Integrating Industrial Black Silicon with High Efficiency Multicrystalline Solar Cells

Project results and lessons learnt

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Executive Summary

This project is focussed on enabling solar cells to more effectively absorb sunlight and thus produce more output power. In current production technology some of the light incident on a solar cell is lost as reflection, essentially it bounces off the surface rather than being absorbed. To reduce this effect, the front surfaces are sculpted with a texture which deflects the reflected light back onto the cell surface, giving it a second chance to be absorbed. This is an effective strategy, however when integrated with cells many compromises in the shape of the texture occur to enable it to work with other parts of the device (e.g. the metal contacts). The goal of this project is to identify ways to use more advanced textures (black silicon) which are known to reduce reflection (in some cases to zero) but which do not currently work with modern manufacturing techniques. The project utilises advanced tools developed at the university to study the fundamental properties of the texture and collaborates with leading industry manufacturers to process these into cells.

This report marks the halfway point for the project. The project has created several new measurement and computer simulation techniques which allow the black silicon textures to be studied in detail. It has used these techniques to identify the causes of poor integration of the more advanced types of texture with higher performing solar cells and has begun to develop solutions to overcome these limitations.

Project Overview

Project summary

The primary goals of the first phase of the project was to (1) determine the current state of black silicon textured solar cells, (2) identify the potential for further improvements and (3) measure and record the specific processing issues that limit performance (i.e. what is stopping the industry from using superior texture and thus improving performance). The project has externally sourced a wide variety of different types of black silicon from both industry and academia. These samples have been studied to determine the key characteristics of a good texture. To improve the study of these materials the project has developed new measurement and modelling techniques that are compatible with the extreme surface features of black silicon. Experimental work has been focussed on supporting this development as well as identifying the fundamental causes of reduced performance and difficultly in process integration.

Project scope

The project is addressing the problem of how to integrate the ideal solar cell texture into a working device. Currently there exist types of texturing technology which reduce the front surface reflection to zero. However, they are not used in production solar cells and in some cases even lab-based cells are difficult to make. The project identified a lack of published details regarding the fundamental properties of these textures, how that relates to optical and electrical properties and what problems are encountered when they are part of a solar cell. Even the definition of black silicon lacks some clarity since it has been used as a blanket term to describe quite a diverse range of texturing types. The project is seeking to solve these problems by first undertaking a survey of the range of black silicon available and performing fundamental studies that allow them to be compared and understood. Part of this task requires the development of more advanced ways to measure the properties of these textures. The project studies the link between surface properties, the ability to improve the absorption of light in the substrate and the implication for the electrical performance. This last point is dealt with in two parts. The first relates to how the textured surface will change the processing technology used to create the other parts of a solar cell (e.g. can the metal make a good connection to an extreme textured surface). The second part looks at implications for a rougher surface on the electrical quality of the device (i.e. gauging the impact of the texture's increased surface on electrical properties). Ultimately the project seeks to identify a path forward to improve cell efficiency on a commercial production line. This is being done by attempting incremental improvements on the existing texturing as well as working with more extreme types of texture.

Outcomes

The project has measured the fundamental surface, optical and electrical properties of a wide variety of black silicon. From this large dataset it has been possible to identify where existing measurement and simulation techniques can no longer be used. It has also been possible to identify common features within the textures (even when made in very different ways) that impact how they will perform optically and as part of a solar cell. The project has delivered a series of specific measurement techniques that are described in more detail in the Lessons Learnt. Limitations to the application of computer modelling techniques have been identified and some initial solutions developed.
Through strong collaboration with industry partners we have identified both the current state-of- the-

art black silicon production technology as well as an improved version of texturing that would increase cell efficiency if it could be used. Interestingly the project has found that some types of extreme academic texture may be easier to integrate into a working solar cell compared to the chemical-based approaches used in mass-manufacturing. This finding is highlighting key fundamental properties of the texture that will be exploited in the second part of the project to achieve higher performing solar cells.

Transferability

Black silicon surfaces and more generally nanotextures have applications in many fields beyond solar energy including detectors, sensors, lasers and LEDs. The enhanced ability to absorb light naturally results in an enhanced emission of light. Therefore, knowledge about the fundamental properties of these surfaces can be used in many ways. The novel techniques developed by the project are directly transferable to these other fields and are not limited to use on silicon wafers. The project is sharing this knowledge by producing scientific papers that outline the specific details of how these are done and when they can be used.

Conclusion and next steps

The project has identified specific roadblocks that must be overcome to enable better solar cell texturing. The second half of the project will develop specific solutions to these problems which if successful will result in improved solar panels. Being closely aligned with the industry development, these advances will quickly be transferred into commercial products resulting in cheaper solar energy for Australian consumers. By communicating the specific details of these roadblocks, the project enables other groups to also attempt to develop solutions.

