Australian Government
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ARENA

1-A060: Development and Commercialisation of High Efficiency Silicon Solar Cell Technology

Project results and lessons learnt

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Executive Summary

The focus of the ARENA 1-060 project has been the development and commercialisation of new technology capable of achieving high efficiency silicon solar cells at low cost. Often, achieving higher efficiencies requires greater levels of sophistication with corresponding increased costs. In comparison, the priority for the technologies being developed in this project has been for the use of increased simplicity and the ability to use lower cost materials such as copper instead of silver for the metal contacts and low quality, low cost silicon wafers instead of those produced using the highest purity of silicon and with minimal crystallograghic defects. The success in achieving the latter has been a particularly important outcome for this project given the dominance that the silicon wafers have in determining the cost of typical silicon solar cells.

The high efficiency solar cell design used in this work is shown in Figure 1 below and is known as the Passivated Emitter and Rear Cell (PERC). This was developed at UNSW during the 1980's and has been responsible for many performance world records, both at UNSW and also by industry partners in collaboration with UNSW. Of particular importance in the commercial implementation of this cell design has been the development and implementation of three important technologies that have each led to significantly reduced costs while simultaneously enhancing the performance of the devices. The first of these has been the elimination of all microelectronics grade processing such as the use of photolithography to pattern dielectric layers, being replaced by a simple laser process which simultaneously patterns the dielectric while simultaneously melting the underlying silicon to facilitate the formation of a heavily doped (n++) region directly under the metal where it has significant performance benefits. The second of these has been 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 automatically to where the laser melted the silicon and formed the n++ heavily doped silicon regions. The third and most important of these, has been the development of a new hydrogen passivation technology that is being widely regarded as a breakthrough for silicon photovoltaics. This is because the costs for making silicon solar cells are strongly dominated by the costs for the silicon wafer and yet this new passivation technology is able to transform low cost, low quality silicon wafers into ones that are comparable in quality to the highest quality wafers that would typically cost >100 times more.

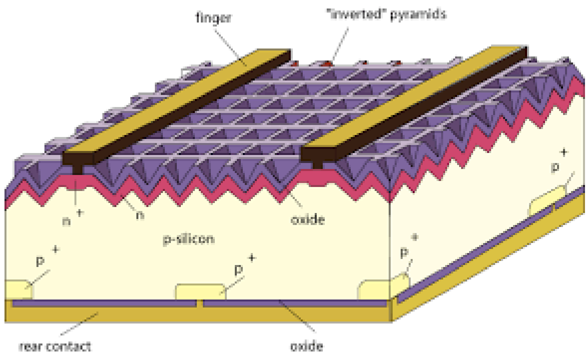


Figure 1: Passivated Emitter and Rear Cell (PERC) diagram

The latter technology through development in this project, has demonstrated its potential to revolutionise silicon solar cell manufacturing. In being awarded the United Kingdom's IET Harvey Engineering Prize in 2014 (widely recognised as one of the world's leading engineering prizes across all fields), the Institution of Engineering and Technology described this new ARENA hydrogenation technology as a "major breakthrough" for silicon solar cells. The technology involves diffusing atoms of hydrogen inside the silicon crystals that form the silicon wafer and then controlling the charge of the hydrogen atoms to determine whether they are positive, negative or neutrally charged. The importance of the charge of the hydrogen is that it has a major impact on how easily the hydrogen can move around inside the silicon wafer to find the defects and imperfections and then fix them up. It appears from the work conducted in this project that virtually any type of defect or imperfection within the silicon can potentially be fixed by the hydrogen if the appropriate techniques for controlling the hydrogen's charge state are successfully implemented. The challenge for this technology is to achieve manufacturability with high throughput, high yield and low cost.

Since that time the ARENA hydrogenation technology has been further developed and progressed towards commercialization. The realization that virtually any defect type or form of contamination that causes recombination can be fixed by the atomic hydrogen has generated enormous interest, not only from solar cell manufacturers, but also from silicon and wafer producers who have provided samples of their materials to test compatibility with the ARENA hydrogenation. Without fail the companies producing the silicon and wafers have recognised the importance and power of the hydrogen passivation to significantly improve the quality of their materials. More than 10 companies have now signed licences and/or agreements for the large-scale manufacturing of the ARENA hydrogenation technology in conjunction with their respective cell manufacturing technologies. Several equipment manufacturers have also worked closely with UNSW in the design and development of novel tools that implement the first generation of the ARENA hydrogenation into large-scale manufacturing for use by the companies that have the rights to use the technology.

