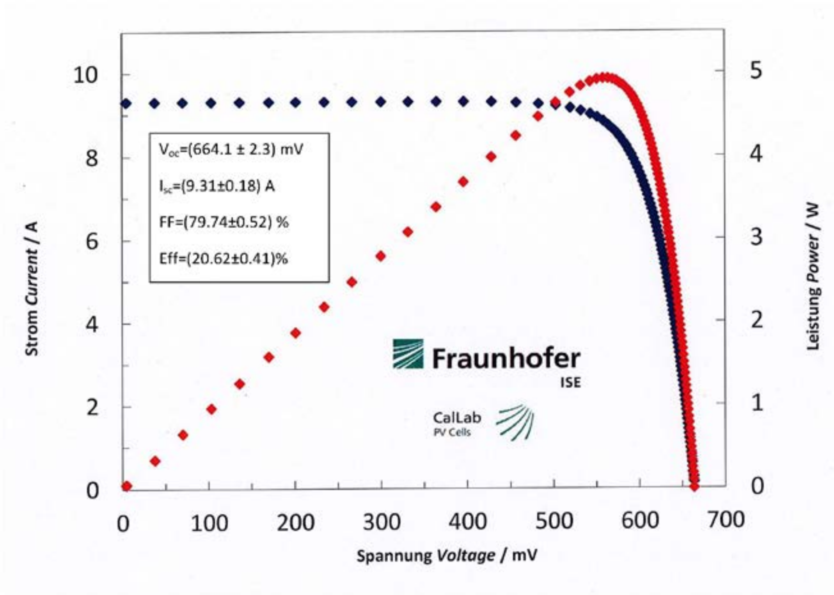


Figure 7: Fraunhoffer independent measurements for the 20.6% efficiency commercial silicon solar cell fabricated in satisfaction of the ARENA 1-082 project milestones

9. 18% Efficiency Multicrystalline Silicon Module

Following the successful adaptation of the Pluto technology for multi-wafers and the subsequent achievement of several module performance world records as listed above, this new generation of Pluto technology with passivated rear surfaces has also been adapted for multi wafers. This has recently led to the achievement of 18% efficiency for a module comprising standard commercial grade multi wafers purchased from TCL in China. The major improvement from the earlier world record 17% efficient module was the addition of the passivated rear surface in conjunction with the use of localised metal contacts. This facilitated the achievement of significantly higher voltages due to reduced recombination at the rear surface plus higher currents, primarily due to improved long wavelength response resulting from the passivated rear surface but also improved optics resulting from the excellent internal rear reflection achieved by the use of the displaced rear metal reflector.

10. International Awards won by UNSW and Industry partner Suntech through 1-082 Achievements

- **UK Energy Institute International Technology Award (2010-11)** for the importance and success of the Pluto technology

- **MIT Technology Review (USA),** listed Suntech as one of the world's Top 50 Technology Companies internationally in 2011

- **Fast Company** named Suntech as one of China's Top 10 most innovative companies in 2011.

- **Australian Collaborative Innovation Award (2012)** for the innovativeness and success of the technology development between UNSW and Suntech in the 1-082 project.

- **PV Tech** awarded Suntech's high efficiency photovoltaic module as the most innovative product of 2011

- **A F Harvey Engineering Prize (2013/14),** awarded by the UK Institution of Engineering and Technology and widely regarded as one of the top international prizes in all fields of engineering

Intellectual Property

Not surprisingly, very valuable IP has originated from this highly successful 1-082 project, including numerous patents in conjunction with the Advanced Hydrogen Passivation technology and new innovative approaches for forming plated contacts to solar cells that solve previous problems with poor metal adhesion and laser induced defects. Suntech, as industry partner supporting the work, has the free right to use all such IP, but all such IP can be made available to any Australian companies wishing to take advantage of these new state-of-the-art technologies

Innovative Large-scale Commercial Plating Baths

The key factor limiting manufacturing expansion and ongoing commercialisation of leading UNSW technologies such as BP's Saturn technology, UNSW's LDSE technology and Suntech's Pluto technology, has been the lack of suitable commercially available plating tools.

This is not just a problem for UNSW technologies. The International Technology Roadmap for Photovoltaics (ITRPV) produced by an international team of experts, predicts that plated cell metalisation will eventually displace the use of screen-printed contacts. This transition however is expected to take as long as 5-10 years (2014 ITRPV), due in part to the lack of suitable commercial plating tools for large-scale manufacturing. Suntech's Pluto technology is a leading example of a technology needing such a tool for forming the plated contacts. To accelerate Pluto's implementation into large-scale manufacturing, the 1-082 project included as a milestone, the fabrication and installation of plating baths, based on the UNSW developed plating technology, that are suitable for large-scale manufacturing. These baths were designed by Dr Ji, a world expert in plating technology and now an academic at UNSW, and have been constructed in China by the company Kuttler. Milestone 9 report documented the successful manufacture, delivery, installation and demonstration of these plating baths shown in SIRF at UNSW in Figure 5 earlier in this report.

