# Hydrogenated and Hybrid Heterojunction p-type Silicon PV Cells

# Project results and lessons learnt

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| **Lead organisation:** | University of New South Wales |

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# Executive Summary

Heterojunction solar cells currently hold the world record efficiency for silicon solar cells at 26.7%. However, to achieve the high-efficiency potential of this technology, expensive, high-quality n-type wafers are required. In addition, normal heterojunction solar cells have all processing performed at low-temperatures, meaning that the devices do not benefit from defect-engineering methods that can improve material quality and are normally incorporated for conventional solar cell technologies using cheap p-type silicon wafers. Another key challenge is ensuring a high quality of surface passivation with the ultra-thin amorphous silicon heterojunction structures, and the movement of electrons throughout the device without excessive resistance, both of which reduce performance. All of these aspects undesirably add to the cost of heterojunction solar cells.

In this project, we have set out to reduce the requirement for the quality of the incoming material for heterojunction solar cells, by looking at ways we can use much cheaper, but lower-quality p-type silicon materials. To achieve this, we successfully developed a multi-stage process to eliminate a number of defects that limit the quality of the p-type silicon material. This was primarily to overcome the thermal constraints imposed by the heterojunction structures. As a result, we use high-temperature processing involving gettering to remove mobile metallic impurities, as well as injecting hydrogen into the wafer to neutralise defects. Subsequently, the heterojunction solar cell formed and an extra process is applied to activate hydrogen, and eliminate defects that can cause a degradation of the solar cell performance under sunlight. We also focused on developing a process to apply at the end of heterojunction solar cell fabrication, which can improve surface passivation and reduce resistive losses in the device, and improve performance.

We have succeeded in improving p-type material quality by more than a factor of 10, to enable finished solar cells with open circuit voltages over 700 mV, even for p-type multi-crystalline silicon, which is substantially higher than the current state-of-the-art PERC solar cell technology in mass production. This suggests that there is a large scope for further improving the efficiency of p-type solar cell efficiencies, and that the next generation solar cell technologies could in fact use low-quality silicon, while still achieving high efficiencies. In parallel, we developed a high-speed post-fabrication process for treating industrial n-type heterojunction solar cells that has increased the efficiency by approximately 0.7% absolute, and has gained significant interest for commercial heterojunction solar cell manufacturers as a way to potentially reduce fabrication cost. While a number of 0.7% absolute may not sound like much, for a large solar cell manufacturer, this could lead to an extra $100 M per year. We plan to further develop these technologies and investigate other solar cell technologies where the knowledge can be applied.

# Project Overview

## Project summary

In the project, we set out greatly enhance the quality of p-type silicon materials, such that they can be used for the fabrication of high-efficiency solar cell structures like the world-record holding heterojunction solar cell technology. We demonstrated significant improvements in the material quality by around a factor of 10, for a range of p-type silicon materials including the higher quality mono-crystalline silicon, as well as the cheaper, but lower quality multi-crystalline material. This was achieved using a multi-stage process involving to treat a number of performance limiting defects in the material, while still taking into account the thermal constraints imposed by the heterojunction structure which can only tolerate low temperatures. From this we were able to fabricate p-type silicon heterojunctions with open circuit voltages over 700 mV, which is substantially higher than the current state-of-the-art PERC (Passivated Emitter and Rear Cell) solar cell technology on both materials. In parallel, we have investigated opportunities to perform post-fabrication processes on industrial heterojunction solar cells to improve performance, to really push the boundaries of what is achievable for this technology and lower fabrication costs.

## Project scope

Heterojunction solar cells, require expensive, high-quality n-type wafers to gain the full benefit of the excellent surface passivation provided by the amorphous silicon layers. As a result, the cost of manufacturing heterojunction solar cells is higher than that for conventional solar cell technologies. The heterojunction solar cells are exclusively fabricated at low temperatures, which also avoids opportunities to improve the quality of the bulk silicon material through defect-engineering methods like gettering, to remove metallic impurities, and hydrogenation, to neutralise a range of defects, including some that form under sunlight. Another key challenge is ensuring a high quality of surface passivation with the ultra-thin amorphous silicon layers, and the movement of electrons throughout the device without excessive resistance.