As the industry moves to the higher efficiency PERC technology of Figure 1, the ARENA hydrogenation is being seen as an essential component of their manufacturing, both in terms of getting the highest efficiencies but also for eliminating instabilities that commonly occur in commercial solar cells fabricated from the lower quality silicon wafers.

Project Overview

Project summary

The aim of the project was to develop new solar cell technology that would both lower the costs for making such solar cells while simultaneously raising their efficiencies with the hope that industry would engage in the commercialisation and large-scale manufacturing of the technology.

In particular, the work involved the development and implementation of three important technologies that have each led to significantly reduced costs while simultaneously enhancing the performance of the devices. The first of these has been the elimination of all microelectronics grade processing that is typically used in lab-based processing such as the use of photolithography to pattern dielectric layers. This has been replaced by a simple laser process which simultaneously patterns the dielectric layer while simultaneously melting the underlying silicon to facilitate the formation of a heavily doped (n++) region directly under the metal where it has significant performance benefits. The second of these has been 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 automatically to where the laser melted the silicon and formed the n++ heavily doped silicon regions. The third and most important of these, has been the development of a new hydrogen passivation technology that is being widely regarded as a breakthrough for silicon photovoltaics. This is because the costs for making silicon solar cells are strongly dominated by the costs for the silicon wafer and yet this new passivation technology is able to transform low cost, low quality silicon wafers into ones that are comparable in quality to the most expensive wafers that would typically cost >100 times more.

Evidence for the success in these technology development areas has been the achievement of several performance world records for the solar cells and the decision of numerous companies to use the new technology in their large-scale manufacturing.

Project scope

The aim in undertaking this project is to increase solar cell efficiencies and reduce their costs to make them a viable alternative for electricity generation throughout the world.

Often, achieving higher efficiencies requires greater levels of sophistication with corresponding increased costs. In comparison, the priority for the technologies being developed in this project has been for the use of increased simplicity and the ability to use lower cost materials such as copper instead of silver for the metal contacts and low quality, low cost silicon wafers instead of those produced using the highest purity of silicon and with minimal crystal defects or imperfections. The success in achieving the latter using novel hydrogen passivation techniques and the corresponding new insights and understanding gained, have been a particularly important outcome for this project given the dominance that the silicon wafers have in determining the cost of typical silicon solar cells. The success in this area of technology development and commercialisation has subsequently led to licences and/or agreements being signed with more then 10 of the cell manufacturers throughout the world for the large-scale manufacturing of this technology.

Outcomes

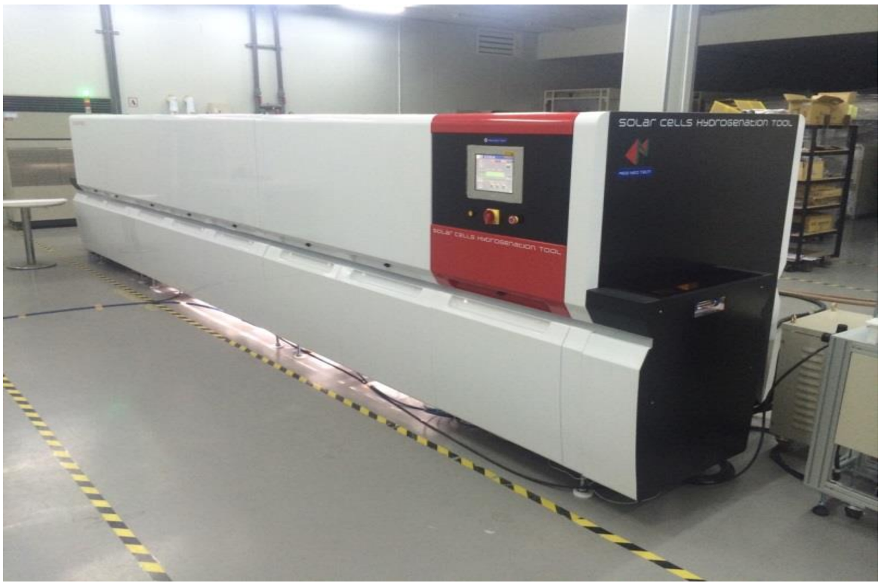
Important outcomes that satisfied aims of this project have been:

1. new solar cell technology for lowering the cost of electricity;
2. new Australian-owned intellectual property;
3. development & adaptation of the technology to suit manufacture with industrial tools;
4. record performance commercial p-type solar cells;
5. the design and development of new industrial tools incorporating the IP from this project for the large-scale manufacturing of the technology;
6. transfer of the technology to industry;
7. signing of licences and/or agreements with numerous companies for the large-scale manufacturing of the technology;
8. successful commercialisation of the technology.

