Development of novel hydrogen trapping techniques for breakthrough Si casting and wafering technologies

ARENA 2017/RND010

Project results and lessons learnt

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Executive Summary

With silicon still a dominant cost of making solar cells, the focus of this project has been to develop new techniques to heal defects that exist in low-cost silicon wafer types. New cheaper wafer sources such as cast quasi-mono silicon (QM-Si) also known as cast-mono silicon, and small-grain mc-Si wafers offer the potential for significantly reduced solar cell cost as well as a lower carbon footprint, but generally have lower performance due to these defects that form during the silicon growth. Previously, testing typical advanced hydrogenation processes on such wafers was shown to be ineffective at healing these grown-in defects, likely due to the rapid dispersion of hydrogen throughout all the silicon. This project focuses on newly patented methods of controlling the hydrogen that utilise the defects to absorb more hydrogen into the silicon and trap it in the defected regions where it is needed the most.

The project aimed to improve the understanding of defects in these materials in order to develop and optimise the new patented hydrogen trapping processes. We have identified a range of different crystallographic and impurity defects that affect these wafers. The different defect types respond differently to different hydrogen trapping treatments. We have developed a range of treatments to target specific defect types and reduce their electrical impact. We have shown that we can reduce the recombination activity of all defect types and completely deactivate some crystallographic and impurity defects so that they are undetectable. As a result, we have been able to significantly improve the electrical quality of these wafers and effectively mitigate light-induced defects resulting in stable cell efficiencies.

We have now built and commissioned a prototype tool using a commercially relevant 'coin-stack' batch processing technique, with a wide parameter space to enable the range of hydrogen trapping and stability processes to be implemented on finished cells with parameter tuning and optimisation. We have demonstrated that this process is beneficial to cells made from different wafer types. We have applied hydrogen trapping processes using commercially relevant processes to a full-size commercial cast-mono p-type passivated emitter and rear cell (PERC) to achieve 22.10% efficiency; this is comparable to commercial cells made on the more conventional but more expensive, less defected wafer types. As such, the developments from this project can enable the use of these potentially cheaper and more sustainable wafers sources in the high efficiency cell structures of the future through commercially relevant hydrogen trapping and stabilisation processes.

Project Overview

Project summary

The aim of the project has been to develop new techniques for controlling hydrogen to maximise and trap it within defects in silicon wafers for enhanced passivation (healing), to enable cheaper wafers such as cast-mono and small-grain mc-Si wafers to be used as a direct replacement for more expensive silicon wafers in solar cells, while maintaining or even improving solar cell efficiencies.

Evidence for project success can be seen in the development of hydrogen trapping techniques, which have led to over 13 times lifetime enhancement in quality of quasi-mono Si, a typical commercial cell structure fabricated on such a wafer with 22.1% efficiency, and a reduction in cell performance non-uniformity across a cast-mono ingot to less than 0.1% absolute. We have developed techniques to shift the excess hydrogen and minimise degradation to less than 1% in both wafer types while also preventing the increased series resistance identified previously as a result of hydrogen accumulation at the metal contacts. Processes have been implemented successfully on the prototype coin-stack batch processing tool and on a similar tool at an industry partner site. As such, all project milestones and outcomes have been achieved.

Project scope

The aim in undertaking this project is to bring down the cost of solar power by enabling the use of cheaper silicon wafers without sacrificing solar cell efficiencies. Typically to achieve high efficiencies or to move to higher efficiency cell structures, it is thought that high quality silicon wafers are required, these are expensive and use massive amounts of time and energy to produce. Cheaper forms of silicon that are grown more quickly are prone to electrical defects that limit the performance. Advanced hydrogenation is a cheap and effective way of passivating many defects in silicon solar cells, however, the electrical defects such as dislocations formed in cheaper wafers such as cast quasi-mono and kerfless wafers have not responded well to these previously developed processes. These established processes were designed to maximise the hydrogen movement all throughout the silicon, which means that the hydrogen easily escapes many of defects where it is needed for passivation. This project sought to overcome this by developing new techniques of controlling and trapping hydrogen within defected regions to specifically target and passivate harmful defects in cheaper wafer sources to enable their use in current and future high efficiency solar cell technologies with reduced cost.

Specifically, the work focused on three important components required for optimization and development of these techniques and the design, build and commissioning of a prototype tool to implement them. The first was the investigation into the potential of the hydrogen trapping techniques on the low-cost silicon wafer types. The second component involved studying and understanding the defects within the wafers. We identified that the reason for variability of lifetime and responsiveness to hydrogen trapping treatments is due to variability of crystallographic defects as well as impurities. This enabled targeted treatments to be developed and was crucial for being able to develop optimised trapping processes for the different types of wafers and defects. The third, and equally as important component, was to ensure stable and reliable solar cells by eliminating the defects that form under illumination and therefore cause modules to degrade during their life in the field.

Outcomes

This project brought together the expertise of UNSW, ANU and the University of Manchester in solar cell processing, hydrogen and defects in silicon, with the expertise in solar cell manufacturing and wafer crystallisation of the various industry partners.

