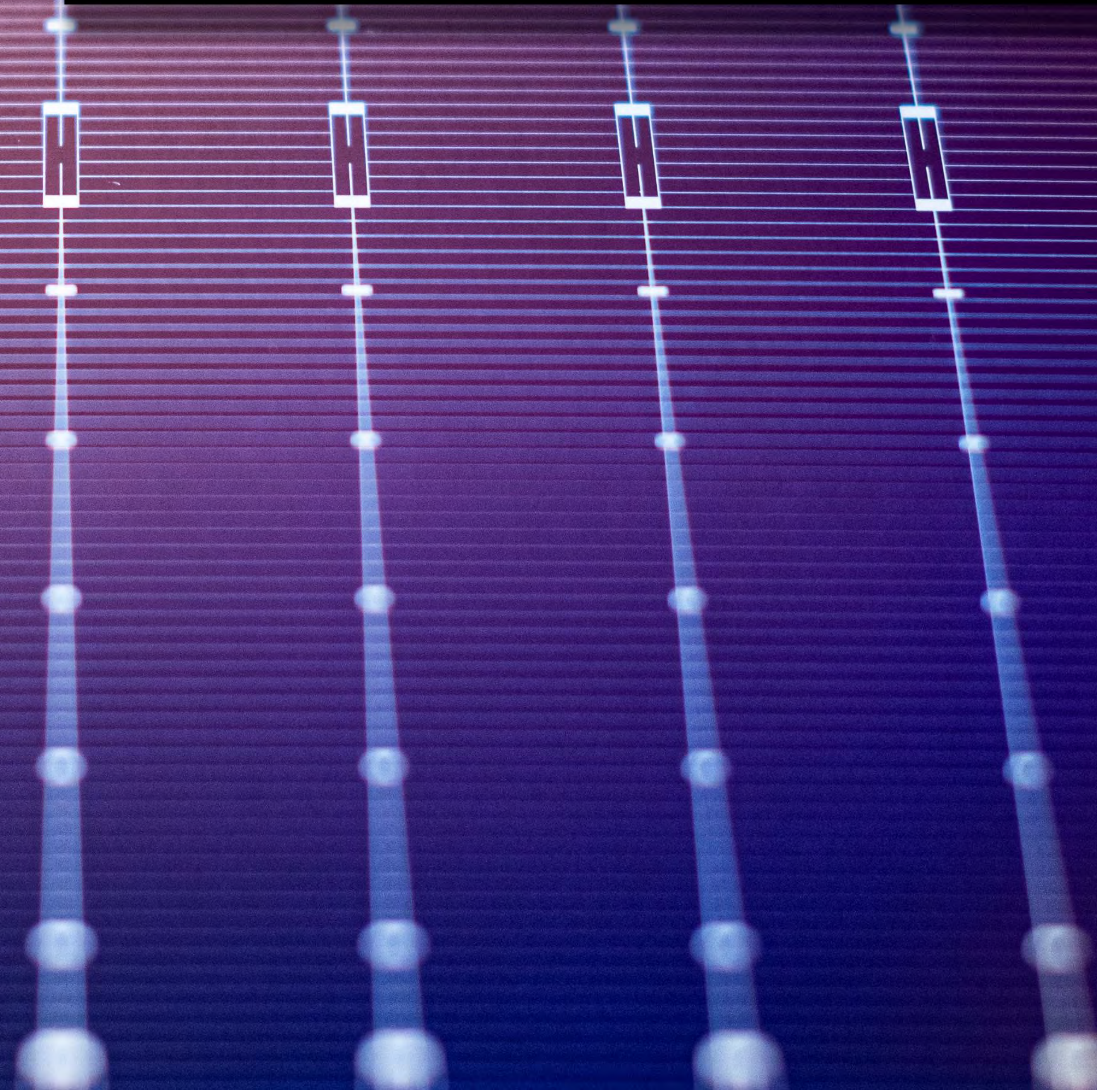
Development and Commercialisation of High Efficiency Silicon Solar Cell Technology

Project Results and Lessons Learnt

School of Photovoltaic and Renewable Energy Engineering
December 2021



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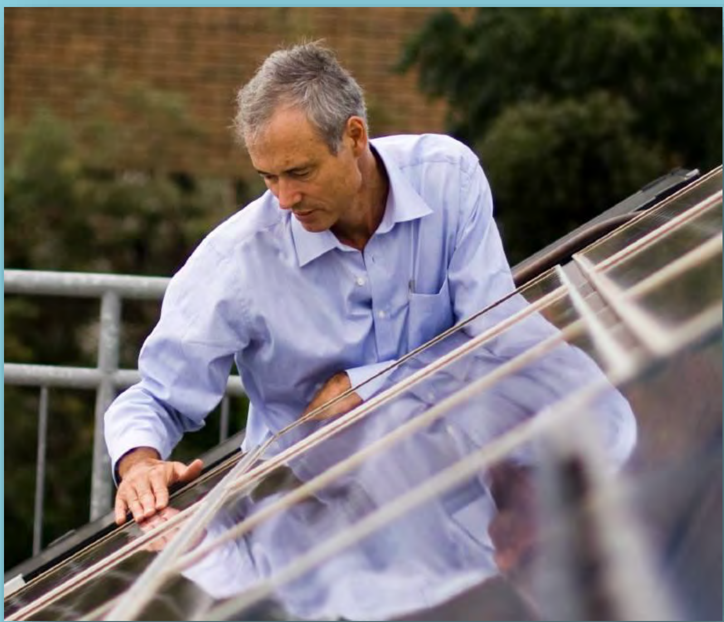

This report is dedicated to the memory of the late Scientia Professor Stuart Wenham who was the brains and inspiration behind the work contained within. His passion, enthusiasm, and unique innovative approach to advance industrial photovoltaic technology was the driving force behind this project. He brought together a multitude of industry and academic partners to solve the issues at the forefront of commercial photovoltaics. His legacy remains in the continued enthusiasm of his team, the ongoing work on commercial technology and an extensive set of scientific resources he created, all set up and ready to tackle the next great problems in solar technology.

Improving the output power and long-term stability of solar panels

New manufacturing technology

The project delivered improved manufacturing and testing techniques. Appropriate use of hydrogen was shown to be critical in maintaining long term solar cell performance. Fundamental studies drove improvements to existing production lines, new tools were created for use at the end of cell production and accelerated testing techniques enabled faster research and in-line production monitoring.

Relevant to 95% of global PV production

The project focussed on the material and cell technology that dominates global production. All forms of crystalline silicon wafers (95% of global production) were studied. In consultation with industry partners, the work focussed on the crystalline silicon PERC cell technology that represented 90% of all commercial solar panels in 2021. The findings had an immediate impact on global production and are anticipated to impact near-term future technology.

Improved stability delivers more clean energy for every GW installed

Technology improvements delivered by the project have already increased the yield for 12 GW of panels installed in Australia since 2019. A further 20 GW of improved panels are expected to be installed by the end of 2022 and each 1% improvement will deliver an additional 280 GWh of clean energy every year.

For 20GW installed,
every 1% improvement in PV performance
delivers 280 GWh valued at $11M for Australia every year.

