Improving World-Record Commercial High-Efficiency n-type Solar Cells through Recombination Analysis & Innovative Passivation

Project results and lessons learnt

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Contact name:	Chee Mun Chong
Title:	Professor
Email: cm.chong@unsw.edu.au	**Phone:** 02 9385 4563
Website:	www.unsw.edu.au

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Executive Summary

The main focus of the project "Improving World-Record Commercial High-Efficiency n-type Solar Cells through Recombination Analysis & Innovative Passivation" is to develop and commercialise technologies for hydrogen charge state control in n-type silicon to improve the material quality and improve the solar cell performance.

The formation of a solar cell using silicon relies on the addition of impurity atoms into silicon to change the electronic properties. In particular, dopant atoms are introduced to provide the material with conductivity. The type of impurity atoms added to the silicon determine whether the silicon is 'p-type' or 'n-type', and both are typically used in different regions of the device to allow the formation of a p-n junction and an electric field in the solar cell. Traditionally, silicon solar cells manufactured commercially have used silicon with a base-doping of boron atoms, which makes the silicon 'p-type'. In recent years, many techniques have been developed which carefully control the charge state and movement of hydrogen atoms in p-type silicon, which has led to significant enhancement in the quality of p-type silicon. Such hydrogen passivation techniques have been adopted by industry and are being widely used today. In 2017, approximately 95% of silicon solar cells were fabricated using p-type silicon; it completely dominated the market. However, the International Technology Roadmap for Photovoltaics, compiled by experts, predicts a significant increase in the number of solar cells made using n-type silicon in the near future.

Due to this vastly increased interest in n-type silicon, the ability to control hydrogen in n-type silicon is now highly important. As the fundamental behaviors of n-type and p-type silicon are different, and much less research and industrial focus has been put on n-type silicon, there are many open research questions when considering the best approach for hydrogen passivation in n-type systems. This work has been focussed on three key research areas to lead to the successful demonstration of enhanced hydrogen passivation on industrial n-type silicon solar cells. First, a comprehensive analysis of defects present in n-type silicon was performed. Results from this work indicate that there are many defects present in n-type silicon crystals, highlighting the importance of techniques to improve n-type silicon. The second research area involves the development of approaches to control the charge state of hydrogen in n-type silicon. Previous work performed by UNSW on controlling hydrogen to improve the performance of p-type silicon has been extremely successful and has led to many leading international cell manufacturers signing agreements with UNSW. Until recently, as the market was completely dominated by p-type cell technologies, little interest was shown by industry in the development of equivalent processes in n-type solar cells. Results in this work have shown promising evidence that controlling hydrogen can be used to cause substantial improvements in the quality of n-type wafers and the efficiency of n-type solar cells. Finally, much work has been done on assessing potential degradation of n-type silicon. Results have shown that degradation, due to illumination and elevated temperature, is also a problem for n-type silicon, potential solutions to this identified problem will be sought in the next phase of the project.

The first phase of the project has led to the successful demonstration of methods to control hydrogen in n-type silicon, which have led to impressive improvements in n-type silicon solar cells. Interesting

insights have also been gained in terms of the types of defects in n-type silicon, and its susceptibility to degradation when exposed to light. In the next phase of the project, the focus will shift to adapting the techniques developed in the laboratory to more industrially relevant tools. The work will be undertaken in conjunction with industry to partners to help to do so, which will lead to commercial solutions for the improvement of high efficiency n-type silicon solar cells.

Project Overview

Project summary

The purpose of this project is to develop new techniques to take advantage of hydrogen passivation in n-type silicon.

