Integrating Industrial Black Silicon with High Efficiency Multicrystalline Solar Cells

Project Results and Lessons Learnt

School of Photovoltaic and Renewable Energy Engineering

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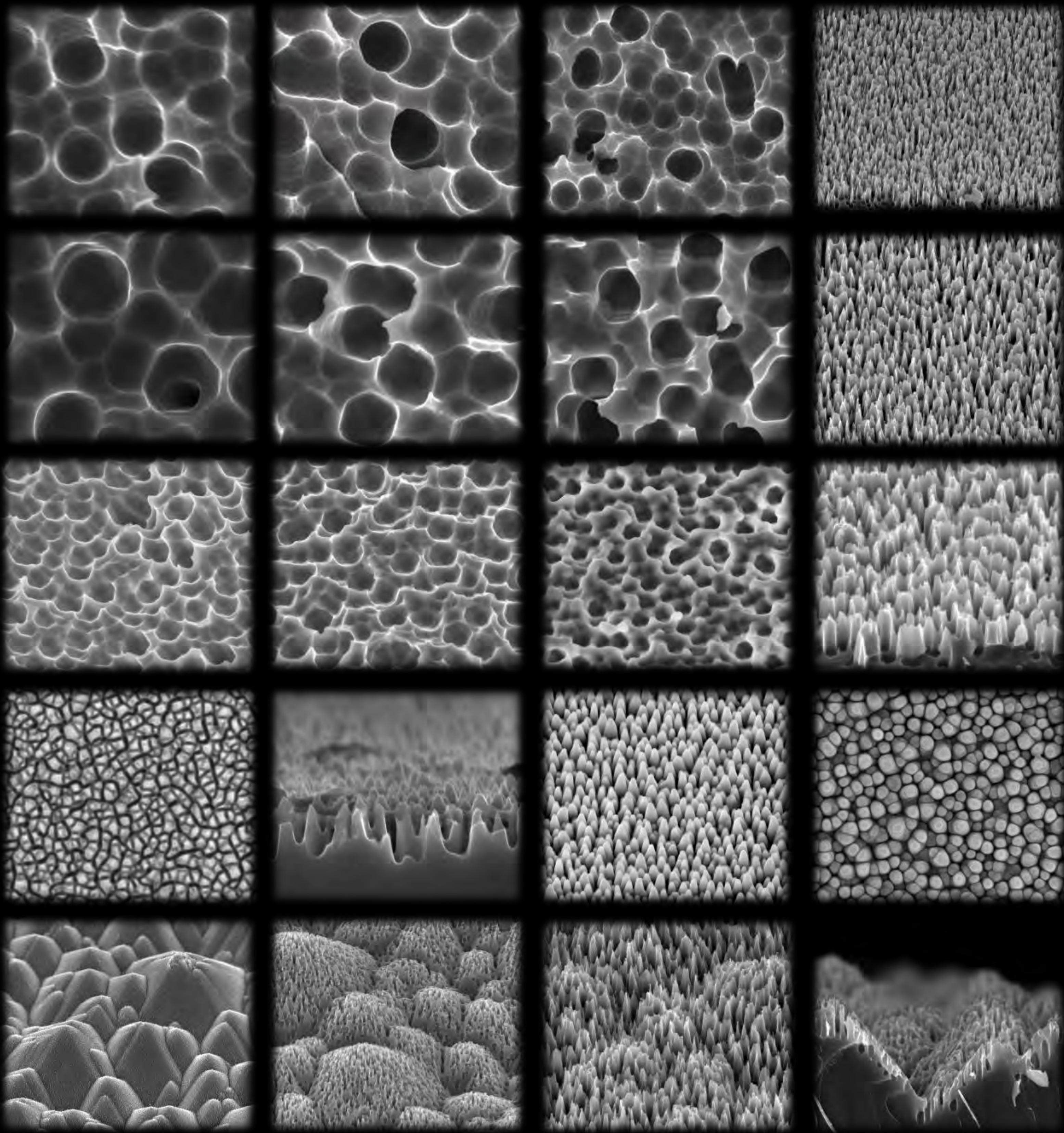

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Executive Summary

Black silicon is a surface texturing technology which can be applied to the sun-facing side of solar cells to improve their output power. It gets its name from its appearance which is extremely dark to the viewer due to the high absorption of light at all wavelengths. Whilst it performs well optically, the complex surface topography presents many challenges when integrating with electrical devices such as solar cells. This project brought together a consortium of industry and academic institutes to address this issue through fundamental studies, production line process optimization and via the development of novel measurement techniques. Work has focused on how black silicon can be measured, how it can be processed into working devices, and how it can be modelled with computer software. The original aim of this work was to enable higher efficiency multi-crystalline silicon solar cells which are cheaper to make. Black silicon was investigated to address the poor front surface optical properties of such devices. However, the work completed is also applicable to other future applications of black silicon such as in silicon detectors, retinal implants, and light emitting diodes.