Important outcomes from the project are listed below:

- Development of a new hydrogen trapping technology
- Significantly improved electrical quality of low-cost silicon wafers
- Improved understanding of the performance limiting defects in these wafers
- <1% light-induced degradation in solar cells made from these materials
- 22.10% efficiency on a cast-mono silicon PERC cell, in line with typical efficiencies made on more expensive substrate types
- Design, construction and installation of an industrial prototype hydrogen trapping tool (see Figure 1)
- Technology transfer to industry partner site

Figure 1: Hydrogen trapping and stability treatment coin-stack prototype tool (a) in operation showing the user interface; (b) showing a stack of 400 cells loaded ready for processing

Transferability

The technology and techniques developed in this project can be applied to many (or all) forms of lower-cost silicon wafers, not just those directly investigated within this work; and potentially even other semiconductor materials where the hydrogen can be similarly controlled due to similar energy configurations within the material. The general study of hydrogen in silicon and its interaction with defects is useful in any silicon technology, solar cell or otherwise. It is therefore important to share this knowledge widely.

Over the course of the project, we published 13 journal publications, 19 conference presentations, one white paper, one media article, one magazine article and a patent. We have held regular workshops to share confidential knowledge to the consortium of partners that are contracted to and currently licensing UNSW technologies, including an online virtual workshop due to COVID-19 travel restrictions. Prior to March 2020, frequent company visits to project partners were also carried out to facilitate technology transfer and to ensure that the latest developments and optimised processes can be implemented as they are developed. In the time of travel restrictions, frequent virtual meetings and results sharing between partners have enabled collaboration and transfer of knowledge to continue. The project design and development of a commercial prototype tool achieved during the project will help to enable rapid uptake of the technology and to make it available for use in industry.

Conclusion and next steps

The new hydrogen trapping technology developed in ARENA 2017/RND010 demonstrated the potential for commercial solutions to passivate (or heal) defects grown in cheaper silicon wafers so that they may be used as direct replacements for more expensive wafers, even in high efficiency cells, with the aim of bringing down the cost of solar cells without sacrificing performance. Many valuable lessons have been learnt throughout the project to date, that will further direct the ongoing investigations and developments in this project, and which have been published and presented via various means, nationally and globally.

We have identified different defects that affect different wafer types and developed treatments to specifically target and heal those defects. Hydrogen trapping treatments have been developed to treat the defects identified in the cheaper wafers. By controlling the hydrogen in new ways that specifically target the defects and maximise the hydrogen where it is needed the most, we have been able to significantly enhance the electrical quality of the poorest quality wafers by over 13x.

Hydrogen trapping treatments were developed to not only improve electrical quality but also ensure stability by mitigating LeTID. At the start of this project, cast-mono silicon degraded by approximately 10% relative due to LeTID and this was seen as a major barrier by the industry for the commercialisation of PERC cells on this material. This project helped to solve this issue, contributing significantly to the model of LeTID based on hydrogen, and solutions to reduce LeTID degradation to <1%. Previous problems with LeTID treatments resulting in increased series resistance effects were solved by using an applied reverse bias to prevent hydrogen accumulation under the metal contacts.

A prototype tool using a commercially suitable 'coin-stack' batch processing technique, has been designed with a wide parameter space to enable the hydrogen trapping and stability processes to be implemented on finished cells with parameter tuning and optimisation.

There were a few areas of research planned for this project that were delayed due to COVID-19, particularly the behaviour of deuterium (heavy hydrogen) in silicon with crystallographic defects. These will be continued in an ongoing collaboration with the project partners.

Lessons Learnt

Lessons Learnt Report: Lessons in prototyping and tool building

Project Name: *Development of novel hydrogen trapping techniques for breakthrough Si casting and wafering technologies*

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

Key learnings and implications for future projects

This project involved the design, construction and installation of a prototype hydrogenation tool, as well as the construction of several other tools for the testing and characterisation of solar cells. Below is a summary of the key learnings from this process, that may be helpful to any future projects involving tool design and construction.

1. **Fail fast / fail forward** – This effectively means testing the riskiest elements of a design as quickly and simply as possible to ensure time is not wasted on something that ultimately isn't going to work. Fortunately, the risks to completion were minimal for the tools built in this project. For the prototype hydrogenation tool, the main risk was addressing the heating limitations of the tool and checking the thermal compatibility and electrical safety of the surrounding components.

2. **Detailed specifications** – Communication at the design stage is essential. Better communication between the researchers and the prototyping engineer to determine the finer points of the intended process can result in finding simpler ways to achieve what the researchers want, or avoid having to build certain new components at all.

3. **Design for safety** – While it may sound obvious, heading off any safety/standards issues at the design stage can prevent a lot of headache (and rebuilding) further down the road. One example of where this could have been done better in this project is in the building of a light soaking station where twin (interlocked) power connections were used to separately power the LEDs and heater, rather than having a single isolation switch. This was done to avoid the long delays experienced in the past having 15A sockets installed at UNSW. A review by an external electrical engineer meant having to rebuild a large part of the control box. Fortunately, the same electrical engineer was able to help review the prototype hydrogenation tool design and list out exactly what was needed to be done.