Testing the stability of commercial silicon solar cells

Light soaking at standard conditions

In the field solar cells are exposed to a range of intensities of sunlight. They also heat up to temperatures as high as 85 °C. This combination of light and heat causes chemical changes within the silicon wafer, which can result in a reduction in the output power of the solar panel. To simulate this process the project used large light-soaking tools that apply controlled amounts of light and heat to the cell. Typical testing times ranged from 48 hours up to 3,500 hours. That is over one hundred and forty days!

Accelerated testing conditions

The project developed numerous accelerated testing tools and processes. These were compared to the results of the standard testing to ensure they produced equivalent results. The project found that by using extremely high intensity light (with elevated temperatures) it was possible to accelerate the failure modes by more than one million times to get answers within seconds. This allowed experiments to be completed faster, speeding up the time to make progress on research and had applications for in-line monitoring of production.

Rapid, accurate testing of solar cell stability enabled fundamental studies and the development of processing solutions

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Executive Summary

The project brought together a team of academic and industry partners to address critical roadblocks to the improvement of industrial solar cells. The work studied all forms of crystalline silicon material that in 2020 represented 95% of all cells produced globally. The first phase (2013-2017) developed and transferred to industry new manufacturing techniques to improve the output power and stability of silicon cells. The second phase (2017-2021) continued the commercialisation of these techniques, adapting them to a wider range of solar cell materials and applying them to solve a new form of light-induced degradation. A particular focus in the second half was on understanding and controlling the use of hydrogen. The work combined fundamental university research with applications in an industrial setting to create a range of critical breakthroughs. Outputs included sixty scientific papers, four patents, improved manufacturing processes for high-efficiency cells, novel reliability testing techniques, contributions to industry standards, and the creation of commercially available tools to improve the performance and stability of mass-produced solar cells.

This report is the final one for the project. The lessons learnt section of this document does not attempt to cover all the technical details contained in the many scientific papers produced, they are already available and referenced at the end of this document. Instead, it attempts to provide a higher-level, less technical summary of the activity and its findings. A major part of the work has been to enable stable, high-efficiency solar cells on a range of silicon materials. The lessons learnt section provides details on three key aspects: the causes of poor cell reliability, testing methods to identify these problems, and processing solutions to mitigate them. A final lesson learnt provides an assessment of the implications of solar cell reliability on the wide-scale deployment of solar energy in Australia.

Project Overview

Project summary

The project worked closely with industry to understand and overcome limitations to the output power and long-term stability of crystalline silicon solar cells. The first phase of the project developed high-efficiency cell processing technology and identified important properties of hydrogen that needed to be further explored and exploited. The second phase of the project (covered in this report) developed a complex understanding of how hydrogen behaves in silicon solar cells, how to control it and how it should best be used when making solar cells, along with potential negative impacts and how to address these. That learning was applied to enable high cell output power on cheaper silicon material and avoid performance degradation in the field. The technical work was done at both industry sites and in academic labs. In many cases, experiments were split between facilities with large scale processing run on industrial pilot lines and specialised techniques (including detailed characterisation and accelerated stress testing) performed at the university labs.

The work developed advanced hydrogenation (AH) processes to enable stable and high-efficiency solar cells. Highly specialised tools were created to enable detailed studies of hydrogenation processes, to develop accurate modelling techniques, to rapidly test thus reducing research cycle time and to develop the AH processes for inline application. Four patents were granted which cover the novelty of the AH processes. Early in the project, a particular emphasis was placed on the study of cheaper forms of silicon, including multi-crystalline and block-cast monocrystalline wafers. Until 2018, cast silicon was the dominant wafering technology, accounting for the majority of a cumulative ~500 GW of installed PV. However, many of the findings were also found to be highly important for more expensive monocrystalline wafers. These substrates rose from a 20% market share in 2017 to 80% in 2020, driven in part by decreasing costs to produce them. At the request of the industry partners, the project scope was expanded to incorporate this wafer type. Developing the AH technology on all available substrate types makes it more widely applicable and provides the industry with flexibility in product design both for their existing manufacturing and for future generations of their products. A key benefit of investigating approaches on a wide range of wafer types is the increased learning that can result and how such learning can be translated from one cell technology to another.

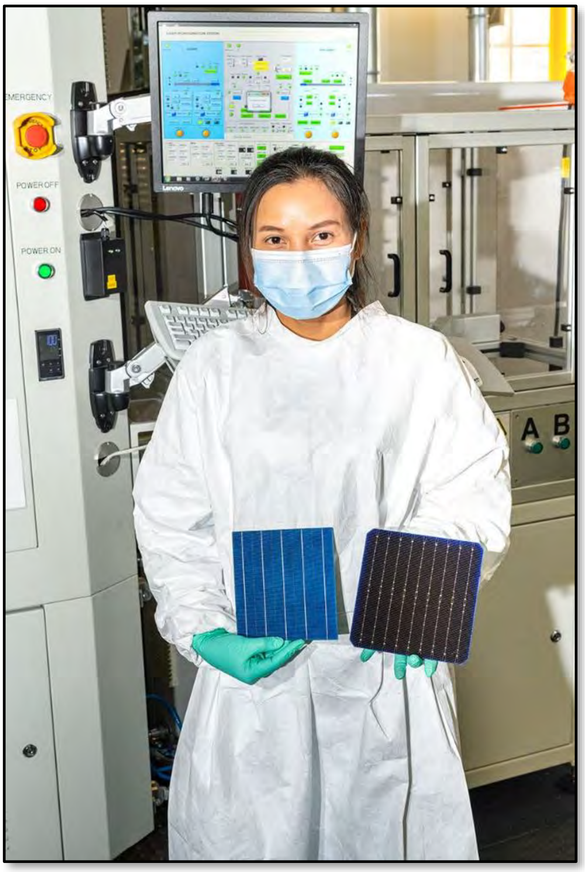
A major activity involved the study and mitigation of Light and Elevated Temperature Induced Degradation (LeTID), a cell failure mechanism first reported in 2012 that can severely reduce the long-term performance of solar cells. When it was first discovered, LeTID was a major roadblock to the widespread deployment of the next generation of high-efficiency cell technology using p-type multi-crystalline silicon wafers, which overwhelmingly dominated the market. At the start of the activity, it was planned to apply advanced hydrogenation processes (developed in the first phase of the project) to mitigate the effects of LeTID. However, fundamental studies revealed that rather than acting as the cure, hydrogen was in fact directly related to the root cause of the problem. The project conducted many studies to (1) understand the root cause, (2) develop rapid testing procedures, (3) study the role of solar cell processing steps, and (4) develop novel post-fabrication mitigation processes. During the project, we identified a susceptibility of all wafer types, including multi-crystalline silicon, and both p-type and n-type mono-crystalline silicon wafers to LeTID. By the end of the project, LeTID is understood, routinely monitored for in production and considered to no longer be a roadblock to the implementation of PERC technology on either multi- or mono-crystalline silicon wafers. As a result, PERC cell architectures have risen to >80% market share in 2020, with more of this technology produced in that single year than all other solar cell technologies ever produced in the proceeding 30 years. The project also investigated the role of hydrogen in other degradation mechanisms, including increased contact resistance and failure of the solar cell surface regions. An important finding was that whilst these harmful mechanisms do not currently impact production solar cells, they may do so in the future. The conditions under which these are likely to cause a problem has been clearly described, meaning that they can be avoided before having a significant impact on solar panels of the future.