This report is the final one for the project. It summarizes the key findings and provides the reader with links to the more detailed published scientific reports. The lessons learnt that are presented cover the three major aspects of the work, how to measure black silicon, how to model it with computer software, and how to process it into devices. Throughout the activity a large variety of black silicon has been studied and measured. The data collected has been made available through an online library and can be used by future projects wishing to make use of it.

Project Overview

Project summary

The project worked with a consortium of industry and academic partners to tackle a variety of challenges related to the integration of black silicon into solar cells. The first part of the project focused on identification of the fundamental causes of reduced performance and the difficulty in process integration. The latter part of the project explored solutions to these limitations. This work was supported through the development of new measurement and simulation techniques as well as via the construction of specialized scientific equipment.

Project scope

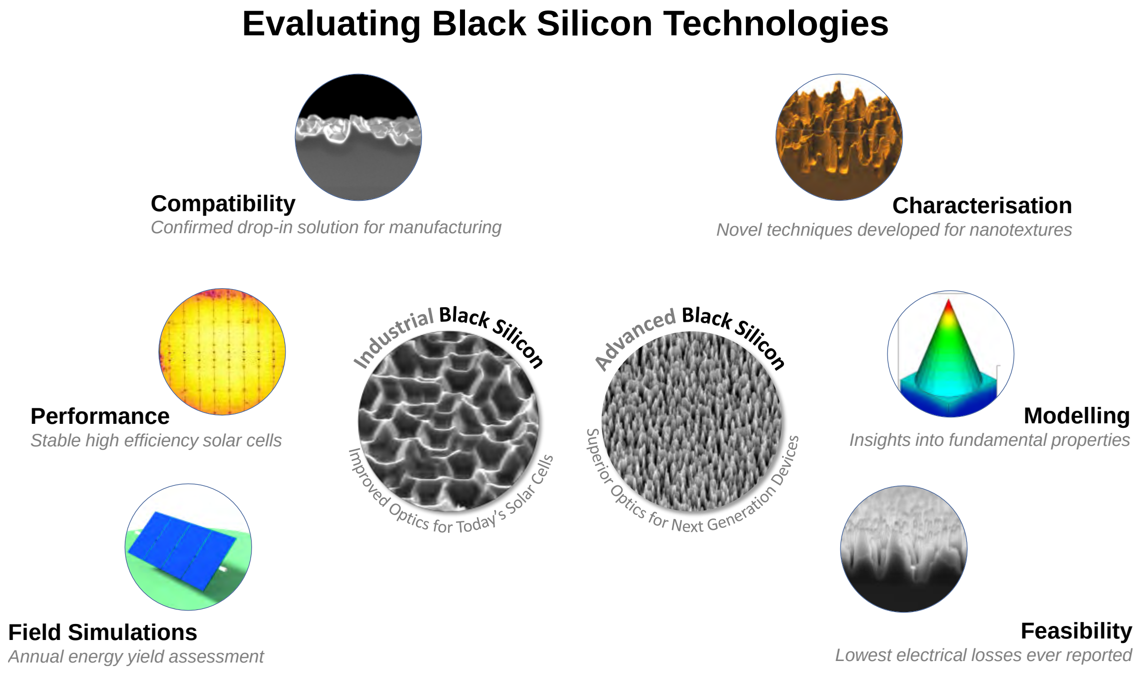
The project addresses the problem of how to integrate the ideal solar cell texture into a working device. Currently there exist advanced types of texturing technology which reduce the front surface reflection to zero. However, they are not used in production solar cells and in some cases even lab-based 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. The second part looks at implications for a rougher surface on the electrical quality of the device. 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.

