Towards Ultimate Performance Commercial Silicon Solar Cells

2014/RND068

Project results and lessons learnt

Lead organisation: University of New South Wales	
Project commencement date: 1 July 2015	**Completion date:** March 2020
Date published:	
Contact name: CheeMun Chong	
Title: Professor	
Email: cm.chong@unsw.edu.au	**Phone:** 02 9385 4563
Website: Unsw.edu.au	

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Executive Summary

The focus of the ARENA 2014/RND068 project was the development and commercialisation of novel device structures and technologies for achieving high efficiency commercial silicon solar cells at a competitive cost. Achieving higher cell efficiency usually requires sophisticated processes, some of which carry considerable costs incapable for transfer to mass production. The priority for this project, however, was to develop technologies focused on increased simplicity and the ability to exploit lower-cost materials. This included the use of low-quality commercial-grade silicon wafers instead of those produced using the highest purity of silicon. Although these materials may contain crystallographic defects, cost effective methods can be used to improve the quality of silicon to be comparable to more expensive wafer technologies.

Four key aspects of solar cell design and production processes were developed during this project:

1. Eliminating the need for expensive microelectronics grade processing such as photolithography and pattern dielectric layers, by instead using laser processes to achieve the patterning;

2. New processes, such as laser processing, were developed and optimised to pattern the rear dielectric layer to form localised rear contacts on the solar cell;

3. Implementation of the new advanced hydrogenation technology into the solar cell design and fabrication to lower cost by transforming low cost, low quality silicon wafers into ones which are comparable in quality to expensive high-quality wafers.

4. Replacement of expensive silver metal contacts with low cost copper plated contacts.

Solar modules fabricated using this technology have achieved IEC certification.

A production “blueprint” (commercialisation package) for the manufacture of these next generation solar cells using the new technologies has been developed to help ensure a smooth transfer of the technology to industry.

Project Overview

Project summary

Recent editions of the International Technology Roadmap for Photovoltaics (ITRPV) have identified two important areas of technology development necessary for photovoltaics to further increase viability and competitiveness as an alternative to fossil fuel generated electricity; namely, increasing device efficiency and lowering cost. The aim of this project was to address these two key areas and engage with industry for the commercialisation and large-scale manufacturing of the technology.

The work involved the development and implementation of four key aspects of solar cell design and production process that have each led to cost reductions and/or performance enhancements of the devices. The first of these was the development and optimisation of laser processes to pattern the front dielectric layer and simultaneously melt the underlying silicon to facilitate the formation of a heavily doped (n++) region directly under the metal where it has significant performance benefits. In addition, this eliminated the need for expensive microelectronics grade processing such as the use of photolithography to pattern the dielectric layers. Secondly, laser processes were also developed and optimised to pattern the rear dielectric layer to form localised rear contacts in conjunction with a well passivated rear surface. This significantly enhanced the performance of the resulting device. The third of these was the implementation of new advanced hydrogenation technology into the solar cell design and fabrication. This significantly decreased the cost of the device, as the hydrogenation technology was able to transform low cost, low quality silicon wafers into ones that are comparable in quality to the most expensive wafers which would typically cost over 100 times more. The last of these was the replacement of the expensive silver metal contacts with low cost plated copper contacts, which can be formed particularly simply since the copper plating naturally aligns to the laser-melted regions on the silicon. This simple plating approach again significantly reduced the cost of the finished device.

Adoption of a number of these technologies by several companies in their large-scale manufacturing is evidence of the success in these technology development areas.

Project scope

The aim in undertaking this project was to increase solar cell efficiencies and reduce their costs in order to help make them a viable alternative for electricity generation around the globe.

Typically, enhancing performance efficiencies requires more sophisticated processes with corresponding cost increases. By way of comparison, the technologies developed in this project helped increase simplicity and the ability to use lower cost materials such as copper for the metal contacts instead of expensive silver; as well as the use of low quality, low cost silicon wafers instead of using high quality silicon with minimal crystal defects or impurities. The success in technology development and commercialisation has resulted in the use of the technology by some key cell manufacturers around the world.