The project activity ends with a significant amount of research momentum. A highly skilled team of researchers, combined with over $11M worth of equipment and continued industry engagement, are all in place and ready to continue to solve reliability and performance issues in solar cells and modules. Throughout the activity, the underlying wafer and cell technology continued to evolve, requiring constant re-engineering of the AH technology. This trend is expected to continue, with rapid change in solar cell architecture and materials predicted to continue.

Project scope

The project focussed on the solar cell technology and materials that were dominant in the industry. Throughout the activity, it worked closely with multiple industry partners to ensure that this scope remained relevant. The work studied the passivated emitter and rear cell technology (PERC) which was originally invented at the University of New South Wales and in 2020 accounted for >80% of global production. These cells are made on crystalline silicon wafers and there are several ways these wafers can be produced. The project provided an early focus on the cheaper forms of this material, referred to as block-cast or multi-crystalline material. These substrates have traditionally been cheaper to produce than mono-crystalline wafers but tend to have a lower electrical quality. Towards the end of the project, the focus shifted onto higher quality material (known as Cz named for its inventor Czochralski of the ingot fabrication method) due to a dramatic shift in market share from 35% in 2016 to 80% by 2020 for that material (ITRPV 2017 and 2021).

Processing and testing technology developed in the project needed to be compatible with high throughput manufacturing of large area substrates. A particular focus on the industrial application was required by the work. Based on processes and technology invented during this project, several large, pilot-scale tools were developed, constructed, and installed in the university laboratories to achieve this. Regular meetings with industry ensured the project continued to use the latest production technology. Many experiments were run at industry sites on the fabrication toolsets used to prepare technology for wide-scale deployment.



Project scientist Dr Sen holding large area, bifacial PERC solar cells in-front of a prototype hydrogenation tool.

A specific problem worked on by the project was to solve the issue of the long-term instability of PERC solar cells. This required fundamental studies that investigated the impact of different processing conditions on this degradation. The project studied degradation of the silicon material electrical quality, formation of defects in the surface regions and failures at the regions where electrical contact is formed between the silicon and metal grids.

Outcomes

The technical outcomes of the project enabled the mass production of stable, high-efficiency PERC solar cells on both multi- and mono-crystalline silicon wafers. Highlights included the creation of commercial tools for inline application of the advanced hydrogenation processes, a comprehensive model for the behaviour of hydrogen in silicon and its response to solar cell processing, the development of rapid testing techniques and a significant contribution to the international light-induced-degradation testing standards. A large amount of knowledge sharing was achieved to ensure the broadest possible impact of the project findings with a total of with a total of 116 outputs including 60 scientific papers, 50 presentations and four patents granted (a complete list is available at the end of this report).

Fundamental studies carried out in the project created an understanding of how hydrogen behaves in silicon wafers and how it should be controlled to achieve the optimal processing outcomes. Many detailed studies were published that, when combined, provide a link between the supply of hydrogen, the response to thermal processing, the interaction with relevant parts of the device architecture and the formation of problems including bulk LeTID and surface degradation. Relating these points to their physical origins provides an explanation for a wide variety of experimental observations and directs the development of models, testing techniques and mitigation strategies. Many practical studies were conducted in tandem with industry teams to determine the impact of standard processing and the advanced hydrogenation process on the efficiency and stability of commercially produced solar cells. Based on this learning, new processes to further stabilise the cell efficiency were achieved.

New processes to rapidly test stability and to improve the long-term performance of PERC cells were developed and patented. The rapid testing techniques developed have enabled faster experimental feedback which has resulted in much shorter research cycles and acceleration of process development to treat such degradation issues. Furthermore, they enabled some level of inline cell testing at manufacturing sites to provide monitoring of the stability of mass-produced solar cells. Tools that implement the new hydrogenation processes were designed, built, tested, and then transferred to industry. It is now possible for manufacturers to purchase inline, high-throughput, advanced hydrogenation tools to add to their production lines.

The findings of the work were transferred to industry via regular workshops and numerous on-site visits. In many cases, the project team worked closely with industry to enable the application and optimisation of the testing and processing at their specific sites. Tool manufacturers were engaged to develop inline solutions for the mass production environment. Industry tools that apply advanced hydrogenation for large-scale solar cell manufacturing are now available on the market for purchase from multiple equipment companies. Also, in place are testing procedures to monitor the stability of cells on the production lines.

Hydrogenation tool developed in the project to improve the performance of solar cells.

As a result of this work the PV panels deployed in systems in Australia and around the world are now more stable and provide higher output power for longer periods of time.

Transferability

The technology and techniques developed by the project provide important insight for all future solar cell technologies. This is particularly true for new, even higher efficiency cell architectures that may become mainstream in the future such as tunnel-oxide passivated contact (TOPCon) and silicon heterojunction (SHJ) solar cells, which all use hydrogen-containing dielectric layers. It is expected that the effects of hydrogen on the performance of solar panels will become ever more important as the output power of cells continues to improve. Surface degradation studies point towards a future potential failure mechanism as those regions become even more highly optimised given the sensitivity to such failure mechanisms as the efficiency is increased.

Some subsections of the work were relevant for specific applications of solar panels. Detailed studies into fundamental defects and their interaction with hydrogen are highly relevant to space applications where solar panels are subject to degradation due to radiation damage.

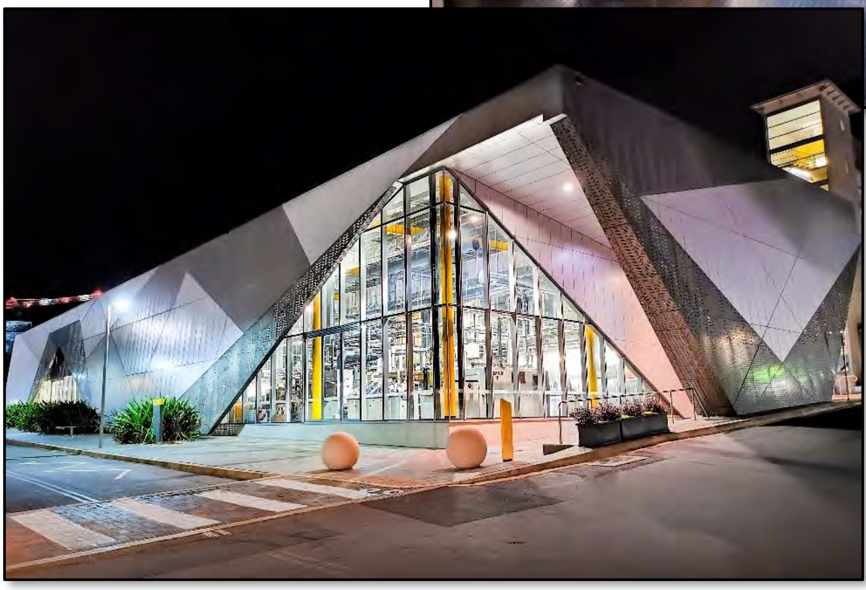
Beyond solar application, the general study of hydrogen and defects in silicon wafers has potentially important learnings for other technology built using those materials.