The fabrication of industrial solar cells relies on the introduction of so-called 'dopant atoms' into the front surface of the silicon wafer to achieve optimal electrical behaviour. Specifically, phosphorus atoms are introduced via a thermal process called diffusion. This process is often re-optimized to increase cell efficiency. Black silicon textures typically enhance phosphorus diffusion resulting in excess phosphorus, which increase electrical losses. Understanding the underlying mechanism for this behaviour is critical to enable effective solar cell optimization. It is also necessary to coat the solar cell surface with a thin layer of protective material that acts to reduce the electrical loss that would otherwise occur at the crystal edge. A problem for black silicon is that this is in practice difficult to achieve due to the very rough nature of the surface. These surface films also provide a supply of hydrogen into the substrates and are crucial in the determination of the amount remaining in the solar cell after fabrication. This is critical to both overall output power and reliability since too much hydrogen is known to cause degradation in power upon exposure to light, and too little results in inferior quality bulk material.

Simulations are widely used within the scientific and engineering community to complement experimental results. They allow measurements to be better understood and provide a far cheaper technique to quickly vary design parameters and study the impact on the end result. Within the solar field simulations are used as part of the construction and commissioning of large-scale power plants. In that case the performance of the devices under a wide range of environmental conditions must be quickly determined. Black silicon presents some specific challenges for modelling due to the complex nature of the interaction between light and the very small surface features. The existing techniques that are applied tend to take many hours to solve and often involve supercomputing. The project investigates alternatives to this which are faster and compatible with the goal of determining the impact of the texture on the annual energy yield when deployed in the field. This work is supported by enhanced measurement techniques which are needed to validate the new techniques and assess their accuracy.

Outcomes

This project evaluated two general classes of textures: (1) industrial black silicon which is intended as a drop-in solution for solar cell manufacturing and (2) advanced black silicon with ultra-low reflectance intended for next generation devices. Significant improvements in the characterization, modelling, and performance of both types of black silicon were demonstrated in this project.



Throughout the three years the project team has collected and measured a very wide range of black silicon samples (some examples shown in Figure 1). These were sourced from both industry and academic partners from across the globe. In total over nine hundred individual samples were created and studied throughout the activity. Where possible the data measured has been shared through the Open Science Framework (https://osf.io/bjswt/) allowing future projects to learn from it, compare to it and use it to help enable black silicon applications for solar and beyond.

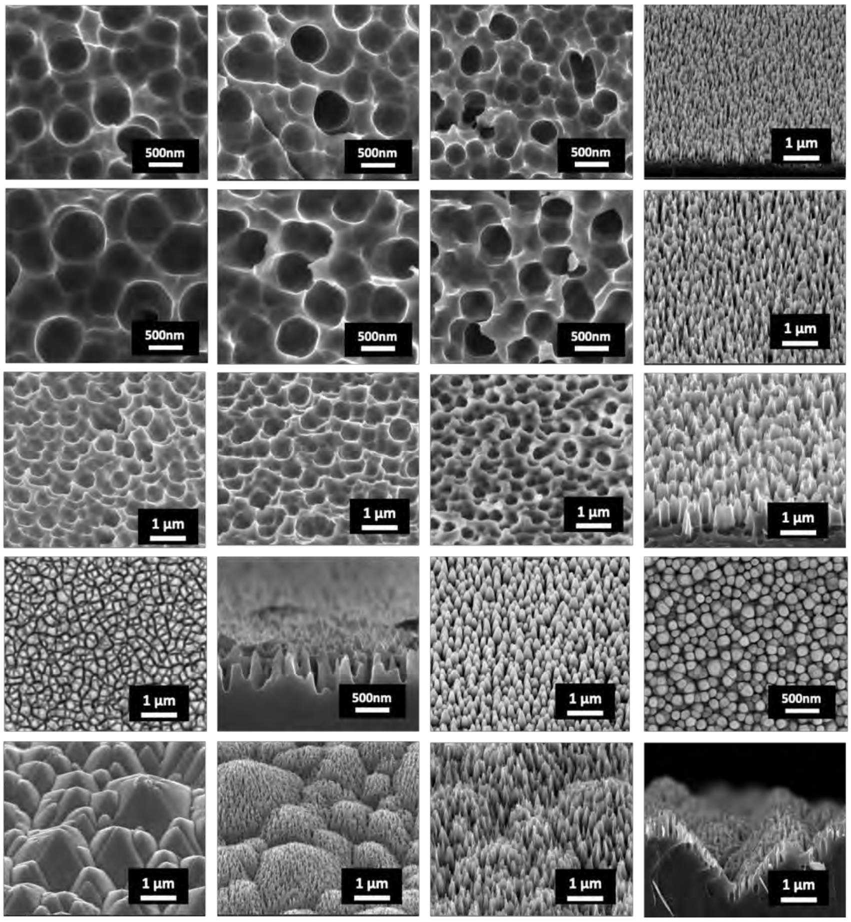


Figure 1: A sample of SEM images showcasing the range of black silicon textures studied in this project