To overcome these barriers, we targeted the development of a multi-stage defect engineering approach with both high- and low-temperature processing to integrate in with the heterojunction solar cell technology. This was designed to perform high-temperature processes such as gettering and the injection of hydrogen into the device, before the formation of the heterojunction structures. Subsequently, we performed a low-temperature process to activate hydrogen with the solar cell to avoid light-induced degradation. We also focused on developing a process to apply at the end of heterojunction solar cell, that can improve surface passivation and reduce resistive losses in the device, and potentially relax constraints for the processing of such solar cells, without reducing performance.

## Outcomes

We successfully developed the multi-stage defect engineering process to allow the fabrication of heterojunction solar cells using cheap, low-cost p-type silicon wafers. We have been able to greatly enhance the quality of p-type silicon material, even multi-crystalline silicon to a level capable of fabricating devices with open circuit voltages over 700 mV. This has been a surprising result for many experts in the field, and has raised the bar for potential efficiency enhancements of solar cells fabricated using this material. In parallel, we successfully developed a high-speed post-fabrication process for treating industrial n-type heterojunction solar cells that has increased the efficiency by approximately 0.7 % absolute, and has gained significant interest for commercial heterojunction solar cell manufacturers as a way to potentially reduce fabrication cost.

## Transferability

The knowledge gained using the p-type silicon wafers has already been transferred to n-type silicon materials to further increase the already high-lifetimes of the material. It is hoped that this could lead to additional efficiency enhancements for industrial n-type silicon solar cells. It could also lead to improved defect engineering processes for conventional p-type solar cell technologies.

The knowledge gained for the application of post-fabrication processes of p-type silicon solar cells have led to the development of post-fabrication processes explicitly targeting industrial n-type heterojunction solar cells, with impressive efficiency enhancements that can be rapidly transferred to industry.

## Conclusion and next steps

The ongoing question is how far can we push the efficiency limits of silicon solar cells using cheap, low-quality silicon? There is an efficiency limit of approximately 29% for silicon solar cells. The current world record is 26.7%, but uses expensive, high-quality silicon, leaving only a small gap to reach the theoretical efficiency limit. However, with the developments in this project, reaching an efficiency of 26.7% using low-cost wafers just became one step closer.

Our ongoing work is targeting translating these improved material qualities to improved efficiencies. Key findings from the project are being published on an on-going basis to ensure others can benefit from this work and can use it to push the efficiencies even higher.

For the Australian Energy System, the developments in this work will lead to higher solar cell efficiencies, that can in turn lead to cost reductions for solar panel systems.

# Lessons Learnt

## Lessons Learnt Report: Essential requirement of gettering and hydrogenation for p-type silicon

***Project Name:*** *Hydrogenated and Hybrid Heterojunction p-type Silicon PV Cells R&D Project*

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

## Key learning

*A key aspect of this part of the project has been the demonstration of how to greatly improve the quality of p-type silicon wafers, so that they can be used to fabricate high-efficiency solar cells that normally require expensive, high-quality n-type silicon wafers. Throughout this, we have identified the complimentary nature of gettering and hydrogenation for eliminating performance limiting defects in silicon, and how gettering can even enhance the response of wafers to hydrogenation. From our studies, both gettering and hydrogenation are essential to incorporate in solar cell technologies for p-type silicon.*

## Implications for future projects

*The results suggest that both gettering and hydrogenation need to be considered for future p-type solar cell technologies. Future projects investigating new solar cell architectures need to consider the impact of cell processes on the lifetime of p-type silicon wafers, and how gettering and hydrogenation can be incorporated into the cell fabrication sequence if they do not naturally occur.*