Conclusion and next steps

The project enabled high efficiency, stable PERC solar cells on crystalline silicon material. At the start of the project, LeTID was causing a reduction in cell efficiency of up to $10\%_{rel}$-$16\%_{rel}$ and was seen as a major barrier for the commercialisation of PERC cells (on mc-Si or c-Si). This fear had extended to the downstream market, where buyers were unsure of the nature of the risk and were hesitant to invest in PERC technology. A major highlight of the project was to help the industry solve the issue of LeTID. Specifically, the project:

- Provided an explanation for the cause of LeTID based on hydrogen, which could explain a wide range of observed behaviours. This allowed the industry to optimise production lines to minimise the amount of LeTID in cells.
- Demonstrated LeTID in Cz silicon material contrary to the belief at the start of this project, highlighting the need to study and solve LeTID in all silicon materials.
- Provided testing procedures to measure the extent of LeTID on finished cells. Rapid tests were developed, which sped up research cycles (testing time reduced from hundreds of hours down to minutes). Project team members participated in the development of IEC standards for LID testing.
- Created novel post cell processing mitigation techniques which reduced the extent of LeTID in PERC cells. Four patents were created on these techniques. Commercial tools are now available to implement them into production lines.

There continues to be technological changes in the PV industry. New substrate doping, substrate sizes, surface passivation technique and cell architectures are all expected to have implications for the continued implementation of the advanced hydrogenation technology. It is important that there is continued development and study of the role of hydrogen to support high efficiency, stable solar cells into the future. Furthermore, other cell level reliability issues, including potential-induced degradation, damp-heat degradation and UV failure should all become topics for close examination by university labs. This project has demonstrated that there is a very useful synergy between academic institutes (who have less product-related time pressures and more ability to deliver conclusive fundamental outcomes) and industry research teams (who have a clear goal to rapidly produce good quality products but less time to determine the underlying causes of problems to prevent them in future development).



The Solar Industrial Research Facility at UNSW where the project developed and tested new technology.

Lessons Learnt

Lessons Learnt Report: Causes of poor solar cell reliability

Project Name: *Development and Commercialisation of High Efficiency Silicon Solar Cell Technology*

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

Key learning

The output power of silicon solar cells may be reduced when exposed to field conditions. The extent of this power loss is dependent on many factors related to the design and manufacturing process used to create the cells. Of all the failure modes that may impact a solar panel, there are two categories which occur primarily at a cell level (as opposed to being related to the module materials and the integrity of the physical assembly). These are (1) light-induced degradation and (2) potential-induced degradation. Both mechanisms were found to impact modern production solar cells, although the extent of the impact related to many factors.

The dominant source of light-induced degradation in crystalline silicon PERC cells was found to be a reduction in the electrical quality of the silicon material. The light absorbed by the wafers provided the conditions needed for a defect to form in the very pure silicon crystal. After much investigation, this was found to relate to an excess of atomic hydrogen introduced naturally during the manufacturing process from hydrogen-containing dielectric layers such as silicon nitride. The technical name given by scientists to this phenomenon is LeTID (light and elevated temperature induced degradation) and we will use that acronym within this report. Studies conducted concluded that LeTID:

- Can affect all the types of crystalline silicon used in manufacturing of silicon solar cells. This includes multi-crystalline, cast-mono, mono-crystalline, wafers doped with boron, phosphorous and gallium.
- Rather than being explicitly caused by light, LeTID Is caused by the charge carriers that result from the absorption of light. These provide a necessary part of the chemical reaction related to control hydrogen to allow the formation of the crystal defect. It is therefore possible to induce this failure mode in the dark with an applied bias or even without an applied bias through thermally generated carriers.
- Is the same failure mode irrespective of the temperature or illumination level at which it is created. This has implications for testing which are outlined in the next lessons learnt.

Based on close collaboration with industry the project made the following conclusions.

- It is possible to produce PV panels that do not suffer from LeTID. This can be achieved through material selection, careful processing, and application of specialised mitigation processes (see next section). Cells and modules with perfect stability were observed on both mono-crystalline and multi-crystalline material.

- Panels created with solar cells based on multi-crystalline silicon typically have a 1% or lower degradation rate, provided the cells are made with the best processing conditions. The extent of the degradation relates to the amount of dislocation regions in the material.
- Cells produced with Ga doped wafers are often more stable, however samples with significant degradation were observed. Given the introduction of Ga doping as the industry standard this was identified as an area requiring further work.
- The failure mode is most likely to impact PERC cells produced prior to 2020 and/or from lower tier manufacturers.

In addition to LeTID, there are other failure modes, related to excess hydrogen in silicon, which do not impact the solar cells currently in mass production, but may do so in the future.

- A failure at the front surface of PERC solar cells, related to a build-up of excess hydrogen in the near-surface region. This failure mode takes a very long time to occur, which has implications for the design of testing methods. The likelihood of this failure is greater with (1) higher emitter sheet resistance values (which is a predicted trend for future cells), (2) mono-crystalline silicon material (which has achieved market share of 80% in 2021), (3) when surface oxide layers are present (which are commonly used to achieve higher efficiency). This mechanism is also likely to affect next-generation solar cells with passivating contacts that are heavily reliant on excellent and stable surface passivation to maintain high efficiency
- A failure at the rear surface of PERC solar cells where a silicon dioxide layer was present. This same type of failure was not found on industrially produced cells that incorporated the commonly used aluminium oxide layer passivation technology.
- A failure of the contact region of solar cells when specific processing conditions were applied after solar cell fabrication. This failure manifested as increased electrical resistance between the metal contacts and the solar cell. It can be explained by a build-up of excess hydrogen in the contact regions.

Implications for future projects

The failure modes described are fundamental to the use of crystalline silicon wafers and, in particular, the use of hydrogen in the manufacture of solar cells. They should therefore be considered with any new cell technology developed where both these materials are present.

Knowledge gap

The work addressed some significant roadblocks regarding the mass production of silicon PERC solar cells. It had been reported that PERC solar cells, and particularly those created on multi-crystalline silicon material, were subject to a severe decrease in output power once illuminated. The source of this reduction was not known, nor was the impact of solar cell design, processing conditions or materials used.

Background

There are many known degradation mechanisms that may reduce the output power of a PV panel when deployed in a field. These are summarised in Figure 1 below (image provided by PVEL[1]). Of these mechanisms, there are several which involve a failure at a solar cell level. These include LID (Light-Induced-Degradation), LeTID (Light and Elevated-Temperature-Induced-Degradation) and PID (Potential-Induced-Degradation).

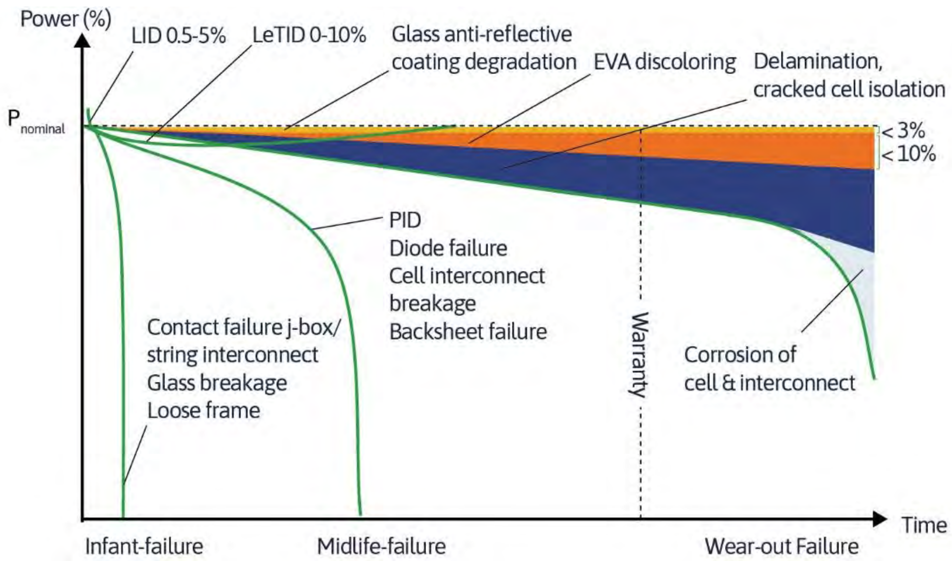


Figure 1. Common modes in PV modules [image reproduced with permission from PVEL]