Commercial Readiness

At the time of writing the 1-082 funding proposal, industry partner Suntech was already in the process of licencing the Pluto technology from UNSW and planning for large-scale manufacturing. The 1-082 project not only facilitated the ongoing development of the Pluto technology with large performance increases and cost reductions, but made possible evaluation and demonstration of the technology in pilot production and then subsequently large-scale production. As testimony to the success of this work, Suntech not only entered large-scale manufacturing ahead of schedule but subsequently scaled the manufacturing capacity to 0.5GW per year. If not for the world financial crisis and subsequent financial problems faced by Suntech that led to control being relinquished to an Administrator, plans to further expand Pluto production would have continued rather than having the technology manufacturing temporarily put on hold in 2013-14 by the administrator.

Perhaps of greatest importance in taking the technology to commercial readiness, was the design, development and manufacturing of suitable plating baths for the large-scale commercial manufacturing of cell technologies requiring plated metal contacts such as those based on copper. This work was contributed to significantly through the 1-082 project with a demonstration and evaluation of the plating tool taking place in SIRF at UNSW as described above and shown in Figure 5. These plating baths are now available, not only to demonstrate the UNSW plating technology to any industry partners, but also to facilitate technology transfers and optimisation.

Transferability

A range of important technology developments took place during the project, particularly in the areas of plated copper contacts for solar cells, advanced hydrogen passivation technology, rear surface passivation with localised metal contacts, improved back surface field formation and adaptation of advanced cell technologies to suit low cost multicrystalline silicon wafers. Although all of these distinct technologies were collectively integrated into the world-leading Pluto technology to achieve numerous cell and module world records, distinct technologies can be transferred and adapted for use in conjunction with a range of other solar cell and semiconductor device technologies. In each of the technology areas, patents have been filed with NSi actively identifying and marketing the corresponding technologies in the various relevant areas where they can be of value. For example, the advanced hydrogen passivation technology can be applied and adapted to all known silicon solar cell technologies world-wide and will likely have broader application also to a range of other semiconductor device types. Similarly, the copper plating technology is expected to be in demand by most cell manufacturers in the future as the world evolves from silver-based metallisation schemes to ones based on plated copper.

Numerous publications of the work have taken place to ensure the research and manufacturing communities are aware of the various technological developments. Material has also been incorporated into the relevant courses within the world's only undergraduate degree in Photovoltaic Engineering.

Considerable knowledge sharing has also taken place through quite extensive media interest and media publications and interviews relating to the technology developments of the project. In particular, numerous international awards have resulted as listed under the section on "Outcomes", with such awards naturally creating numerous opportunities for publicising the work and the achievements such as through press releases, radio and tv interviews, a range of published article types in newspapers and journals, invited presentations, lectures (classroom based and online) and various reports.

Conclusion and next steps

The conclusions from this project and the strategies for steps forward can be separated into four areas.

1. **World-record Pluto cell technology**

   Various new technology developments and innovations have lead to a new generation of Pluto technology employing a selective emitter structure, well passivated front and rear surfaces, low area metal contacts, low surface reflection including fine-line metallisation capabilities and well passivated metal/silicon interfaces with low contact resistance. Record performance levels have been achieved and independently confirmed with commercial viability and significance demonstrated through the use of standard commercial tools. Innovative aspects contributing to the record performance levels included the laser-based techniques for selective emitter formation, the light-induced plating technology for copper deposition, the rear surface passivation and contacting techniques and the advanced hydrogenation technology.

   Development and application of this technology to suit both SG p-type mono wafers and multi wafers was successfully accomplished leading to record performance levels for both. Pilot production in the facilities of the industry partner was successfully achieved demonstrating commercial viability and paving the way for future large-scale production.

   Future ongoing technological developments have been identified and patents secured for inclusion in a new ARENA project RND068 which is expected to facilitate new innovations that will both further improve efficiencies and reduce costs. Efficiencies approaching 23% are expected using standard commercial grade wafers.

   All corresponding patents are Australian owned via NSi at UNSW, facilitating technology transfer and licensing to any interested Australian and overseas companies.

2. **Commercialisation of Copper plating technology**

   To expedite commercialisation of the new technologies developed in this project, attention has also been given to the design, development, construction and evaluation of additional manufacturing tools needed for the implementation of large-scale manufacturing of the newly developed solar cell technologies. In particular, the lack of commercially available large-scale plating tools has restricted the commercialisation of many cell technologies such as Pluto that require plated contacts.