Outcomes

Important outcomes which have satisfied the aims of the project include:

1. Developed a greater understanding on the impact of groove morphology on the quality of laser doped selective emitter contacts. A novel process for groove formation using a line scan laser was used to form narrow grooves significantly thinner than the width of conventional laser-doped lines. Detailed characterisation of the laser-doped structure demonstrated the ability to simultaneously dope the groove walls, thus suitable for subsequent plating;

2. We have shown that the surfaces of the laser doped specimens can be subsequently passivated using conventional dielectric layers, resulting in a minimisation of damage induced by the laser on the dielectric films. Given the narrow width of the groove opening (3-5 microns), the groove walls remain exposed after the application of dielectric layers, leaving the region directly suitable for plating;

3. Adhesion testing of metal contacts plated into the grooves highlights a significant improvement not only over conventional laser-doped and plated architectures but also of the widely available screen-printed contacts;

4. A prototype tool has been successfully designed and manufactured to assist in the electroless plating of laser-doped solar cells, whereby dual-surfaces of the silicon wafer are plated simultaneously to reduce time and cost. From this demonstration, we successfully demonstrated finished cell efficiencies of over 20% on full-size commercial wafers;

5. Developed a greater understanding of the rear passivation and contacting process with carefully controlled diffusions, highlighting the potential for this technique to deliver low resistant contact to silicon solar cells;

6. Developed new Australian-owned intellectual property;

7. New solar cell technology for lowering the cost of electricity generation;

8. Development of the technology to suit manufacturing with industrial tools;

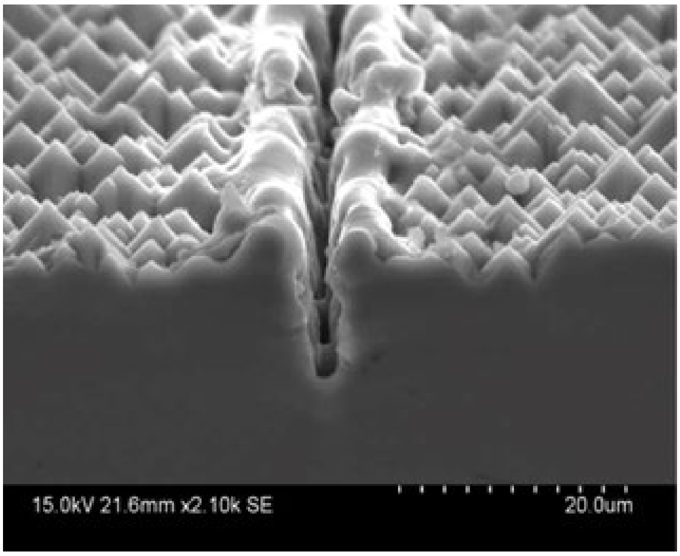
9. Designed and developed new industrial tools incorporating the intellectual property from this project for large-scale manufacturing of the technology;

10. Transferred the technology to industry and successful commercialisation of the technology;

11. Achieved IEC certification of the solar modules fabricated using this technology.

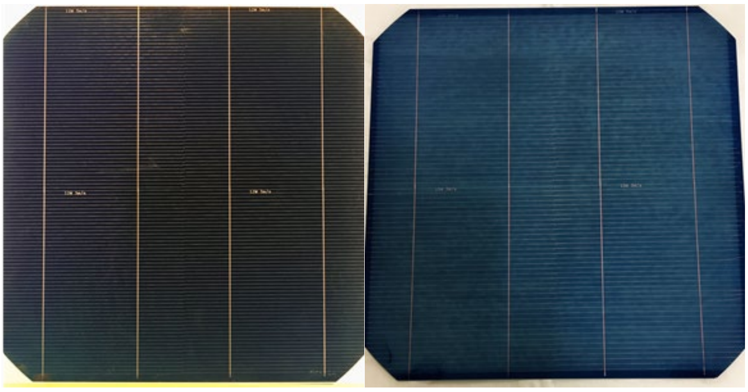
By carefully controlling the laser process, we have been able to form narrow grooves on the top surface of the solar cells while simultaneously heavily doping the groove walls. These front surface grooves using a Q-switched laser system as shown in the image below:

The Scanning Electron Microscope (SEM) image below shows the geometry of the resulting narrow and deep laser-doped grooves:



Similar laser processes are used to create openings on the rear of the solar cell and then both sides of these solar cells are metallised using an electroless copper plating process. A prototype tool was designed and developed to streamline this plating process:

The photos below show the front (left) and the rear (right) of the bifacial plated and laser doped solar cell fabricated using the prototype bifacial plating tool:



The solar cell is fabricated using full, commercial-sized silicon wafers on industrial tools. The cell then underwent the UNSW hydrogenation process and was independently verified by the Solar Energy Institute of Singapore (SERIS) to have an efficiency of over 22%. The current-voltage characteristics of the cell as measured by SERIS is outlined below:

The 1-V parameters for the cell (UNSW-0BB-02) are:

Open-circuit voltage (mV)	670.4
Short-circuit current (A)	9.834
Fill factor (%)	81.96
Efficiency (%)	22.12

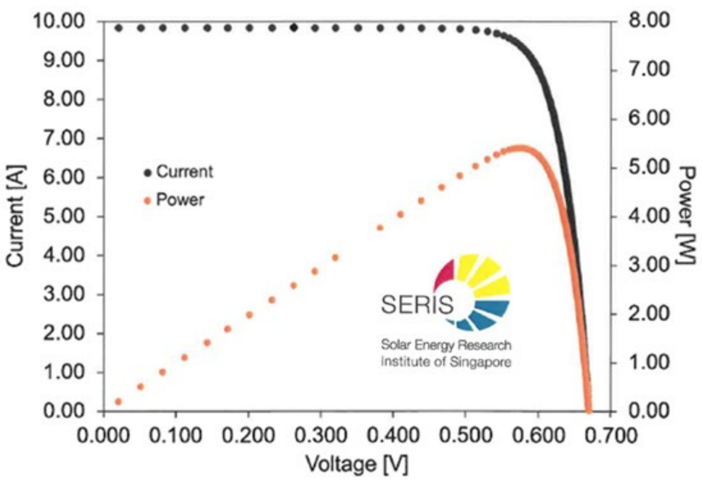


Figure 1. I-V characteristics of test solar cell UNSW-0BB-02

Adopting the new technologies developed during this project, particularly the hydrogenation technology, solar modules are expected to have an efficiency boost of around 0.3% absolute and degradation over the first year of operation in the field is expected to be lowered from 10% to 0.5% relative to the original output of the solar panel. This translates to a significant reduction in the Levelised Cost of Electricity (LCOE) which is outlined below.

Modelling a 130 MW solar farm project in Australia, solar modules with the technology developed in this project will lower the LCOE by 13% from US$2.66 per KWh to $2.36 per KWh.

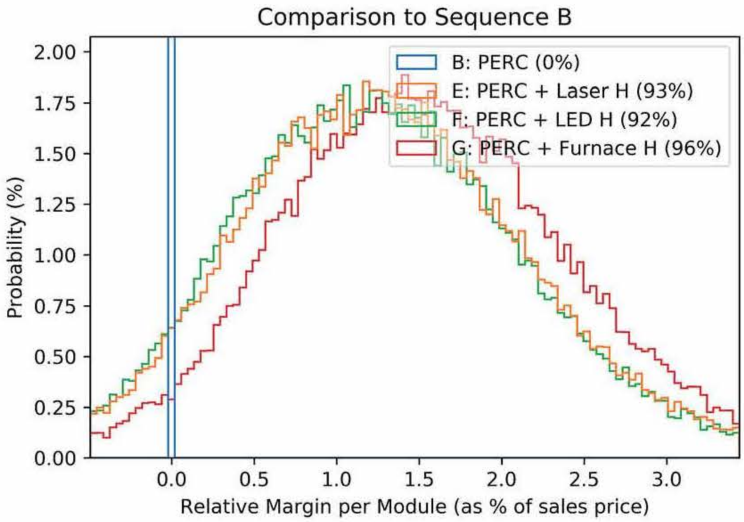
Importantly, the IRR for such a solar farm project using the modules fabricated with the technologies from this project will increase from 6.64% to 8.0%. Typically, the market requires an IRR of at least 8% before investors will finance a solar farm project in Australia.