There have also been two somewhat surprising outcomes. One has been the realisation that the new hydrogen passivation technology developed for improving the quality of the silicon wafers appears to have the potential to fix virtually any defect or imperfection within the silicon, therefore transforming it into the highest quality of silicon that would normally cost orders of magnitude more to purchase. The second has been the recognition by the UK Institution of Engineering and Technology that this new hydrogen passivation technology is a "breakthrough for silicon photovoltaics", a conclusion drawn by the UK IET while awarding the project team the prestigious international Engineering Award of the A F Harvey Engineering Prize in 2014.

The commercial readiness of the technologies were greatly advanced during the project by:

1. adapting & developing the technologies for implementation with industrial tools;
2. transferring the technologies to industry;
3. developing a new commercial tool (see figure below of new tool manufactured under licence to UNSW by Asia NeoTech in Taiwan) for the large-scale manufacture of the new hydrogen passivation technology;
4. signing commercial licences with companies for large-scale manufacturing.



Transferability

Many conference and journal publications, media articles and patents have been published by the research team relating to the developments in this project. Large numbers of companies are now interested in learning more about and using the technologies developed in this project. UNSW has therefore signed many licences and/or agreements for the use of the technology. All such companies attend workshops once or twice each year during which extensive training, technology transfer and information dissemination takes place. The material in these workshops is in general confidential to the industry partners or companies with licences.

A particularly important aspect of the transferability of the new hydrogen passivation technology to other areas has been the design and development of industrial tools incorporating the technology that can make it available for use in any industry and by any company under licence. This was achieved by the UNSW research team working closely with several leading tool manufacturers (Schmid in Germany, DR Laser in China, Asia NeoTech in Taiwan and Ke Long Wei in China), to transfer the technology to these technologies for incorporation into new industrial tools for commercial manufacturing. A photo of one of these tools by Asia NeoTech is shown in the previous section.

Conclusion and next steps

The new technology developed in ARENA 1-060 not only enabled all milestones and outcomes to be achieved for the project, but more importantly has been transferred to industry, commercialised and is now in large-scale manufacturing by many companies. This applies particularly to the advanced hydrogen passivation technology, now in use by many of the large companies in their cell manufacturing. This allows significant improvement in the quality of the standard commercial grade wafers, facilitating significantly increased efficiencies. However, with the cost of silicon wafers dominating the cost of making solar cells, the new passivation technology opens up the opportunity to significantly reduce the cost of such wafers by lowering their purity and crystal quality and then using the hydrogen passivation technology to raise their quality to match or even exceed the quality normally achieved by the more expensive conventional wafers used in commercial manufacturing. An important conclusion from this work is that it appears that the hydrogen atoms, if properly controlled, have the potential to fix up or passivate basically any defects or imperfections in the silicon wafers.

This opens the opportunity for a very important new area of work focusing on significantly reducing the costs for making solar cells by developing and producing lower cost silicon wafers. Such wafers cannot currently be used by the industry due to the much lower efficiencies that would result from their use due to the lower quality of the wafers. However, with appropriate development and adaptation, It appears likely that the new hydrogen passivation could be implemented in such a way as to transform such low cost wafers into matching the quality of the much higher cost wafers currently being used. An Extension to this ARENA 1-060 project has therefore been proposed by the researchers and approved by ARENA for developing, applying and evaluating the use of the hydrogen passivation technology for lower quality, lower cost wafers. A particular problem with lower quality wafers is that they also tend to be unstable, degrading further in quality when exposed to light. This effect has even been observed in present commercial p-type multicrystalline silicon wafers used by the industry.

Preliminary work has also shown that the new hydrogen passivation technology may be able to solve such instabilities in the lower quality silicon wafers. This work forms the focus of the ARENA 1-060 Extension, with 5 new industry partners requesting participation and involvement in the project, believing it has the potential to revolutionise silicon photovoltaics by facilitating the use of lower cost, lower quality silicon wafers but while simultaneously achieving higher efficiencies. These new industry partners will collectively be contributing \$5 million in cash in support of the research to match the \$2.5 million in additional funding from ARENA. All new IP will be owned by UNSW and the world-leading team in defect analysis of Dan MacDonald and Fiacre Rougieux from ANU, will be collaborating with the UNSW to help better understand the impact of defects and imperfections in the lower quality silicon wafers.