At the start of this project, it was known that certain types of silicon material experienced a decrease in electrical quality when illuminated. One major source of this was the formation of a defect in the silicon crystal related to the boron and oxygen atoms it contains. This is shown as LID in the figure above. The first phase of this project studied this problem and developed techniques to accelerate the testing and to mitigate the problem in cell production. It was found that with the correct processing, hydrogen could be persuaded to cancel out the negative effects of this defect. It also demonstrated that the application of very high intensity light (or the injection of large currents) was able to accelerate the healing process. This led to the routine application within the industry of accelerated mitigation processes and light soaking to test the stability of solar cells and the panels that contain them.

To increase the output power of solar cells, and after many years of development around the world, the industry began to change the fundamental design of the cells. The new higher efficiency design was the industrial passivated emitter and rear cell or PERC, an architecture originally presented by the UNSW research team in the nineteen-eighties. This design included high-quality surfaces and was, therefore, more sensitive to any decrease in the quality of the silicon material itself. Of key importance, although it was not known at the time, was the fact that these surfaces also contained significantly more atomic hydrogen than previous production solar cells. These cells provided a significant boost to the output power, however, as their deployment ramped up, it was observed that this power would decrease when they were deployed in the field. This new form of degradation, although like the previously studied LID, was much more severe and impacted the output of the solar cells over a much longer

[1] PV Evolution Labs – module reliability scorecard (https://modulescorecard.pvel.com/)

period. This was labelled as LeTID, and given the success of creating hydrogen-based solutions to the earlier LID problem, it was proposed that the second phase of this project apply those same methods to investigate and solve LeTID.

Objectives or project requirements

Identify the cause of reduced performance that occurs in PERC cells when exposed to illumination. Determine the fundamental reason for this degradation and how it relates to material, cell design and processing conditions. Understand the fundamental behaviour, including response to light and heat, and measure the detailed signature of the defect to enable it to be rapidly and conclusively identified. Study the relationship to hydrogen and any interactions (positive or negative) that occur.

Process undertaken

The project studied the root causes of solar cell reliability through a process of both studying industrially produced cells as well as creating test structures that isolate specific aspects of the solar cell structure. This was supported by the development of rapid testing techniques (described in the next lessons learnt) which enabled much faster feedback of the results.

Project scientist Dr Mai operating a solar cell characterisation tool, capable of measuring and decoding the performance of a solar cell in sunlight.

Supporting information

Model for the behaviour of hydrogen in silicon

Figure 2 demonstrates a generalised model of hydrogen that links the supply of hydrogen, its interaction with emitter and bulk, its response to thermal processing, and its ability to cause bulk LeTID and surface-related problems. The model was developed to incorporate known behaviours of hydrogen in silicon and experimental results from the project and the literature.

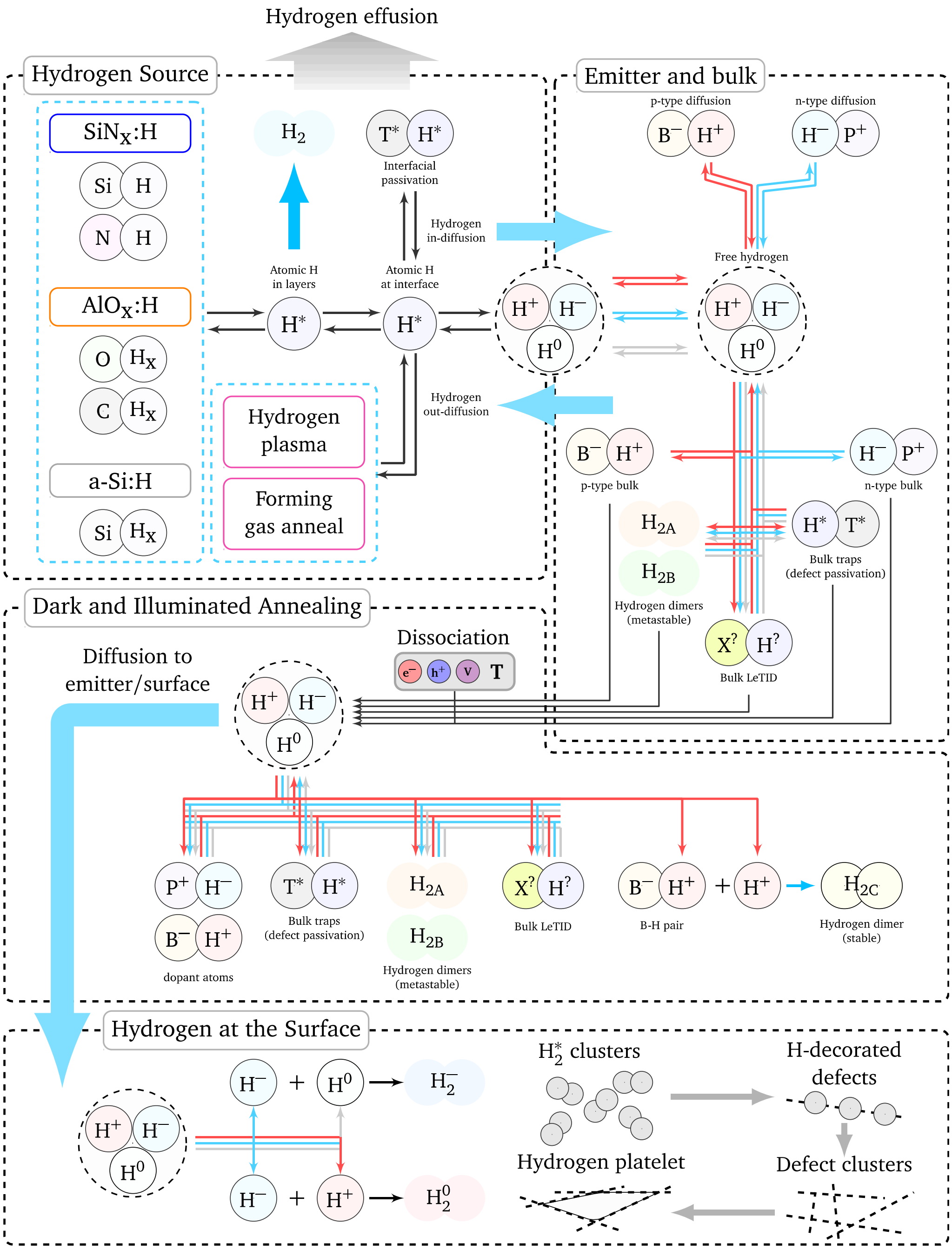


Figure 2. Generalised model of hydrogen and LeTID in silicon [from Daniel Chen PhD Thesis]

Lessons Learnt Report: Accelerated Degradation Testing

Project Name: *Development and Commercialisation of High Efficiency Silicon Solar Cell Technology*

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

Key learning

Rapid and accurate testing of light-induced degradation is critical to solving this issue. The project found that using standard test conditions, it would take 100 to 1000 hours for LeTID failure and >1000 hours for hydrogen-related surface failure to occur. These time scales are too long to be applied to inline production monitoring and slow down the time to create experimental results. The project found that it can be accelerated more than 1 million times by increasing both the light intensity (or by increasing the amount of current applied to the solar cell) and increasing the testing temperature. This accelerated technique was shown to induce the same failure mode as under standard test conditions within 10 seconds of exposure to high-intensity illumination at elevated temperatures. The extent of the failure was measured to vary with the applied testing conditions, something that could be predicted with accurate modelling of the defect kinetics. This provides confidence that the accelerated tests are providing an accurate signal of the expected performance of the device in response to real-world light soaking and that the test conditions do not induce new failure modes.