Lessons Learnt

Lessons Learnt Report: Nanotexture Characterisation

Project Name: *Integrating industrial black silicon with high efficiency multicrystalline solar cells*

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

Key learning

While commercial tools for the specific purpose of nanotexture 3D mapping and statistical analysis are available and well-established, work carried out within this project has revealed that these tools have limitations that can lead to inaccurate or inadequate results for certain types of nanotexture. Furthermore, it was found that suitable tools for the rapid measurement of texture uniformity and for detailed optical scattering characterisation of low-reflectance textures are not commercially available and require custom development.

Implications for future projects

Part of this project has involved identifying specific characterisation limitations and developing new approaches to mitigate them. Novel alternatives for this purpose have been devised and are being continually tested and further developed throughout the project work. These solutions will be directly applicable to future projects which will benefit from this recent advancement of tools and methods. This will enable rapid collection of accurate characterisation data that was not previously feasible, expediting project timelines and usefulness of results.

Knowledge gap

With regards to black silicon surface topography, it is well-known that conventional surface characterisation may be inaccurate for some types of texture. However, there are gaps in the literature regarding the specific limits of such methods when applied to black silicon nanotextures, and with regards to useful and practical alternative approaches. Within this project the texture feature types that present challenges to conventional methods have been identified and an alternative approach has been demonstrated to accurately characterise these challenging textures. The accuracy and potential limitations of this alternative approach present a further current knowledge gap, these factors are in the process of being gauged.

Additionally, this work has determined that some commonly used forms of black silicon texture processing can lead to relatively non-uniform results. The extent to which this impacts the performances of a finished solar cell is not yet known, the project work continues to investigate this through practical experimentation and simulation in order to fill this gap in the scientific literature, this includes the development of novel methods for rapidly yet accurately determining texture uniformity.

Finally, there is a gap in the knowledge regarding how the angular distribution of light scattered from solar cell textures varies with texture type, and the resultant impact of this distribution on cell and *module performance. This project has developed new tools and rapid modelling approaches which will increase knowledge and understanding in this area.*

Background

Objectives or project requirements

The project aims to improve the understanding of black silicon textures and how they interact with subsequent solar cell fabrication processes, with the goal of improving process compatibility and enabling superior forms of black silicon. In order to study the fundamentals of such textures, their characteristics must be determined. Information required includes characteristics such as the size, shape and layout of texture features, how the texture interacts with various wavelengths of light, and how reproduceable and uniform the texturing process is. The project therefore requires tools and methods for gathering this information with adequate accuracy. Commercial tools for this purpose exist and are available to the project through UNSW and project partner facilities. However, thorough analysis of results from some of these tools has revealed limitations when applied to the specific, complex black silicon nanotextures studied within this work. New tools and methods were therefore required.

Process undertaken

Standard characterisation was carried out on a range of black silicon textures, some that are currently used in commercial solar cell manufacturing, and some next-generation textures that are known to provide some superior qualities but present challenges for solar cell fabrication. The size and shape of features was first qualitatively observed using scanning electron microscopy (SEM) imaging and then three-dimensionally mapped using conventional atomic force microscopy (AFM). Comparison of results from these two techniques revealed mismatching information in some cases, demonstrating that the more quantitative AFM approach can lead to inaccurate data for textures of high aspect ratio, or complex overhanging features. An alternative approach of using Focused Ion Beam (FIB) slicing and SEM imaging to produce an array of cross-sectional images for analysis and processing into quantitative 3D surface maps was therefore developed. Initial results show good agreement with qualitative SEM surface imaging.

For the case of measuring uniformity, it was found that existing tools can adequately characterise this through point-by-point reflectance mapping, however, this is typically a slow process, taking several hours to achieve suitable results. Such timescales become unreasonable when studying a broad array of different textures, or for quality control within a production line. Initial development of a more rapid but equally accurate approach has therefore been carried out.

Lessons Learnt Report: Rapid Modelling of Solar Cell

Project Name: *Integrating industrial black silicon with high efficiency multicrystalline solar cells*

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

Key learning

Computer modelling can be used to determine the optical properties of black silicon textures. However, the most accurate programs for this require large amounts of computing power and are not very fast. The project has explored the use of much more rapid simulation techniques and found that they can be solved quickly enough for use in very large scenarios such as the simulation of the annual energy output of a solar power plant. However, the project has also identified several limitations to these techniques that may limit their accuracy. This limitation is not found to be universally applicable, but rather applies differently to different textures. A fundamental characteristic that was found to impact this was the size of the texture. The project has created a series of scientific publications that outline these limitations in detail [1-6]. Importantly it found that the current form of production black silicon can be rapidly and accurately modelled to determine the absorption of sunlight to generate electricity. Some areas for improved accuracy were identified, particularly as related to performance once encapsulated within a module. More extreme textures were found to not be accurate enough and further development identified.