In particular, the work is focussed on three key research areas which will lead to the successful demonstration of enhanced hydrogen passivation on industrial n-type solar cells. First, a comprehensive analysis of defects present in n-type silicon was performed. As p-type silicon has been much more widely studied, the understanding of defects or crystal impurities in n-type silicon is limited. Results from this work indicate that there are many defects present in n-type silicon crystals, highlighting the importance of techniques to improve n-type silicon. The second research area involves the development of approaches to control the charge state of hydrogen in n-type silicon. Previous work performed by UNSW on controlling hydrogen to improve the performance of p-type silicon has been extremely successful and has led to many leading international cell manufacturers signing agreements with UNSW. Until recently, as the market was completely dominated by p-type cell technologies, little interest was shown by industry in the development of equivalent processes in n-type solar cells. Now that the market share of n-type silicon is set to rapidly increase, this is of crucial importance. Results in this work have shown promising evidence that controlling hydrogen can be used to cause substantial improvements in the quality of n-type wafers and the efficiency of n-type solar cells. Finally, much work has been done on assessing potential degradation of n-type silicon. Results have shown that degradation due to light and temperature is also a problem for n-type silicon, potential solutions to this identified problem will be sought in the next phase of the project.

Substantial evidence for the improvement of n-type solar cells using laboratory approaches has been produced during this work. The next important step for this research is to adapt the developed technologies so that they can be used in an industrial setting, to produce commercial solar cells.

Project scope

The main aim of this project is to develop commercial approaches to significantly improve the efficiency of n-type solar cells via the control of hydrogen atoms in the silicon crystal.

Hydrogen passivation of defects in p-type solar cells have led to significant enhancements in performance. This has led to multiple companies adopt hydrogen control techniques to improve solar cells which are produced on a commercial scale. The main question posed by this project is, how do we develop equivalent techniques of hydrogen control in n-type silicon which provide enhancements similar to those seen in p-type silicon solar cells? Given the increased popularity of n-type silicon in the solar industry, the application of such techniques would be readily adopted by solar companies.

Outcomes

The following outcomes have been achieved in the first phase of the project:

1. Comprehensive analysis of defects in n-type silicon wafers and solar cells
2. Development of multiple techniques to control hydrogen in silicon crystals
3. Demonstration of significant enhancements in n-type silicon using these techniques
4. Design of a laboratory system to achieve hydrogen control in n-type silicon
5. Filing of a patent describing this approach
6. Provided evidence for degradation in n-type silicon

The last outcome is particularly surprising. It is well known that p-type silicon suffers degradation due to exposure to illumination and elevated temperatures. However, it was traditionally thought that n-type silicon is immune to this. In past years, some companies have claimed that their n-type solar cells are 'degradation free'. Comprehensive analysis from this project, using a wide range of testing conditions and sample preparation, has shown that n-type silicon does indeed undergo degradation. One of the key focusses for the future of this project is to develop techniques to overcome this problem.

Transferability

During the first phase of the project, much work went into the development and understanding of the control of hydrogen in n-type silicon solar cells. Although impressive results have been observed on a laboratory scale, the next important step will be adapting the lessons learnt in the laboratory to tools which are compatible with an industrial environment. Such an environment requires a high throughput, so an understanding of how these processes can be exploited on a very short time scale will be investigated. The facilities and expertise of solar industrial research facility at UNSW will be leveraged for the adaptation of laboratory results to an industrial tool.

Conclusion and next steps

The first phase of the RND003 has been a success, as all key milestones and outcomes have been achieved for the project. Significant progress has been made in terms of insights into the way n-type silicon behaves, in terms of both the types of defects present and the way it can degrade under certain conditions. This understanding will help drive the next phase of the project, whereby solutions will be delivered to some of the material properties identified.

Most importantly, approaches for improving n-type silicon by controlling the way hydrogen atoms behave in silicon have been successfully demonstrated. All IP from the first phase submitted by UNSW will be Australian owned. The crucial next step of for the project will involve adapting the successful techniques demonstrated in the laboratory to an industrial setting.