Lessons Learnt

The following is a summary of the lessons learnt from Project ARENA 1-060.

1. How to use lasers to pattern surface dielectric layers as a low-cost replacement for sophisticated and complicated photolithographic processes typically used when making lab-based solar cells.
2. Working with leading tool manufacturers to design and develop new industrial tools incorporating new UNSW technology is a particularly effective way to rapidly commercialise such technology and make it widely available.
3. Hydrogen atoms, if appropriately controlled within silicon crystals, appear capable of passivating virtually any defect or imperfection within the crystals
4. Silicon wafer costs can be significantly reduced by producing lower quality wafers and then using hydrogen passivation to transform them into being equivalent in quality to wafers of much higher cost.

Lessons Learnt Report: How to use lasers to pattern surface dielectric layers as a low-cost replacement for sophisticated and complicated photolithographic processes typically used when making lab-based solar cells.

Project Name: **DEVELOPMENT AND COMMERCIALISATION OF HIGH EFFICIENCY SILICON SOLAR CELL TECHNOLOGY**

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	New South Wales

Key learning

For many decades, record performance lab-cells have relied upon of the use sophisticated microelectronics grade processing techniques and materials such as for patterning dielectric layers and defining metal contact locations and dimensions. The high costs for such processes make them unsuitable for large-scale manufacturing. In this work, laser technology has been developed as an alternative and demonstrated that it can be an effective replacement with low cost and high throughput and high reliability. However, the use of lasers in this way creates some damage to the silicon, necessitating the simultaneous use of the new hydrogen passivation technology developed in this project, to fix such damage and allow the devices to match the performance of equivalent much more expensive devices produced in the lab using microelectronics grade processing.

Implications for future projects

Much work was done in this project trying to optimise the laser ablation process to minimise damage to the silicon. Now that it has been shown that such damage is no longer a problem if used in conjunction with the low-cost hydrogen passivation technology, future use and optimisation of the laser ablation process for making solar cells is greatly simplified.

Knowledge gap

Where hydrogen is used to repair damage to the silicon created by the laser, thorough testing and evaluation needs to be carried out to ensure that such repair is stable against all the operating conditions solar cells will face when operating in the field.

It will also be useful from an academic perspective to better understand the nature of the defects created by the laser and the ability of the hydrogen to passivate or fix such damage.

Background

Objectives or project requirements

The aim of this part of the work was to find a low cost alternative way to pattern surface dielectric layers on the silicon wafers that could avoid the use of the expensive and sophisticated photolithographic processes typically used when patterning dielectric layers for making high efficiency lab solar cells.

Process undertaken

All known existing laser systems throughout the world were evaluated for patterning the surface dielectric layers on silicon wafers. None were found suitable. Important parameters were determined and included laser light frequency, power density, laser pulse duration, laser pulse frequency, energy content in each laser pulse tail, the use of top-hat optics to minimise damage to adjacent regions, diameter of laser beam and laser scanning speed. For such a specialised and new application for lasers, a unique laser system design was necessary and a prototype industrial tool incorporating UNSW IP was developed through collaboration between UNSW, Suntech and Newport. This tool is now located in SIRF.

Supporting information (optional)

The prototype industrial tool for carrying out this laser patterning is located and can be viewed in SIRF at UNSW.

Lessons Learnt Report: Working with leading tool manufacturers to design and develop new industrial tools incorporating new UNSW technology is a particularly effective way to rapidly commercialise such technology and make it widely available.

Project Name: **DEVELOPMENT AND COMMERCIALISATION OF HIGH EFFICIENCY SILICON SOLAR CELL TECHNOLOGY**

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	New South Wales

Key learning

Working with leading tool manufacturers to design and develop new industrial tools incorporating new UNSW technology is a particularly effective way to rapidly commercialise such technology and make it widely available.

Implications for future projects

Through previous success using this approach to develop new industrial tools for the commercialisation of UNSW PV technology, it is now relatively easy to work with several of the leading equipment manufacturers to repeat this process as newer generations of UNSW technology are developed and progressed towards commercialisation.

Knowledge gap

The rapid development and deployment of new tools capable of implementing unique new technology in photovoltaics, creates a huge gulf of unknown opportunities as to alternative ways that such tools could potentially be used for other purposes such as in a range of semiconductor device types. The research team is focused solely on pv technology, without the capacity to explore such alternatives.

Background

Objectives or project requirements

Design and develop a new industrial tool to facilitate the commercialisation of technology developed in this project.