Implications for future projects

Initially the project compared the output of computer models with measured characteristics of actual samples. Whilst this was an important consideration, it tended to make a thorough comparison difficult. The reason for this was that a more complete validation of a modelling technique requires a wide variation in samples which can span many extremes. Often it can be difficult, costly and time consuming to achieve this in the laboratory. The results may also be more difficult to compare to since they will always include some degree of experimental error. To solve this issue the project combined measured data with randomly generated surface textures. By creating artificial surfaces, it was found to be much faster and cheaper to explore a wide range of texture sizes. The slow but accurate simulation techniques can be used to determine the correct output, and this is compared to the result determined by more rapid techniques.

The project found that very small textures do not actually act like a texture under sunlight. Instead the optical behaviour much more closely matches that of a thin surface film applied to the surface. This phenomenon is not new; however, it is important to point out to other solar projects since it can often be neglected particularly when projects attempt to develop the so-called texture on texture solutions.

Finally, the project found that one of the most commonly used forms of solar cell texturing works better than traditional models have predicted. All projects that are comparing their performance to the incumbent technology should take account of the improved parameters determined by the project.

Knowledge gap

The work has identified a specific set of surface heights and wavelength ranges where the rapid models cannot be considered accurate enough. Further development of the rapid techniques is *required to extend them into these regions. The project has also identified some areas related to the interaction of texture with the angles of light that have not been well tested for the rapid techniques.*

Background

Objectives or project requirements

The project objective is to enable accurate and rapid modelling of all forms of solar cell texture. The goal of this is to improve the accuracy of simulations that determine the annual energy output of a solar power plant. At this stage the project has identified the limitations and gaps in the existing knowledge. These can now be addressed in the second part of the work.

Process undertaken

The project has built up a set of measurement tools capable of accurately determining the detailed optical performance of a texture. A range of textures have been measured and compared to the existing best-known method for simulations. This has been supplemented with the creation of artificial surfaces and the results from much more intensive solving (achieved using a supercomputer).

Supporting information (optional)

A technique to determine the validity of different modelling approaches is to measure the surface height statistics and compare those to the wavelength of light. This can be done using the validity chart shown in Figure 1 below [7], which relates surface height statistics to the type of modelling technique needed to simulate the optical properties of a given surface. With regards to black silicon this chart identifies a region in which ray tracing of geometric shapes can be used and another region that requires more rigorous solving (the electromagnetic region). Added to the chart are four typical solar cell textures measured by the project (shown for the wavelength range absorbed by the silicon). As indicated by their position on the validity chart, three of the commonly used textures (random pyramids (black colour), iso-texture (blue colour) and chemical black silicon (green colour)) can be ray traced. However, the texture formed with plasma etching crosses the boundary between two of the regions and can therefore only by ray traced accurately for short wavelengths of light. This limitation is further confirmed with the comparison between modelling results from ray tracing (lines) and measured texture reflection (symbols) shown in Figure 2. Three textures indicated on the validity chart show good agreement between modelled and measured data, while the plasma texture only works at short wavelengths.

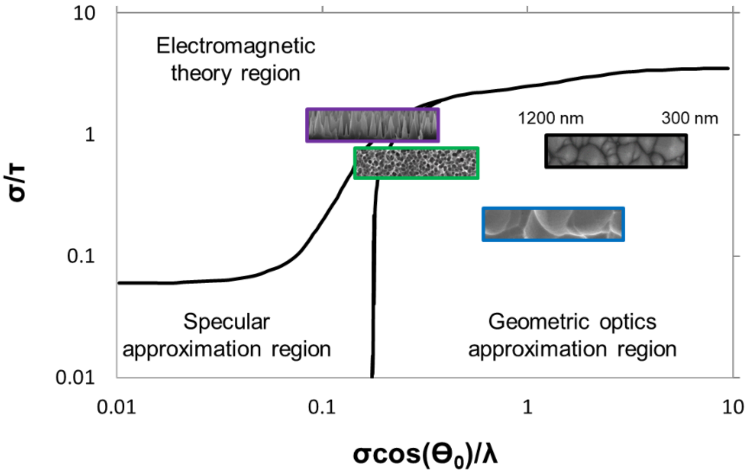

Figure 1. Surface scattering domain plot that relates surface height statistics to the type of modelling technique needed to simulate the optical properties of a given surface. Insets: four typical solar cell textures are shown, (black) upright random pyramids, (blue) iso-texture, (green) chemical black silicon, (purple) plasma black silicon.