Detailed studies of specific properties and behaviours of failure modes enables them to be identified and separated from other problems. Inducing specific types of failure modes enables their properties to be isolated and measured. This in turn creates a fingerprint of the defect which can be used to identify the specific problem is occurring. This is important as there are many causes for LID, some of which may be yet unknown. Once failures start occurring in mass production, it is very helpful to be able to quickly identify the root cause. For the LeTID defect the project was able to measure its defect fingerprint using highly specialised tools and to provide details of how it would respond to thermal processes. The project also developed and applied techniques that can make these measurements on finished products which are not directly measurable with standard techniques. It was found that the defect fingerprint could be obtained on finished solar cells using temperature-dependent measurement of the voltage response of the device.

Implications for future projects

This project developed rapid testing procedures for light-activated defects affecting both the bulk and surface properties of silicon solar cells by using high-intensity laser-illumination at elevated temperatures. The same processes can be used to identify stability issues in other solar cell technologies such as TOPCon and SHJ solar cells, which have already been demonstrated under projects 2017/RND003 and 2017/RND005, based on the learning from this project. This will be particularly important for surface-related degradation issues that have substantially longer timescales of degradation than existing known bulk degradation effects such as boron-oxygen LID and LeTID. Future studies should utilise such progresses to rapidly identify potential long-term reliability issues.

Knowledge gap

Rapid testing

The industry standard for testing LeTID at the start of the project was at 75 °C for approximately 1000 hours under 1-sun illumination. A key knowledge gap was how to accelerate such processes to accelerate research cycles to timeframes more suitable for research in the range of seconds to minutes. Furthermore, on certain types of silicon, this testing process would induce multiple types of problems. Alternatives were also explored that enabled the isolation of individual failure modes.

Background

Objectives or project requirements

This project set out to create testing procedures that induce degradation mechanisms on a timescale faster than the time taken for it to form in the field. The objective of this was to rapidly identify stability issues in solar cells and rapidly test the response of solar cells to mitigation processes, allowing an acceleration of research cycles. A key aspect of this was to validate that the accelerated testing techniques induce the same failure mode with an extent of degradation representative of exposure to field conditions. This included using rapid processing for fundamental studies to focus on identifying defect kinetics and therefore the most appropriate mitigation strategies to apply.

Process undertaken

Accelerating Degradation Mechanisms

The project drew on earlier work demonstrating an accelerated defect formation for B-O related degradation by using high-intensity illumination that proved vital for the rapid elimination of B-O light-induced degradation. From this, we investigated the use of high-intensity laser illumination (~100 suns) to accelerate degradation with a targeted process temperature of 100-150 °C to significantly accelerate degradation compared to 75 °C at 1 sun but ensure that passivation mechanisms are still sufficiently slow to highlight the degradation mechanism, which occurs more readily at higher temperatures.

Accelerating Degradation Mechanisms in the Dark

From the understanding of the behaviour of hydrogen in silicon, we also investigated processes to cause LeTID in the dark and how such processes could accelerate degradation kinetics. We tested a range of time and temperatures for dark annealing processes and observed that short dark anneals at 250°C could accelerate degradation kinetics when exposed to subsequent illumination.

Investigating Degradation Kinetics

A custom build laser-hydrogenation tool was vital in the development of accelerated degradation processes. For large area devices this was achieved in a DR Laser Advanced Hydrogenation tool for use with ex-situ monitoring. In addition, a laboratory tool was developed with in-situ characterisation capability based on contactless photoluminescence imaging to provide the real-time response during degradation studies in high resolution. These methods were coupled with numerical simulations to determine degradation kinetics.

Supporting information

Specialised tools for rapid degradation

The project developed techniques to accelerate the formation and recovery cycle of defects within the silicon wafers. Initially these were tested by constructing an experimental setup within a specialised laser laboratory. Later the technique was implemented in a commercial tool by the company DR Laser. A first version of the tool was installed in SIRF, where it was heavily used by the project to conduct fundamental studies and to develop and test mitigation strategies. Images of the tool are shown in Figure 3 below.

Figure 3. DR Laser Hydrogenation tool in the UNSW SIRF labs, capable of both rapidly inducing LeTID in silicon wafers and for developing advanced hydrogenation solar cell processes based on high light intensity.

Using accelerated and modified degradation tests to understand LeTID

Figure 4 shows the response of a PERC solar cell to different types of light stress. In the top figure, conditions close to those experienced in the field were used. The maximum point of degradation occurred at slightly longer than two hundred hours, followed by a very slow recovery. The bottom graph shows the response of a very similar cell, however, in that case, the DR laser tool was used to stress the cell. Maximum degradation occurred after 25 seconds of light stress. The project demonstrated that the defect formed in the cells was the same in both cases, in other words, the use of elevated temperatures and light intensities did not cause a different type of failure. Modelling the forwards and reverse chemical reactions (and their dependence on temperature) found that the accelerated case would tend to result in a less absolute amount of degradation. Those same models could be used to scale the accelerated result to those that would result from standard light stress.