   The International Technology Roadmap for Photovoltaics (ITRPV) produced by an international team of experts, predicts that plated cell metalisation will eventually displace the use of screen-printed contacts. This transition however is expected to take as long as 5-10 years (2014 ITRPV), due in part to this lack of suitable commercial plating tools for large-scale manufacturing. To accelerate Pluto's implementation into large-scale manufacturing, this project has successfully embarked upon the design, fabrication, installation and evaluation of plating baths, based on the

UNSW developed plating technology. Such baths have been demonstrated to be suitable for large-scale manufacturing. These baths were designed by Dr Ji, a world expert in plating technology and now an academic at UNSW, and have been constructed in China by the company Kuttler.

The success of the plating baths was such as to prompt Suntech to implement 500MW manufacturing capacity for the Pluto technology, satisfying one of the objectives of the project. This has been achieved through Suntech purchasing 17 such sets of plating baths from Kuttler, each with an annual throughput capacity of 30MW, demonstrating the commercial viability of the UNSW plating technology and with manufacturing yields in excess of 99%. The plating baths are now functional at UNSW and able to be used for technology transfers, manufacturing demonstration and other research projects. These baths will also be used as a “Test Bed” for the ongoing development and improvement in the UNSW plating technology and its demonstration. Such plating baths are now commercially available for cell manufacturers.

3. Advanced Hydrogen passivation technology

A new approach to hydrogen passivation based on controlling the hydrogen charge state has been demonstrated to significantly improve both the mobility and reactivity of the hydrogen. Several new patents have been sought to protect the new technology and various techniques have been developed for its implementation. A particularly exciting new area for work involves applying these new passivation techniques to much lower cost types of silicon wafers that appear capable of significantly reducing cell costs provided the new passivation technology can prevent significant performance loss.

These new developments have been heralded by experts and media as a major breakthrough as demonstrated through the award of the 2013 IET A F Harvey Engineering Prize, arguably the leading international engineering prize based on prestige and prize money.

It appears that this new passivation technology can be developed in the future for application to all wafer-based cell technologies.

4. Large cost reductions

Many of the technological advances in this project have contributed to reducing the costs for photovoltaic devices. All of the advances that have led to improved performance automatically leads to reduced costs as a result of the additional electricity generated, provided the enhancements do not increase manufacturing costs.

In addition, some of the developments have directly contributed to large cost reductions, such as through the costs of materials used. The two dominant costs for making commercial silicon solar cells are the cost of the silicon wafers and the cost of the silver for the metal contacts. Two important innovations in this project have been the replacement of most of the silver with low cost copper and the ability to use much cheaper wafers without losing performance through the use of the hydrogen passivation technology. This latter development in particular has been recognised internationally for its importance as demonstrated through the award of a leading international engineering prize.

From Australia's perspective, the reduced costs have been shown to enable pv to compete with fossil fuel generated or conventional electricity supplies at retail level. This is particularly important given the rapidly rising costs for electricity in Australia and the geographically diverse population for whom pv can now provide relatively low cost electricity without expensive grid extensions etc. The rate of uptake of pv in Australia is exceeding that in most countries, aided also by our abundance of sunshine. However on an international basis, the cost reductions for pv have been so substantial in recent years that grid parity has now been reached in most locations. Government policies however, both in Australia and overseas, is often not as conducive as necessary to allow full exploitation of the developments and reduced costs that pv can now provide.

Technology transfers and licensing of the developments from this project will allow not only Australian companies, but also manufacturers world-wide to take advantage of the developments if they are convinced that the new technology offers them advantages over their existing technologies. Regardless of whether subsequent manufacturing takes place in Australia or overseas, royalties will flow to Australia. In addition, the significant cost reductions that should result will allow wider and more economical use of the technology by consumers in Australia to reduce electricity costs, reduce pollution, allow point-of-use generation, provide more environmentally friendly energy sources and create many new Australia jobs with studies showing that most job creation for the industry occurs through the use of the technology rather than its manufacture.

Lessons Learned

The following is a summary of the lessons learned from Project ARENA 1-082.

1. How to use hydrogen passivation of fix defects in silicon to reduce costs and improve performance
2. The underlying theory of hydrogen charge state control and why it is so effective in improving both the mobility and reactivity of the hydrogen
3. How to implement UNSW novel plating technology into a full-sized commercial manufacturing tool.
4. How to plate copper to both polarities of metal contact
5. How to improve rear surface passivation and metal contacting to Pluto solar cells
6. How to form deep junctions, particularly in the vicinity of metal contacts and for electrical isolation
7. How to significantly reduce the material costs associated with commercial pv devices
8. The value of a Solar Industrial Research Facility for:
    a. demonstrating the commercial significance and viability of technologies developed in the lab;
    b. carrying out collaborative research with industry;
    c. conducting technology transfers;
    d. providing education and training;
    e. equipment development;
    f. for establishing pilot production;
    g. technology evaluation such as processing parameter tolerances, yields, throughput, costs etc.