Process undertaken

Five leading tool manufacturers (Newport Lasers, Dr Laser, Schmid, Kei Long Wei and Asia NeoTech) were identified, each of which were willing to sign agreements with UNSW whereby they would fund the development of such tools in return for the right to sell such tools incorporating UNSW IP. UNSW researchers proceeded to transfer the technology and know-how to the respective tool manufacturers and assisted with the design of the new tools.

Supporting information (optional)

Several tools produced through this process are now located in SIRF at UNSW. Three photos of such tools are shown below.

(a) (b) (c)

Commercial prototype tools developed for implementation and commerciallisation of advanced hydrogenation for p-type Cz silicon wafers. The tools are developed by (a) Asia NeoTech, (b) DR Laser and (c) Ke Long Wei

Lessons Learnt Report: Hydrogen atoms, if appropriately controlled within silicon crystals, appear capable of passivating virtually any defect or imperfection

Project Name: **DEVELOPMENT AND COMMERCIALISATION OF HIGH EFFICIENCY SILICON SOLAR CELL TECHNOLOGY**

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	New South Wales

Key learning

Hydrogen atoms, if appropriately controlled within silicon crystals, appear capable of passivating virtually any defect or imperfection within the crystals.

Of particular importance has been the knowledge gained in relation to how to control the hydrogen in a way that makes it far more effective in carrying out its passivation role. This work has been particularly novel, with important patents, publications and new tool designs arising from the work.

Implications for future projects

This new hydrogenation technology should be relevant to any silicon-based device, particularly solar cell technology, as a way of reducing losses and improving cell efficiencies. In particular, it allows lower quality silicon wafers to be used that cost less to produce and yet still facilitates the making of high efficiency solar cells. It should therefore be an integral part of any future projects or solar cell technologies that are using the low cost commercial grades of silicon. In particular, the technology is Australian owned and so can be available to any Australian projects or Australian solar cell technologies and manufacturing.

Knowledge gap

The extraordinary ability of hydrogen to apparently passivate any kind of defect or imperfection opens up a huge knowledge gap as to how to develop lower cost silicon wafers of lower quality that can then be transformed into higher quality using the new hydrogen passivation technology. Studying and understanding the various defect types and their ability to be passivated or fixed by the hydrogen will be exciting new areas of work with potentially huge impact given that silicon wafers dominate the costs for making solar cells.

Background

Objectives or project requirements

The project was aiming to improve the efficiencies of solar cells. An important part focused on minimising the losses associated with silicon wafers from which the solar cells were made. Through this, new techniques were developed for controlling the charge state of the hydrogen atoms that were diffused into the silicon, providing the opportunity for improved mobility and reactivity for the *hydrogen atoms. This in turn increased their ability to bond to any types of defects within the solar cell, therefore removing their detrimental effects.*

Process undertaken

A large variety of silicon material types and qualities were studied in terms of their interaction and response to the hydrogen atoms diffused into the silicon using a plasma source. It was realised through this study, that virtually any type of defect could be fixed, but that the challenge would be to simultaneously fix different types of defects, each of which would potentially need the hydrogen atoms to be behaving in a different manner and potentially need different charge states (hydrogen atoms can be positive, negative or neutrally charged). New insights into the mechanisms determining the charge state for hydrogen atoms were gained through extensive literature research covering the last three decades. This revealed the large benefits potentially achievable if the charge state of the hydrogen could be controlled, such as a million times improvement in the hydrogen's diffusivity within the silicon. Several important breakthroughs came when extensive experimentation with a range of innovative approaches let to the successful demonstration of new approaches that allowed the charge state for the hydrogen atoms to be controlled. These were subsequently used on a range of wafer types and quality to show that it was possible to passivate or fix virtually any defect type. The challenge however was to transform such capability into a manufacturable process.

Supporting information (optional)