Lessons Learnt

The following is a summary of the lessons learnt from ARENA project RND003:

1. Although n-type silicon is typically higher quality, it can still contain many defects
2. We can improve the performance of n-type silicon solar cells by carefully controlling hydrogen in silicon
3. The type of degradation seen in standard p-type silicon is also observed in n-type silicon

Lessons Learnt Report: Although n-type silicon is typically higher quality, it can still contain many defects

Project Name: Improving World-Record Commercial High-Efficiency n-type Solar Cells through Recombination Analysis & Innovative Passivation

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

Key learning

Over the past ten years, the silicon solar cell market has been dominated by low quality p-type silicon. In recent years, industry has been moving towards high quality n-type silicon cells, as they can lead to high efficiency cells. However, there is much less information about the formation of defects in n-type silicon. In this work, we show the presence of multiple defects in n-type silicon wafers and n-type silicon solar cells. The effect of these defects was shown to have a significant impact on the performance of solar cells.

Implications for future projects

Extensive work has been done to identify and understand defects in n-type silicon. After identifying defects and crystal imperfections, it is important to develop processes to overcome these challenges, to realise the full potential of n-type silicon. Such processes must be suitable for use in industry. If this can be achieved, leading solar cell manufacturers will be very interested in these solutions.

Knowledge gap

From an academic perspective, it is important to understand how much these defects influence the performance of solar cells. Also, industrial solutions must be sought to overcome defects in n-type silicon.

Background

Objectives or project requirements

The aim of this part was to find the presence of defects in n-type silicon which could reduce the performance of n-type solar cells.

Process undertaken

Various techniques were used to identify defects in a range of n-type materials, both for high quality mono crystalline material and low quality multi material. The influence of these defects on the quality of n-type silicon crystals was shown to be substantial.

Supporting information (optional)