## Knowledge gap

*A key knowledge gap is how high the quality of p-type silicon wafers can be raised by defect engineering processes, and how such processes could be incorporated into future solar cell technologies. In addition, it is unclear what the exact composition is of defects that the current gettering processes have eliminated.*

## Background

### Objectives or project requirements

*The objective of this work was to identify how the quality of a range of p-type silicon wafers commonly used for solar cells, can be improved through defect-engineering processes such as gettering and hydrogenation. In particular, whether it can be improved to a quality suitable for making high-efficiency heterojunction silicon solar cells.*

## Process undertaken

*Commercial grade p-type wafers were obtained. Gettering was performed in a high-temperature phosphorus diffusion furnace to remove mobile metallic impurities such as iron and measured using the quasi-steady-state photoconductance technique. Subsequently hydrogenation was performed using the deposition of the standard hydrogen-containing anti-reflection coating used on solar cells, followed by a high-temperature firing process to release hydrogen from the anti-reflection coating and distribute hydrogen throughout the device. The quality of the material was monitored using photoluminescence imaging to spatially resolve the implied open circuit voltage of the material and defects in the material. As shown, a greatly improved quality of the material was obtained free of saw damage and recombination caused by grain boundaries.*

# Supporting information (optional)

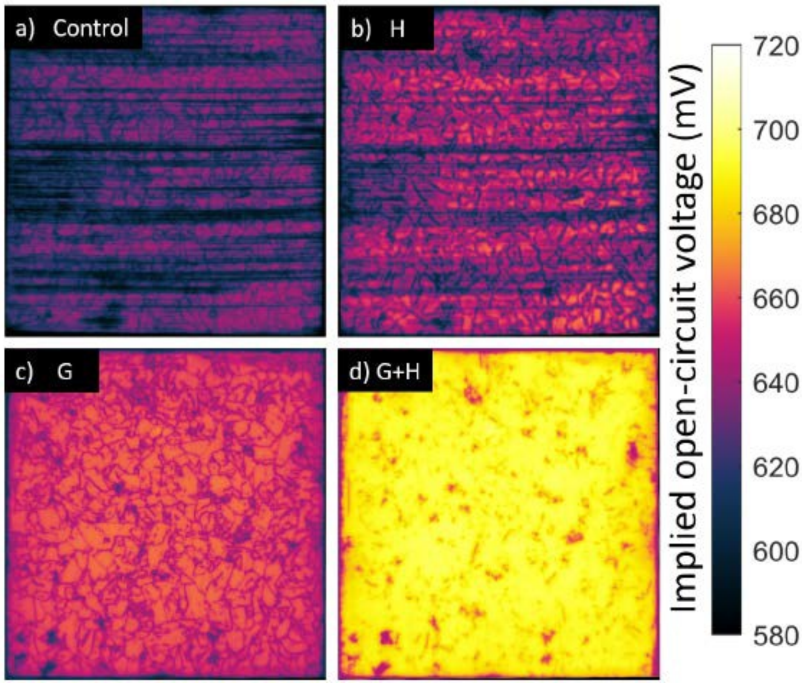


Figure: Implied open circuit voltage maps from photoluminescence imaging highlighting the complementary nature of gettering (G) and hydrogenation (H), and how gettering can enhance the response of hydrogenation.