Therefore, the technologies developed in this project reduces the cost of renewable energy (LCOE) by 10% but more importantly, the technologies enable the continued deployment of solar farms in Australia by helping to meet the financial hurdle rate of 8% for such investments.

The table below outlines the key results from our model:

LOCATION	**Australia**	Monofacial	Monofacial
Project capacity (MWp)		130.00	130.00
Module Type		Standard Module	Advanced Hydrogenation
Module Power(W)		400.00	405.45
Module price (USD cents/Wp)		21.00	21.00
Power Warranty (year)		25.00	25.00
First year degradation (%)		10.00	0.50
Annual degradation (%)		0.70	0.55
KEY ANALYSIS RESULTS			
LCOE (USc/kWh)		2.66	2.36
IRR		6.64%	8.00%
Overall Project Cost (USD/Wp)		$0.6434	$0.6405
Lifetime energy production (MWh)		6,229,373	7,022,250
SECONDARY ANALYSIS RESULTS			
Capital Investment		$ 83,640,767	$ 83,265,581

Further, techno-economic analysis conducted by UNSW researchers on research and investment decisions for silicon PV and applications[1] determined that implementing advanced hydrogenation technologies from this project in module manufacturing results in an average of 1.5% increased profit margin per module (see below, PERC + Laser H (93%) graph). This is significant given the slim margins that exist in module manufacturing. This is further evidence of the positive commercial outcomes of this project.



[1] Chang et al, DOI: 10.1039/c8se00047f

The commercial readiness of the technologies developed during this project have been greatly advanced by:

1. Adapting and developing the technologies for implementation with industrial tools;

2. Preparation of a production "blueprint" (commercial package) for the manufacture of the next generation of solar cells, including detailed specifications of key parameters and tool requirements;

3. Developing new commercial tools;

4. Transferring the technologies to industry.

Transferability

Conference and journal publications as well as patents have been published by the research team relating to the innovations developed over the course of this project. Solar cell manufacturing companies have expressed interest in learning more about and using the technologies developed in this project. UNSW has signed agreements and/or licences for the use of the technologies. UNSW research team members visited these companies to present and discuss with the technical teams. In addition, these companies were also invited to attend a confidential workshop at least once a year where technology transfer and information dissemination took place.

Conclusion and next steps

The innovative technology developed in ARENA 2014/RND068 has enabled all project milestones and outcomes to be met. In addition, the developed understandings and processes have been transferred to industry, commercialised and is now in use for large scale manufacturing at solar cell companies. This applies particularly to the advanced hydrogenation technology which is now in use by many large companies in the manufacture of PERC solar cells.

A key area of work was to incorporate laser doping in the rear surface of PERC solar cells which helped to further enhance the performance of these production solar cells. Such doping of the openings in the rear surface was shown by UNSW researchers to significantly improve passivation and hence improve the open circuit voltages of solar cells.

Industry is considering the mass manufacture of heterojunction silicon solar cells. The manufacture of such cells requires low temperature processing and this has led to the development of low-temperature firing pastes. A simple alternative is to use plating which is naturally done at low temperatures. The double-sided plating technology is very suitable for this purpose. UNSW researchers have started looking into adapting the double-sided plating technology developed during this project for depositing the required metal contacts on heterojunction solar cells.

Lessons Learnt

Lessons Learnt Report: Working with tool manufacturers

Project Name: *Towards Ultimate Performance Commercial Silicon Solar Cells*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

A particularly effective way to rapidly commercialise technology and make it widely available is through working with leading tool manufacturers to design and develop new industrial tools incorporating the newly developed technology.

Implications for future projects

Where relevant, we will aim to include tool manufacturers as industry partners in future projects where these partners would be responsible for helping to design and develop the industrial tools to implement the technologies developed in the project.

Knowledge gap

Need to adapt technical processes for large-scale manufacturing tools for each technology developed in the project.

Background

Objectives or project requirements

The purpose was to lower the cost of electricity generation by silicon solar cells through performance improvement and cost reduction of mass production silicon solar cells.