The characterization work has been supported via the development of new techniques to measure complex black silicon surface morphologies. These techniques have allowed for a greater understanding of the fundamental nature of black silicon and have enabled the development and validation of the rapid simulation techniques described below. Details of these new measurement techniques are provided in the first lessons learnt section of this report.

The project has created and validated modelling techniques that allow the optical performance of a wide range of black silicon textures to be rapidly predicted. This has included both the industrial forms as well as the advanced variety. These models have been integrated with commercial software enabling the annual energy yield of black silicon textured devices to be determined within minutes (rather than many hours with incumbent modelling techniques). Advances were also made on the techniques used to simulate the existing types of texture, enabling better comparison when developing black silicon. More detail on this is included in the second lessons learnt report.

Extreme surface features found in black silicon textures are difficult to integrate into solar cells for a variety of reasons. The project completed several fundamental studies that were able to relate the shape and size of the texture to changes in how manufacturing processes occur and the subsequent impact on solar cell performance. This work resulted in an explanation for the reported phenomenon of enhanced phosphorous diffusion on some black silicon surfaces, the development of an improved metric for describing such surfaces and the adaptation of a technique to image the distribution of phosphorus within nanotextures. The project produced a design guide for how top surface coatings should be configured which can be used for future work. Using more traditional materials the project (combined with the team at Aalto University in Finland) achieved the highest quality front surface reported in the literature at that time [Fung2020]. The project also completed a study on the impact of black silicon on the incorporation of hydrogen into a solar cell. Optimized processing recipes (implemented at industry partner site Canadian Solar) were able to achieve stable solar cell performance with a high efficiency. An interesting outcome of this work was the fact that black silicon, of both an industrial and academic nature, is beneficial in reducing the degree of light-induced-degradation in solar grade wafers [Khan2021].

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

A consortium of industry and academic partners have been brought together within this activity to make several significant advances on black silicon technology. All the project outcomes were achieved, and a significant amount of new scientific advances have been shared. The limitations of each type of black silicon have been studied and the future path to further improvement identified.

The project achieved its goal of integrating rapid modelling techniques into large scale annual energy yield simulations. Several academic papers have been published describing a number of advances in this area. These models have been integrated into commercial software and are now in use by the industry and academic community.

New measurement techniques were developed that overcome existing limitations in the measurement of black silicon. These enabled the project to meet its goals and have been published in detail to allow them to be used into the future. The large set of data measured on the samples collected and studied throughout the activity has been made available via an online platform. This will enable future work to compare and benchmark performance to what was achieved in this activity. Such a dataset is particularly useful for future activities with a narrow scope where a wide range of experimental data cannot be gathered easily.

The project found that significant barriers remain to integrate the more extreme forms of black silicon into high-efficiency, industrial solar cells. The project demonstrated improvements in the electrical performance of advanced black silicon via optimization of diffusion processing and to a lesser extent in the use of coating layers to improve performance. However, a fundamental issue related to the ability to collect blue light from tall thin needle shaped texture remains difficult to solve. Furthermore, the nature of very small texture features is that they do not effectively scatter the light internally into the silicon wafer. This can only be overcome by combining the nano-texture with a larger texture (although that texture need not be very extreme).

Working with industry partners the project has demonstrated that the less extreme, industrial forms of black silicon are compatible with high efficiency, stable multi-crystalline devices. The addition of black silicon was found to reduce the instability of cell power in response to light soaking, likely by enabling excess hydrogen to leave the substrate more effectively. Furthermore, the optical properties of these textures were shown to be superior even to the incumbent texturing used on more expensive substrates. In the future it would be worth exploring the application of black silicon onto mono-crystalline substrates, particularly given the cost reduction seen by those in recent times.