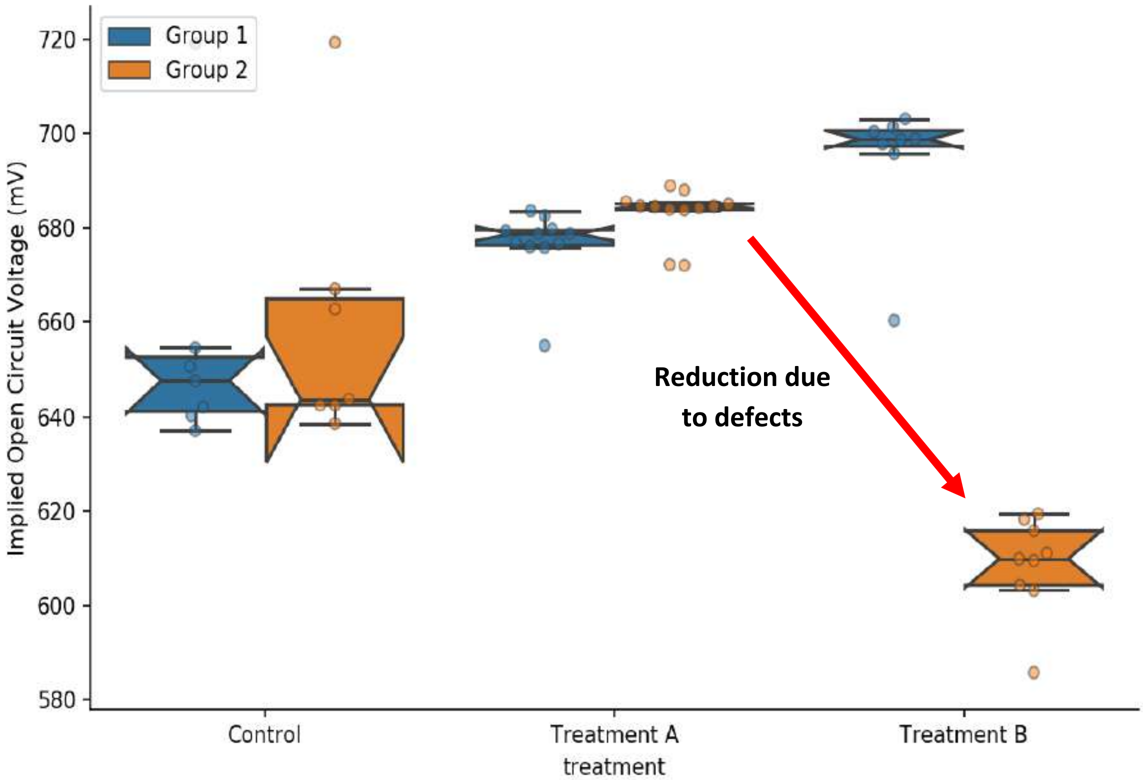

Figure: A severe reduction in the implied open circuit voltage, a property used to measure n-type silicon wafer quality, is observed due to the presence of oxygen-related defects.

Lessons Learnt Report: We can improve the performance of n-type silicon solar cells by carefully controlling hydrogen in silicon

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

Key learning

It is well known that controlling hydrogen atoms in p-type silicon is an effective method to passivate defects in the silicon crystal. However, the fundamental physics of the increasingly popular n-type silicon is different, therefore, new approaches and understanding were required to improve the quality of n-type silicon.

From this study, several approaches were developed which were able to control the movement of hydrogen in n-type silicon crystals. This led to significant improvements in both the material quality of n-type silicon, and the efficiency of solar cells made using n-type silicon.

Implications for future projects

With a rapidly increasing market share projected for n-type solar cells, these methods to improve the performance by controlling hydrogen are relevant for all future project working on this material. From an industrial perspective, the efficiency improvements will be very advantageous for companies. The approaches used have been submitted for IP protection and will thus be Australian owned.

Knowledge gap

The demonstration of these improvements on a laboratory scale is very impressive, however, further work is required to transfer this technology to a technique which is more relevant for an industry setting. The solar industrial research facility at UNSW will be utilised to help drive the required adaptations.

Background

Objectives or project requirements

Design new approaches to improve the quality of n-type silicon by carefully controlling hydrogen atoms in the silicon crystal.

Process undertaken

A variety of laboratory approaches were explored to allow for the control of hydrogen in n-type silicon. Important processing parameters in these investigations included the silicon response to temperature, wavelength of illumination, power of illumination intensity, cooling rates etc. Insights were gained into how these processes influence the quality of the wafers, as well as the efficiency of n-type solar cells.

Supporting information (optional)

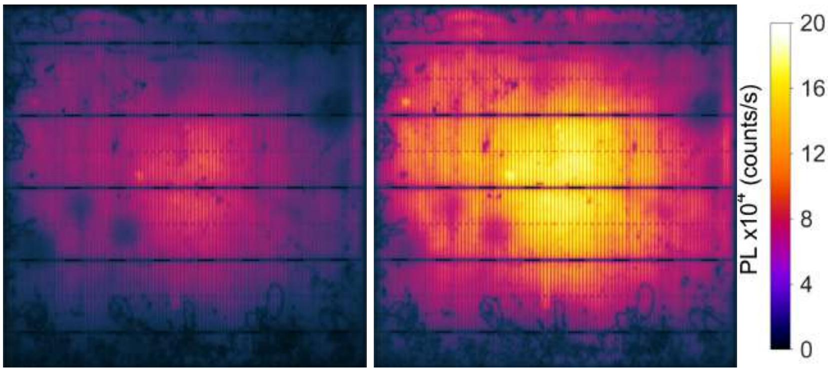

Figure: Photoluminescence images of a n-type silicon solar cell before (left) and after (right) a treatment to control hydrogen in the silicon. The bright regions indicate higher material qualities.

Lessons Learnt Report: The type of degradation seen in standard p-type silicon is also observed in n-type silicon

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

Key learning

Many studies over the past ten years have shown degradation in p-type silicon due to light and temperature. Initial wisdom suggested that this was not the case for n-type silicon. In fact, some manufacturers claimed that n-type silicon products were 'degradation free'.