# Lessons Learnt Report: Post-fabrication treatments for improving the efficiency of industrial heterojunction solar cells

***Project Name:*** *Hydrogenated and Hybrid Heterojunction p-type Silicon PV Cells R&D Project*

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

## Key learning

*Industrial n-type silicon heterojunction solar cells can greatly benefit from post-fabrication processes to improve surface passivation and the transport of electrons within the device. In the past, illuminated annealing processes have been shown to lead to improvements in the efficiency of heterojunction solar cells in the range of 0.2% - 0.4% absolute, but hundreds of hours are required to achieve these improvements. Of particular importance in this project, has been the development of a high-speed process to transform heterojunction solar cells within seconds, to improve the efficiency by 0.7% absolute.*

## Implications for future projects

*The new process should be relevant for a number of high-efficiency n-type solar cell structures featuring amorphous silicon-based contacts. The results suggest that similar to p-type silicon solar cells, future research projects investigating n-type solar cell technologies should study the impact of post-fabrication processes as a method for improving solar cell performance.*

## Knowledge gap

*While impressive efficiency enhancements have already been realised on industrial heterojunction solar cells, little is known about the mechanisms at play. Further research is required to understand the fundamental mechanisms of the efficiency enhancements and what opportunities there are for further efficiency enhancements. We plan on investigating in the remaining duration of the project.*

## Background

### Objectives or project requirements

*The objective in this part of the project was to develop post-fabrication processes for heterojunction solar cells that can improve solar cell efficiencies.*

### Process undertaken

*Industrial n-type heterojunction solar cells were obtained from heterojunction solar cell manufacturer, CIE Power in China. Subsequently, we applied a rapid patent-pending process to improve the quality of the surface passivation and transport of electrons in the solar cell. The* *improved surface passivation resulted in an increase in the open circuit voltage of the due to the improved charge transport and reduced resistance in the device. This led to improved solar cell efficiency.*

## Supporting information (optional)

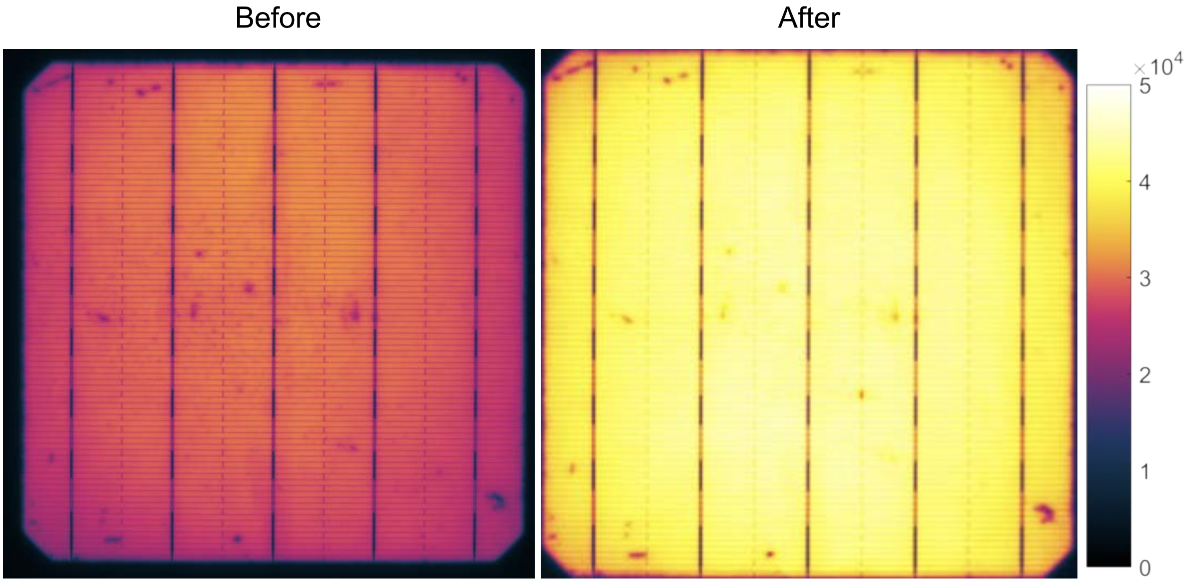


Figure: Photoluminescence response of an industrial heterojunction solar cell (left) before and (right) after the post-fabrication process, indicating the improvement in the device voltage with the process (brighter = higher voltage).