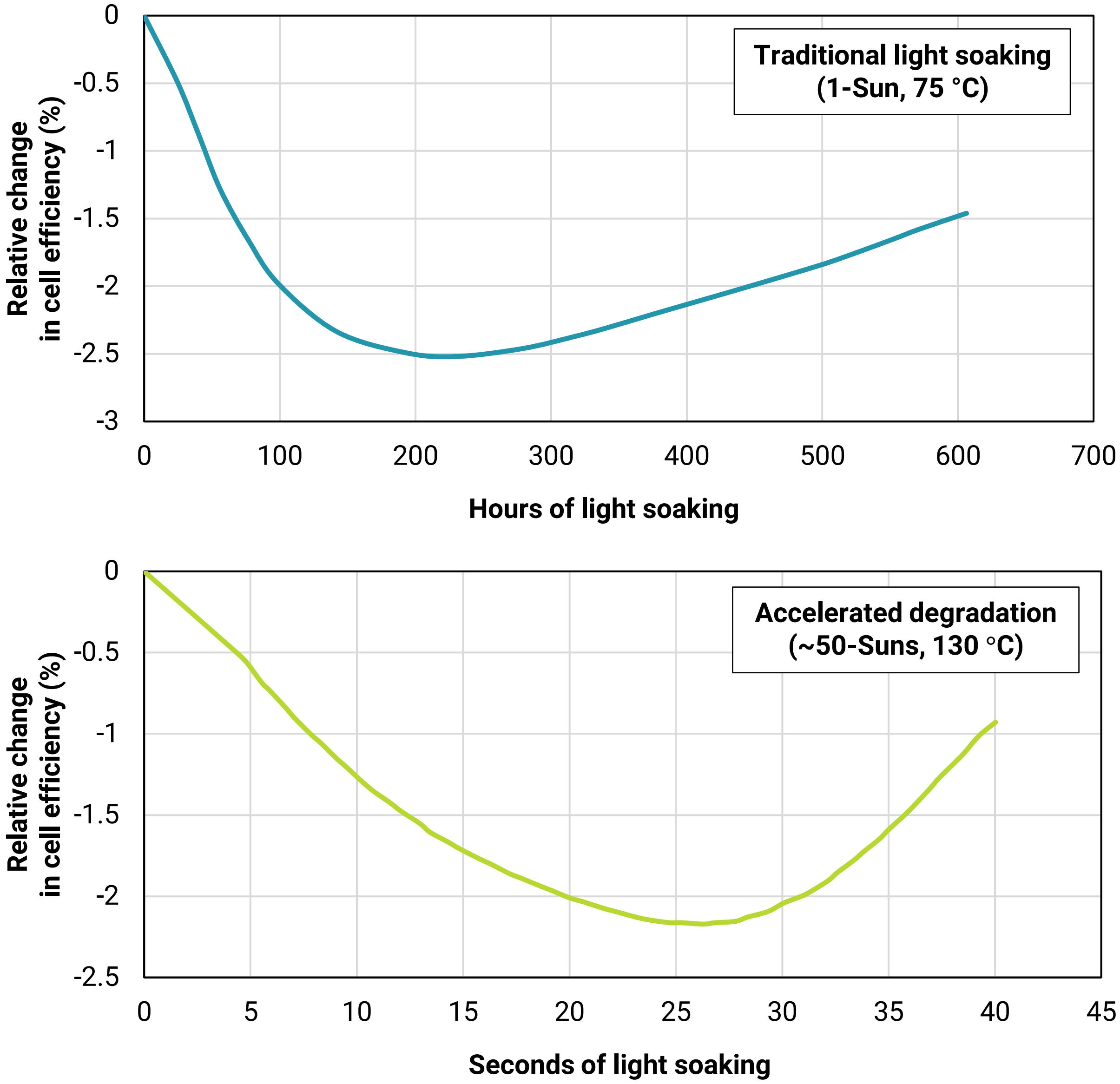


Figure 4. Example of accelerated degradation of an industrial PERC cell. Top figure shows the relative change in efficiency of the cell in response to traditional light soaking conditions. The bottom figure shows the degradation and recovery cycle of a similar cell, this time induced with the DR Laser tool.

Using accelerated and modified degradation tests to understand LeTID

The project also used dark annealing (heating the solar cell without illumination) to induce the defect formation and recovery cycle in silicon wafers. Figure 5 shows measurements of the wafer electrical quality, normalised to the starting point, after different amounts of heat stress applied in the dark. The different colours on the figure indicate different solar cell processing conditions used to prepare the samples (the peak temperature applied during a fast-firing step typically used to cure the metal contacts). This sort of testing was critical for identifying LeTID in Cz silicon (c-Si) with the same signature kinetics as in the cheaper multi-crystalline silicon (mc-Si) wafers. It enabled the defect formation to be studied without undesirable impacts introduced by other types of degradation, which would simultaneously occur when light-soaking the Cz samples.

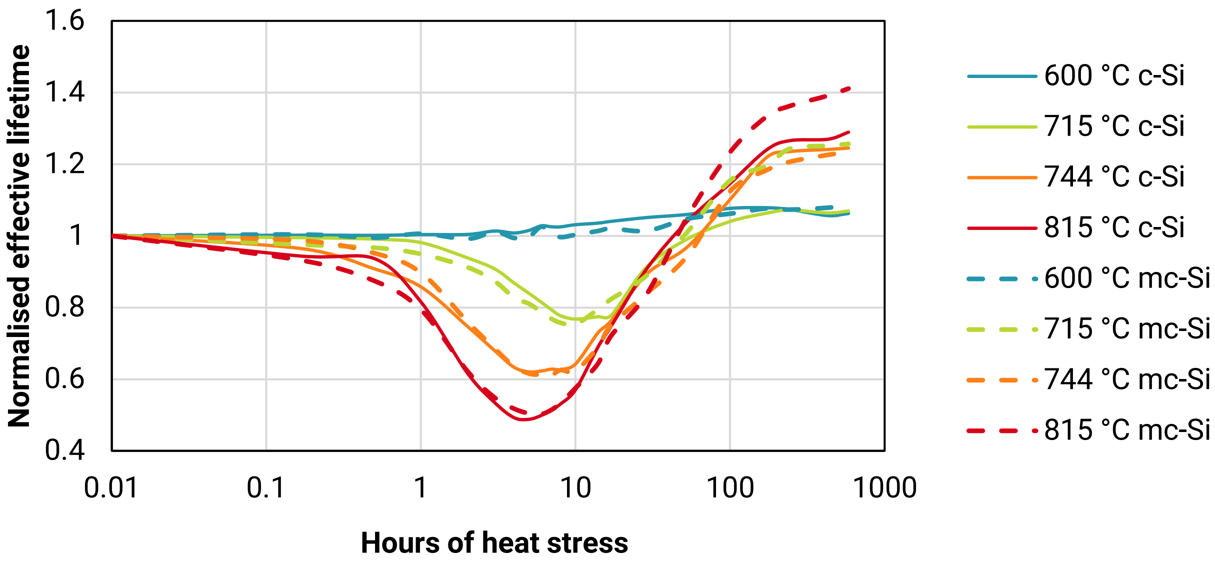


Figure 5. Normalised effective lifetime as a function of heat stress time, measured on test structures fabricated with (solid lines) high-quality mono-crystalline Cz silicon (c-Si) and (dashed lines) lower quality multi-crystalline silicon (mc-Si). Samples were prepared with different peak temperatures during a rapid firing process. Figure shows a clear impact of the peak firing temperature with the behaviour replicated on both types of silicon wafer.

Lessons Learnt Report: Solving LeTID

Project Name: *Development and Commercialisation of High Efficiency Silicon Solar Cell Technology*

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

Key learning

Processing steps to create solar cells should consider that the root cause of LeTID relates to the presence of an excess amount of hydrogen within the silicon. The final concentration of hydrogen within a solar cell relates to many aspects of its design and fabrication. Some crucial factors include:

- The amount of hydrogen within the surface films.
- The density of the surface films and their ability to trap hydrogen within the silicon.
- The level of doping in the surface regions, particularly in the emitter.
- The peak firing temperature used to cure the metal pastes that form the electrodes of the cell.

Other mitigation strategies were created to reduce the amount of hydrogen that remains within the solar cell either during the cell creation process or after it has been finished. These included:

- Firing the cell at lower peak temperatures (although this requires re-engineering of the metal pastes).
- Firing the cells at a lower temperature prior to the screen printing and the contact firing step.
- Adding an additional lower temperature hold after the peak firing but before the cell is cooled to room temperature.