4. **Modularity and standardisation** – When designing or modifying multiple tools/equipment, it would take a lot longer if both the hardware components and corresponding software building blocks weren't standardised. Maintaining a list of common components and software modules for things like thermal control, power supplies, motion control etc. is incredibly helpful. Deviation from established standards should be avoided, and if there is a

standard solution available off-the-shelf for a reasonable price, it is usually worth it to just buy it. A good example of the benefit of the software modularity was being able to use effectively the same software for both the single wafer lab-based hydrogen trapping tool and the prototype batch tool.

5. **Outsourcing** – It is tempting (especially for any tinkering engineers!) to want to do all the hands-on work yourself. These people often forget to factor in the cost of their own time for these tasks. There are plenty of suppliers out there providing rapid prototyping services, so it is generally a lot easier, faster, and cheaper to outsource production of components, particularly mechanical and electrical parts.

Lessons Learnt Report: The value of industry partner in-kind contributions

Project Name: *Development of novel hydrogen trapping techniques for breakthrough Si casting and wafering technologies*

Knowledge Category:	Financial
Knowledge Type:	Inputs
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

The PV industry has rapidly advanced in the past decade. In many cases, manufacturers can now perform processes at the highest level of quality and at significantly less cost than can be achieved in Australian labs. As a result, their in-kind contributions to research projects can ultimately be more valuable than a cash input to perform the same processes at UNSW. An additional benefit of in-kind has been identified that partners can take on a higher level of involvement in the collaboration when they are part of the processing sequence.

Implications for future projects

In future, we would be more collaborative in designing projects with partners, to make the best use of their processing capabilities and recognising the value of the in-kind that they can offer rather than spending cash to do the same processes for increased costs ourselves.

Background

Objectives or project requirements

Originally we sought cash contributions to conduct most of the experimental work and technology demonstration at UNSW.

Process undertaken

Ultimately, after some major shifts in partners on the project due to changes in their strategic direction, we worked more closely with the new partners who were providing significant in-kind and had better longer-term alignment with the project. Large amounts of the processing have since been conducted by the partners resulting in high quality commercial processing for less cost overall and highly engaged collaboration.

Lessons Learnt Report: Alternative explanation for measurement artifact in wafers with crystallographic defects

Project Name: *Development of novel hydrogen trapping techniques for breakthrough Si casting and wafering technologies*

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

Key learning

Quasi-steady-state photoconductance is commonly used for measuring the effective lifetime (essentially the electrical quality) of silicon wafers. This method utilises eddy currents, or currents travelling laterally through the silicon wafer. A known artifact of this measurement, unrelated to the sample's lifetime, is a strong increase in lifetime at low carrier densities. This artifact is commonly observed in lifetime measurements performed on multicrystalline and cast-mono crystalline silicon (wafers with crystallographic defects). It is often attributed to bulk defects changing their charge state and is referred to as “minority carrier trapping”.

We investigated an alternative explanation of this phenomenon for materials with crystallographic defects. In this interpretation, crystallographic defects are barriers to lateral current flow in the wafer and the extent to which they are a barrier to these lateral current flows changes with illumination. During a lifetime measurement, the wafer is flashed with high intensity illumination which then decays. This change in illumination causes changes to the strength of these barriers and affects the current flow through the wafer, causing the lifetime to appear higher than its true value as the illumination decays. We have shown that regions with higher concentrations of grain boundaries or dislocations exhibit this effect more strongly (show stronger trapping-like artifacts). Thus, it is not necessarily bulk defects or impurities in the wafer that are responsible for this effect in wafers with crystallographic defects.

Implications for future projects

It is important to recognise that high apparent lifetimes measured using eddy current techniques may not necessarily be due to traps or specific impurities in a wafer. In wafers with crystallographic defects, the “minority carrier trapping” artifact observed is at least in part due to the presence of the crystallographic defects and we have developed methodology to identify this.

Background

Objectives or project requirements

Studying the lifetime of silicon wafers with crystallographic defects was a significant part of this project. It was therefore important to understand the mechanism behind the artifact present in lifetime measurements on this material.

Process undertaken

Experiments were performed to understand the conductivity of cast-mono crystalline silicon wafers in the dark (dark conductance) and under illumination (photoconductance) at a variety of positions that contained different amounts of crystallographic defects. Microwave detected photoconductance decay (uPCD) was also used to measure the photoconductance, which does not rely on lateral eddy currents for the measurement, allowing us to rule out effects due to potential barriers at grain boundaries/dislocations.

Supporting information

Supporting information can be found in the publication:

Samadi, A., Ciesla A., Chan, C., Juhl, M. "Implications of grain boundaries on quasi-steady-state photoconductance measurements in multicrystalline and cast-mono silicon" Solar Energy Materials and Solar Cells 2022 11163