Process undertaken

New industrial tools developed through close collaboration with leading equipment manufacturers enabled the design and development of industrial tools relevant for implementing the new technologies developed in the project.

Lessons Learnt

Lessons Learnt Report: Assessing PLDB contacts

Project Name: *Towards Ultimate Performance Commercial Silicon Solar Cells*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

The nature of the point contacting inherent to PLDB rear contacting scheme, while highly desirable for solar cell rear structure, does present challenges when trying to characterise the contacts in a manner that is comparable to other contacting techniques. This was a somewhat unexpected challenge, but through innovative structure and experimental design we were able to determine in great detail the performance of PLDB contacting.

Implications for future projects

Future projects including a current project need to take care when assessing the contact performance, because of this issue.

Knowledge gap

A verified model for extracting the specific contact resistivity for point contacts from a standard measurement technique would be helpful not just for this work, but for any work investigating point contacts.

Background

Objectives or project requirements

The purpose was to establish that PLDB produces contacts with equal or better contact performance than conventional techniques. To do this in a sensible manner it is usually the specific contact resistivity of a contact that is used for comparison. This proved exceedingly difficult to determine.

Process undertaken

Since the usual arsenal of characterisation techniques were not useful we had to re-think how we determine these parameters, returning to the most fundamental questions of how the devices operate. It also meant we had to re-think how these parameters affected final device performance. So, in the end, rather than one easy to interpret measurement, we had to perform multiple measurements and use these to determine the contact resistivity of our PLDB contacts.

Lessons Learnt Report: Applications for PLDB

Project Name: *Towards Ultimate Performance Commercial Silicon Solar Cells*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

This aspect of the project began by being focussed on replacing current high thermal budget processes for forming rear contacts to silicon solar cells. The point contact form of the final product was also seen as a big advantage that could be leveraged to make an alternate contacting technique. As the project progressed, we realised that PLDB's advantages opened up a range of possibilities for devices that incorporate silicon with other materials. We have investigated the case of III-V material with silicon, but the biggest lesson learned was that this can be applied to any number of silicon based devices due to the lack of high temperature steps. This could extend to solution based layers that are currently making remarkable progress in increasing performance. The flexibility of the PLDB process means it can be integrated into process flows that are extremely incompatible with conventional silicon flows.

Implications for future projects

PLDB contacts are a viable replacement for conventional thermal contacts, but in terms of replacing these at an industrial level for silicon solar cells, this appears to not be feasible at this stage. PLDB is, however, an excellent choice for devices that are integrating novel materials as well as those materials systems with fabrication processes that are incongruent with those for silicon.

Background

Objectives or project requirements

The overall aim of this work was to investigate the use of PLDB with other laser based techniques to produce the next generation in silicon solar cells.

Process undertaken

Using samples with III-V material grown on silicon we were able to contact to the rear silicon solar cell using PLDB, without any complicated processing to protect the III-V material. The performance of the devices was not satisfactory, but this was determined to be due to an unrelated problem that afflicts the silicon when growing the III-V material.

Lessons Learnt

Lessons Learnt Report: Improved Laser Doping Techniques for Enhanced Adhesion

Project Name: *Towards Ultimate Performance Commercial Silicon Solar Cells*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

Adhesion of plated contacts can be improved by modulating underlying laser-doping morphology. The implementation of conventional electro-plated contacts requires careful control of the laser-doping process to minimise laser-induced defects whilst maintaining tall profiles for the plated metal to reduce resistive losses. By developing a deep laser-doped grooving approach, various new benefits are learnt, allowing for the preservation of surface passivation whilst increasing contact adhesion and reducing series resistance.

Implications for future projects

This new technology is relevant to all emerging and future silicon-based solar cell devices as a method for improving conversion efficiency. Plated contacts have historically provided a significant advantage over conventional screen-printed contacts due to immense control over contact width as determined by the laser openings. With the prominent use of laser technology in recent years particularly in PERC solar cells, the reduced cost of implementing laser-doped selective emitters makes this technology extremely viable and easy to implement at cost.

At this point in time, we have demonstrated that technique we have developed works promisingly. This technique may ultimately be adapted for implementation in plated silicon heterojunction hybrid devices.