Finally, it was also shown to be possible to accelerate the formation and recovery of the LeTID cycle by applying elevated temperatures and high-intensity light. Alternatively, the cells can be stacked vertically and a large amount of current injected into the electrodes. Both techniques result in the solar cell being artificially pushed forwards to a point at which it will subsequently not degrade once deployed in the field.

To achieve the ideal output power and stability of a solar cell, the manufacturing process should incorporate as many of these concepts as possible. The strategies of reducing firing temperature, lowering the amount of hydrogen in the surface films, and then applying post-production stabilisation (with elevated temperature and high-intensity illumination) can be combined to greatly enhance the stability of the final product.

Implications for future projects

The knowledge gained in this project on developing processes to solve LeTID in PERC solar cells will assist in avoiding LeTID in future solar cell technologies such as TOPCon and new degradation mechanisms as they emerge, such as surface-related degradation. High-intensity illuminated annealing has proven to be a key method to accelerate both degradation and regeneration kinetics to time scales feasible for both experiments to understand fundamental mechanisms involved as well as for processes to improve the stability of solar cells.

Knowledge gap

At the start of the project, it was not clear what was the cause of LeTID, how manufacturing processes affected it and what is the best way to avoid the problem. There was a need to investigate each element of the solar cell and each processing step used to create it, to understand how it would vary the extent and rate of degradation. Early testing indicated that the problem was quite complex, with many complex behaviours and responses to processing temperatures observed.

Background

Objectives or project requirements

This project set out to create manufacturing-ready solutions to the problem of LeTID in commercial solar cells. Working closely with industry manufacturers, these solutions needed to be compatible with high-throughput manufacturing and cost-effective. Furthermore, there was a need to continually evolve the solutions in parallel to the technological evolution of the cell production process. Throughout the project, it was necessary to continually retest the level of production cell stability, verify the nature and extent of LeTID and re-engineer the solutions accordingly.

Process undertaken

Benchmarking studies

Industry partners regularly provided samples of the latest production solar cell technology for testing. Degradation testing was performed with both standard conditions (75 °C 1-sun illumination) and accelerated techniques described in the previous section. Results were compared to previous years to understand any changes in the behaviour or kinetics of the degradation.

Production technology isolation

Test structures were created that removed some parts of the solar cells and isolated others. This enabled the specific impact of each solar cell component to be studied. Furthermore, by not needing to make fully completed solar cells, it was possible to vary the processing inputs beyond the settings that would be required for a working device. This enabled a strong signal to be measured and the fundamental aspects to be clearly highlighted. From these fundamental studies, an important set of learning could be fed back into the actual cell production processes. New, improved production steps could be trialled and the impact on cell stability measured.

Project scientist Dr Borojevic depositing surface coatings onto wafers.

Testing and development of novel processes

New ways to mitigate LeTID were proposed based on the findings of both the benchmarking and technology isolation studies. These were then tested in the UNSW SIRF labs using specially designed equipment to control temperature and illumination intensity. Large experiments to test the process space were conducted, followed by the application of optimised recipes. The results were continually compared to the current best approach produced by industry partners on their production lines.

Scale-up of solutions

The project worked closely with tool manufacturers to develop specialised equipment to apply the LeTID mitigation strategies. Prototype tools were built and tested at the UNSW site, initially at a small scale and later with full-sized tools. These were installed at the UNSW SIRF facility and used to further test and optimise the performance. Later in the project, the specialised tools were deployed at industry sites and the project worked with the relevant engineering teams to test, optimise, and deploy these into production.

Advanced characterisation

For each of the processes described above it was necessary to perform detailed measurements of many aspects of the solar cell performance. Advanced characterisation was performed to monitor the formation and recovery of the LeTID defect as a function of time as well as spatially within the solar cell. Techniques based on the measurement of carrier lifetime within the silicon were used, particularly the imaging techniques based on the photoluminescence technology created at UNSW.

Supporting information

Specialised tools for LeTID mitigation

Advanced hydrogenation processes were integrated into high throughput commercial tools, which are now available for use in manufacturing. Figure 6 shows one example of these tools produced by Asia Neo Tech and installed in the UNSW SIRF laboratory.

Figure 6. Solar cell hydrogenation tool in the UNSW SIRF labs, capable of improving the performance and stability of commercial solar cells.

Enhanced cell stability (LeTID mitigation)

Figure 7 shows the impact of a dedicated step to mitigate LeTID in PERC solar cells. It compares the response to standard light stress of untreated PERC cells to those with an extra stabilisation step. A significant reduction in cell degradation was achieved.

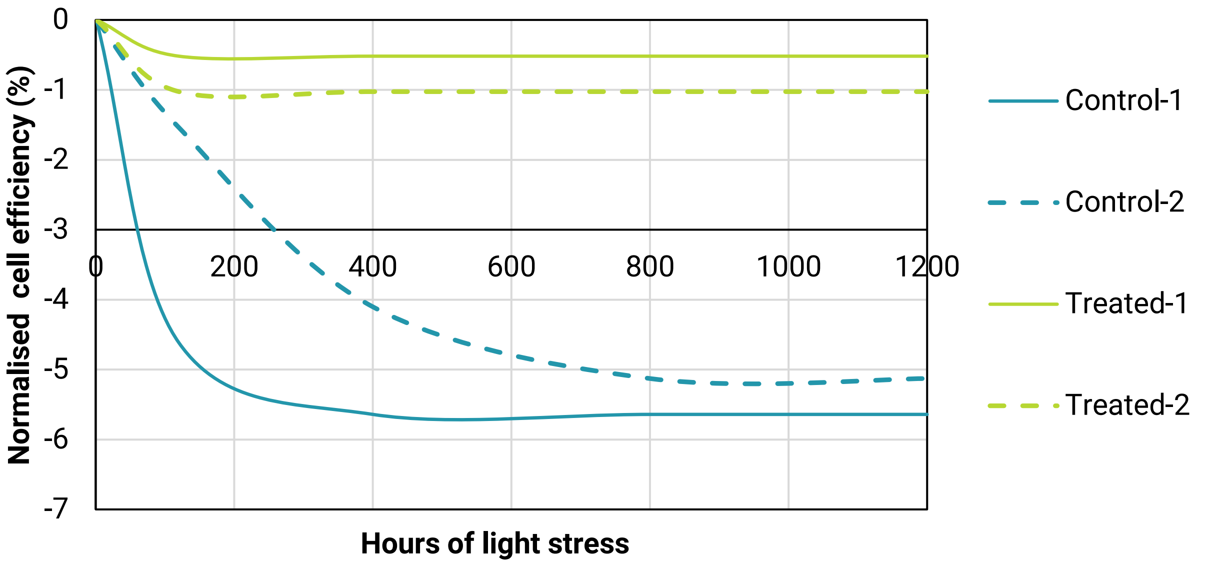


Figure 7. Relative change in PERC cell performance, in response to standard light soaking conditions (75 °C, 1-Sun). Samples shown in blue had no LeTID mitigation step after production and after 900 hours had lost 5-6%$_{rel}$ in output power. In contrast, the cells shown in green were processed with an LeTID mitigation recipe after production and showed only 1-1.5%$_{rel}$ degradation.

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For more information and technical details on the contents above, the reader is referred to the scientific literature. Below is the complete list of papers published during the second phase of the project. Also included is a list of four patents granted in the US (also filed in other jurisdictions).

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