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

Studies of key surface metrics revealed that traditional techniques were unable to provide accurate measurements, particularly for ultra-low reflectance black silicon. In response, the project developed several new techniques and published in the scientific literature the details of both the methods and their application to nanotexture. This included:

- A 3D imaging technique that could measure large enough areas of the most extreme surface shapes to provide quantitative statistics. Based on existing PFIB-SEM the project found that improvements in sample preparation and data analysis were required to extend the capabilities onto nanotexture. This overcomes the limitations in the AFM technique for measuring surface topography and related statistics.

- A 2D imaging technique capable of identifying the spatial distribution of dopant atoms. Taking advantage of the capability of scanning electron microscopes to detect regions with different dopant types, the project extended the technique to black silicon textures. It found that the form and volume of nanotexture features play a critical role in the distribution of dopants both within the texture and into the underlying wafer.

- A rapid technique to scan the wafer surface and create a map of texture uniformity. The project found that it was possible to match the reflection of short wavelength light to the actual shape of the texture. This provides a much easier and faster way to quickly scan very large areas and provide important information on the texture quality. It was even shown that this technique could predict how the surface would respond to solar cell fabrication processes (based on interactions between the changing surface shape and the chemical processes).

- An improved system for accurate measurements of the angular dependent scattering of light from textures. The project developed a custom experimental tool which required improved sensitivity over previous versions due to the extremely low intensity of light reflected from nanotextured black silicon surfaces. This was achieved using a high-power white-light laser in combination with state-of-the-art CCD spectrometers. Measurements of the angular distribution of scattered light revealed that the majority of black silicon textures scatter light in a near-Lambertian way, which is known to be the ideal case for a non-periodic rough surface.

In general, it was found that when measuring black silicon, it is critical to (1) measure large areas to gather enough statistics to reveal the true surface properties (which were always found to be described by Gaussian distributions), (2) employ measurement techniques that are fast enough to make measurements in a practical timeframe and without introducing additional uncertainty due to tool drift, (3) prepare the samples for testing in a way that will minimize the errors caused by the extreme physical and optical nature of the surface, (4) include the ability to measure across large surface areas since localized results may not always describe the average performance of a large area wafer.

Implications for future projects

The characterisation techniques developed and applied in this project have addressed critical gaps in the black silicon research space. The adoption of these techniques will allow for more quantitative and more accurate correlation studies between black silicon surface metrics and key properties for solar cell integration leading to a better understanding of how processes interact with nanotextures. Furthermore, these techniques will be useful for other black silicon applications beyond photovoltaics.

Knowledge gap

3D Imaging of Black Silicon

Black silicon surface data, for example distributions of feature heights, angles, surface area, roughness, etc., are critical for studying various texture properties. However, it is difficult to extract accurate surface data for ultra-low reflectance black silicon textures with tall, narrow features using traditional microscopy techniques. The best existing technique to measure the surface was based on using a Focused-Ion-Beam to progressively slice away silicon and measure the cross-sectional shape each time with a Scanning-Electron-Microscope. However, applications of this to nanotextures that had previously been reported were filled with measurement artefacts. What was needed was an improvement to the technique to better prepare the samples to avoid these. Furthermore, it was necessary to push the limits of the measurement to record even smaller feature sizes, over larger areas, than had previously been possible. A signal processing approach to convert the series of images into a reproduction of surface topography did not exist. Nor had any actual validation via comparison to good measurements on less aggressive surfaces been reported.

Spatial Imaging of Dopants in Black Silicon

The fabrication of industrial solar cells relies on a critical step where foreign atoms, referred to as dopants, are strategically introduced into the silicon by a process called diffusion. More specifically, phosphorus atoms are diffused into the front side of solar cells, creating an electrical asymmetry which allows electrons created by sunlight to flow in one direction. Measuring the distribution of dopants is therefore critical for solar cell characterization and optimization. However, traditional techniques used to measure dopant distributions are not reliably applicable to the complex structures of black silicon textures. Furthermore, a qualitative 2D imaging technique referred to as dopant contrast imaging, employed in an electron microscope, is well established, but the imaging of phosphorus is difficult and typically involves modifications to the microscope hardware. As such, this project has addressed the lack of phosphorus distribution monitoring capability for black silicon by successfully applying phosphorus dopant contrast imaging to black silicon. As a result of this work, we have identified the quantification of such dopant contrast images as the next gap to address. Work in this area is already underway.