By testing n-type wafers using a variety of industry standard tests, we show that instabilities are also relevant for n-type silicon. This was particularly relevant for lower quality n-type material, with reduced crystalline quality.

Implications for future projects

These results have significant implications for solar cell manufacturers. To make their product more attractive, the performance of solar cells is typically guaranteed by manufacturers for long time periods, e.g. 25 years. Therefore, degradation of n-type silicon solar cells could have significant cost implications for manufacturers. Understanding how to solve this problem, from an academic and industrial perspective, should be an integral part of future projects investigating n-type silicon.

Knowledge gap

After identifying this significant problem for n-type materials, solutions must be sought to overcome these instabilities. As previously demonstrated in p-type silicon, controlling the charge state and movement of hydrogen may hold the key to stabilising these solar cells.

Background

Objectives or project requirements

The aim of this part of the work was to assess whether n-type silicon wafers also suffer from degradation in the same way that p-type silicon does.

Process undertaken

Both n-type silicon wafers and n-type silicon solar cells were subjected to a series of industry standard testing methods to assess the potential degradation of the silicon material. The key parameters of these investigations include the intensity of light, the temperature of the solar cell and duration of light soaking. Degradation curves, whereby an initial drop off in performance was observed, indicate that this problem is not solely associated with p-type silicon.

Supporting information (optional)

Degradation test results on n-type silicon have shown that this material undergoes degradation. The image shows a significant reduction in the material quality of n-type silicon tested under light and high temperature.

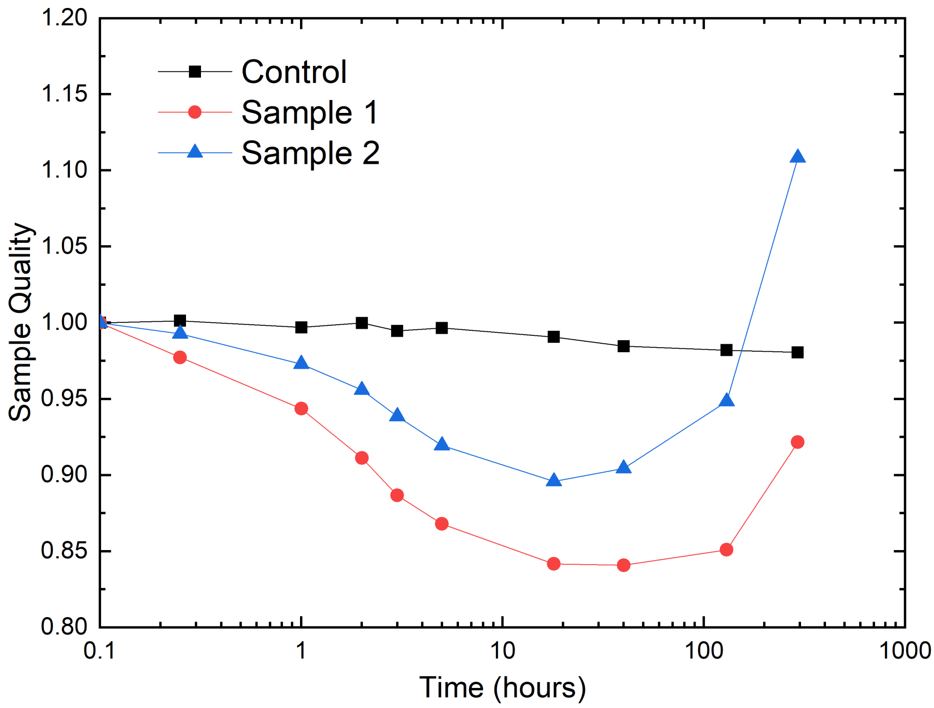

Figure: Change in material quality for all three different n-type silicon samples that were tested under 1 sun equivalent light intensity at 75 °C. The control sample (without diffusion) was not degraded; sample 1 and 2 with boron and phosphorous diffusion respectively were degraded under 1 sun and 75 °C.