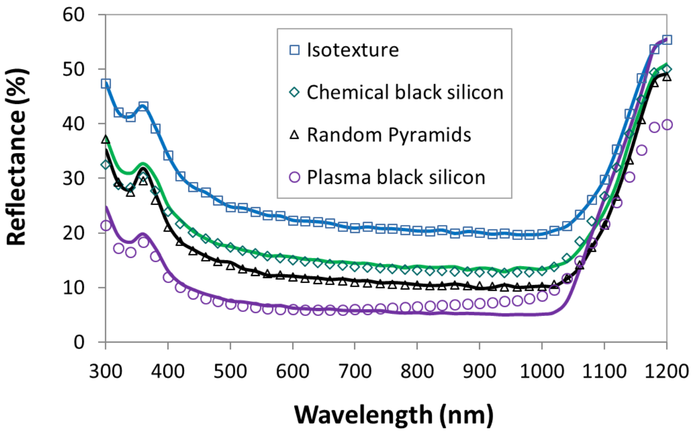

Figure 2. Comparison between (symbols) measured and (lines) simulated front surface reflection of typical solar cell textures, (black) upright random pyramids, (blue) iso-texture, (green) chemical black silicon, (purple) plasma black silicon.

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Lessons Learnt Report: Cell Integration

Project Name: *Integrating industrial black silicon with high efficiency multicrystalline solar cells*

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

Key learning

Black silicon texturing has been successfully integrated into solar cell production resulting in improved performance compared to the old texturing technology. However, these commercial black silicon solar cells are not taking full advantage of the ultra-low reflectance capability of such texturing technology and therefore the potential to further increase the power output of the cell. Low reflectance black silicon cannot currently be used as a drop-in solution for solar cell production. Only moderately low reflectance black silicon textures are being implemented in production (what can be referred to more appropriately as "grey silicon" as opposed to truly "black silicon") in order to maintain compatibility with the current industry standard front side coating and metal contact techniques. The nano-sized features of the more aggressive black silicon texture interact negatively with critical front-end processing resulting in decreased electrical performance that out-weighs the increased optical performance. Integration of such textures requires the optimization of front-end cell processing as well as alternative deposition coating techniques and metal contact approaches. These limitations are marginally addressed in the scientific literature with fundamental aspects not fully explored.

Implications for future projects

For the second half of this project we are requesting more aggressive (i.e. lower reflectance) black silicon textures from our industry partner in order to focus our research on roadmap texture technology as opposed to marginal changes from current state-of-the-art texture technology. Focusing on lower reflectance black silicon texture will enable progress towards available efficiency entitlements. Such an approach falls in line with the established milestones for the second half of the project.

Knowledge gap

Much of the optimisation of commercial black silicon for solar cell applications has occurred in industry resulting in a lack of published scientific details. We have identified several significant knowledge gaps that should be filled. These are most appropriately done at a university where they can be studied at a deep fundamental level. The learnings from this will then help remove industry roadblocks.

These gaps include:

An understanding of the fundamental morphology of black silicon and its interaction with subsequent solar cell production techniques. Particularly in the case of chemically produced textures, the impact of the porous surface on critical solar cell processing steps needs to be identified.

The root cause of poor performance at the front surface needs to be understood in more detail and the individual components separated and clearly quantified. Specifically, the role of (a) front-end processing, (b) conformality and electrical properties of surface coatings, and (c) the dimensions of extreme surface features.

A commercially viable coating technique that will maintain the electrical performance of processed black silicon surfaces.

Background

Objectives or project requirements

This project set out to identify the limitations of black silicon integration into commercial solar cell production. Specifically, the project aimed to verify if current industry standard cell processes in the areas of front side deposition coating and metal contact technologies are compatible with aggressive, low reflectance black silicon textures. Testing various cell process steps on both commercial and academic textures were proposed in order to identify existing limitations and possibilities for future implementation.

Process undertaken

Industry standard and more advanced surface deposition techniques were tested on academic textures in order to identify conformal coverage limitations for ultra-low reflectance textures. The limitations of industry standard techniques were also tested on moderately more aggressive commercial textures. Interestingly, it was found that the relationship between the type of texturing and ability to form a good electrical surface was not obvious. In fact, textures that were assumed by convention to be impossible to passivate worked better than expected whilst less aggressive texture morphologies encountered more problems. This has allowed the project to identify some fundamental characteristics of a texture that determine its electrical potential. This will be exploited in the second half of the project.

Industry standard metal contact technology was tested on commercial black silicon textures by making solar cells on an industrial pilot line. The project found that for moderately lower reflectance textures the metal contact failed and thus identifying a need for testing more advanced metal contact approaches in the second half of the project. Such approaches are in line with the expertise at UNSW SPREE.