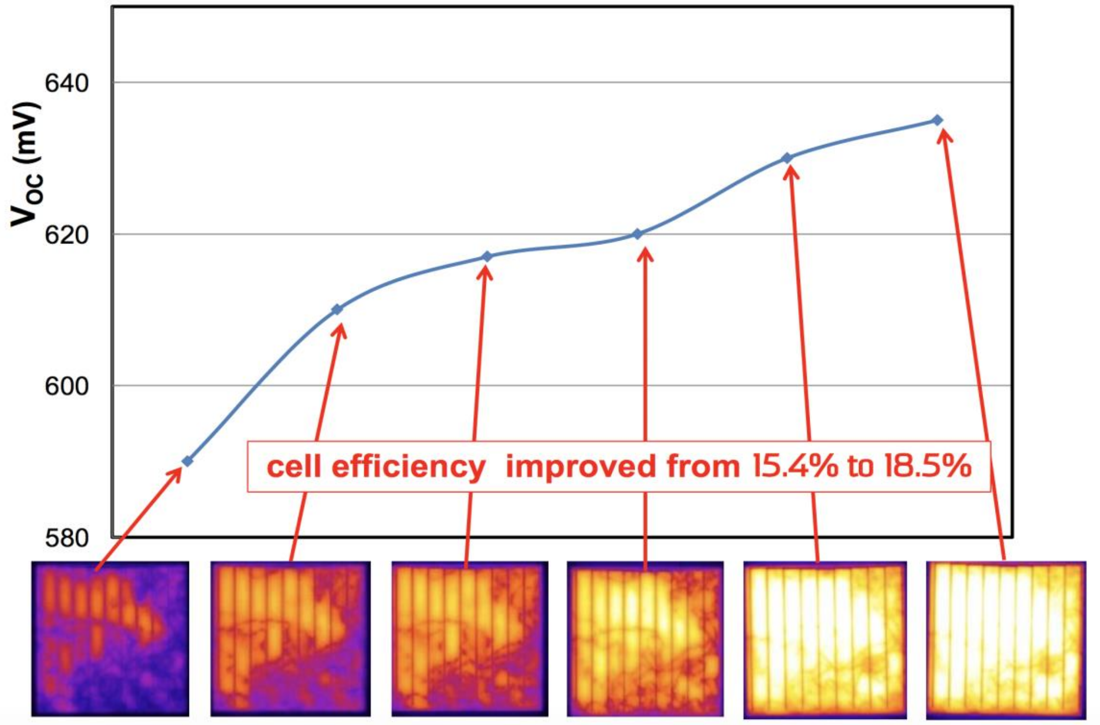


Figure: Reject solar cell of 15.4% efficiency (bottom left) receives 5 varying hydrogen passivation treatments, each further improving the material quality until the silicon wafer is almost defect free (bottom right). The brightness indicates the material quality as measured by photoluminescence while the graph shows the corresponding cell efficiencies indicating the hydrogen treatments raised the efficiency of the reject solar cell from 15.4% efficiency progressively to the excellent value of 18.5%

Lessons Learnt Report: Silicon wafer costs can be significantly reduced by producing lower quality wafers and then using hydrogen passivation to transform them into being equivalent in quality to wafers of much higher cost.

Project Name: **DEVELOPMENT AND COMMERCIALISATION OF HIGH EFFICIENCY SILICON SOLAR CELL TECHNOLOGY**

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	New South Wales

Key learning

Since it appears that hydrogen has the potential to fix virtually any imperfections or defects in silicon wafers, this implies silicon wafer costs can be significantly reduced by producing lower quality wafers than currently used by the industry and then using hydrogen passivation to transform them into being equivalent in quality to wafers of much higher cost. This could be a particularly important finding for the industry given that silicon wafers dominate the costs for making silicon solar cells.

Implications for future projects

There is considerable merit to pursue future projects that aim to significantly lower the costs for silicon wafers, with any reduction in corresponding quality evaluated for compatibility with the new hydrogen passivation technologies.

From the perspective of the industry, a shift to lower cost wafers of lower quality in the future could be feasible without sacrificing solar cell performance.

Knowledge gap

New understanding and insight is now needed, both with regard to producing lower cost silicon wafers but also with regard to how to adapt and optimise the new hydrogen passivation technology to optimally treat or repair the corresponding defects and imperfections.

Background

Objectives or project requirements

Develop a range of new approaches for controlling the hydrogen atoms within the silicon to enable them to passivate all the different defect types found in low quality silicon wafers. In particular, this involves finding new ways to transform the hydrogen atoms between its various charge states so as to impact their diffusivity (ability to move) and their reactivity (ability to passivate different defect types).

Process undertaken

A thorough theoretical analysis allowed a range of new approaches for controlling the hydrogen charge state to be proposed for development and evaluation. Important parameters for the silicon included temperature, injection level, background doping concentration and polarity, response to transient changes in injection level, response to electric fields etc. Extensive experimentation, optimisation and evaluation have allowed several new approaches for controlling the hydrogen charge state to be developed and then patented.

Supporting information (optional)

This area of work will provide the basis for much of the future work in the extension to this project being funded by ARENA and five new industry partners, commencing in July 2017.