Knowledge gap

Plating process have been well developed for industrial application and have been implemented on commercially manufactured solar cells (e.g. Suntech PLUTO). However, existing techniques often suffer from laser-induced damage during dielectric opening which cannot be entirely removed or passivated. Furthermore, due to the reduced surface area when using flat-profile laser doping, in particular as fingers become thinner, surface adhesion between the silicon and plated metal remains a common failure mode once cells are made into modules.

Background

Objectives or project requirements

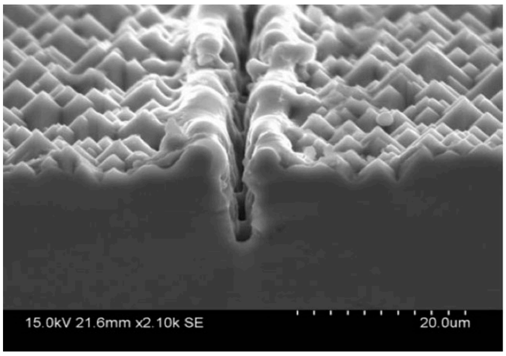
This project aimed to develop the ideal geometry for laser doping profiles to enhance adhesion properties.

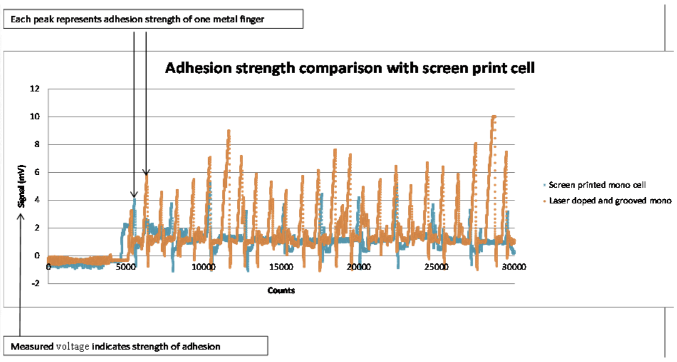
Process undertaken

A new process for forming grooves on the silicon surface while simultaneously doping the walls of the grooves was successfully developed. This new process is able to form narrow grooves of 3-5 microns width and heavily doped groove walls in a single step. The microscopy image below shows the geometry of these laser- doped grooves. A particular benefit of forming the grooves in this way is that it facilitates deposition of the surface passivating dielectric after groove formation without interfering with the ability to subsequently selectively plate only the silicon within the grooves.

This structure has several benefits over conventional laser-doping processes, including:

1. The grooves can be very narrow which facilitates the subsequent formation of very narrow metal fingers during plating (minimise shading).
2. The SiNx passivation layer can be deposited after groove formation and this helps avoid much of the laser-induced damage formed during the conventional laser doping method in LDSE solar cells that results from the thermal expansion mismatch of the silicon and the passivation dielectric
3. Testing of plated solar cells demonstrated adhesion performance better than what is achieved using commercial screen printing.





Lessons Learnt

Lessons Learnt Report: Advanced Plating Technology for Laser-doped Silicon Solar Cell

Project Name: *Towards Ultimate Performance Commercial Silicon Solar Cells*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

The duration and cost for the plating of bifacial solar cells can be reduced by plating both surfaces of the solar cell simultaneously.

Implications for future projects

The low-cost electroless copper plating technology can be a viable alternative to the screen-printing of expensive silver contacts on solar cells.

Knowledge gap

Although there have been many known and commercialised methods of electro-plating available for solar cells, simultaneously plating both sides of a bifacial cell was an area that required further development and investigation.

Background

Objectives or project requirements

The objective for this project was to design and implement a prototype tool capable of plating of bifacial cells that could also be easily scaled into a large commercial tool.

Process undertaken

To demonstrate this improved technology for plating both polarities of contacts, a new smaller prototype plating tool was designed and developed. The photo below shows this new innovative smaller prototype plating tool set up at UNSW. Furthermore, metal was successfully simultaneously plated to laser-doped fingers on the front and rear surfaces of the full-size silicon solar cell using the newly developed innovative plating tool located in SIRF at UNSW.