Spatial Mapping of Black Silicon Surface Area

Black silicon often exhibits altered behaviour compared to untextured or traditionally textured silicon such as different process interaction and modified optical or electrical properties. Such altered behaviour is often attributed to black silicon's increased surface area. Furthermore, when applied to large area substrates the texture can vary at different locations. This can indicate problems with the manufacturing process. Traditional techniques used to monitor black silicon surface area provide extremely limited statistics making any correlation studies very difficult. Furthermore, they are far too slow to employ in a manufacturing line as part of process control. The project identified the need for a rapid, accurate, large area measurement of the texture properties. Ideally, a measurement of the texture surface area, which is known to correlate with performance, would be implemented. In other fields it has been proposed that optical properties of certain wavelengths of light provide information about the mixture of silicon and air. There has not been any work using such relations to probe surface properties of nanotexture.

Light Scatter from Black Silicon Textures

The wavelength and angular distribution of scattering from a textured surface or interface plays an important role in both the optical absorption of the device and in the aesthetics. Accurate measurement of this information enables improved modelling and optimisation, however, extracting this characterisation data from low-reflectance surfaces such as black silicon is challenging and cannot be achieved using traditional commercial lab tools. As such, there is no wavelength and angle resolved scattering data in the literature for these types of surfaces. The project developed a custom-made experimental tool to enable these measurements to be carried out with sufficient sensitivity, accuracy, and repeatability. Thus, enabling detailed characterisation of scatter from black silicon surfaces, as well as improved data for more conventional silicon textures such as random-pyramids and iso-texture.

Background

Objectives or project requirements

A key project aim was to improve the understanding of black silicon textures and how they interact with industrial solar cell processes to enable the highest optically performing forms of black silicon. The ability to accurately measure surface metrics with ample statistics is therefore critical for such integration studies. The ability to measure post-processing metrics is also critical. This project has identified several characterization gaps in the black silicon research space. New characterisation techniques were developed, and an existing technique was applied to black silicon for the first time to address these gaps.

Process undertaken

3D Imaging of Black Silicon

This project collaborated with electron-microscopy experts to develop a technique to quantitatively characterise complex nano-texture surfaces by employing a so-called "slice-and-view" approach. This technique used an automated process of sequential nano-scale slicing combined with electron microscope imaging. A large series of these nano-sliced images were then reconstructed to create three dimensional renderings of the complex surfaces, which allows for quantitative analysis of surface features. A significant part of this work was the development of appropriate sample preparation techniques. This included the application of a Durcupan resin to fully infiltrate the needle like black silicon surface and to protect the top-surface from potential PFIB milling artifacts.

The project validated the technique by comparing the measurements to those extracted via traditional techniques on less extreme surfaces. Further validation was achieved by comparing the predicted optical modelling output of different extracted surface shapes. Applying the technique to extreme surface textures demonstrated the errors that result when the advanced technique is not employed. Other surface features that are not normally captured were also recorded including regions of over-hanging silicon caused by under-etching.

Spatial Imaging of Phosphorus in Black Silicon

The project demonstrated 2D contrast imaging of phosphorus doped black silicon textures using electron microscopy without any hardware modifications. Samples were prepared with a range of surface textures as well as different electrical doping properties. These were used to explore the detailed impact of different tool properties and measurement settings to extract a reliable dopant-dependent signal. The calibration of the signal with actual doping concentrations was also explored.

The technique was used to demonstrate how different texture surfaces interact with solar cell processing. It was able to provide evidence for the enhancement in the depth of the processed region that is observed when the surface nanotexture was formed. It demonstrates how the electronic junction follows the shape of large textures but forms a uniform interface for nanotextures. Such behaviour leads to fundamentally different electrical performances when applied to a solar cell.

Spatial Mapping of Black Silicon Surface Area

This project developed a technique to monitor the spatial variation of silicon nanotexture surface area across full-sized wafers. The technique uses silicon's clearest optical signal, which is related to its fundamental material properties and is very sensitive to nano-etching. It was possible to calibrate this 'fingerprint' signal to texture surface area and apply it to spatial mapping of black silicon wafers. The technique was tested on a range of textures which contained different levels of spatial variation. Localised measurements of the actual surface area (taken using slow but accurate surface probing techniques) were used to validate the results in specific map locations. The technique was found to provide accurate, high resolution, full-wafer surface area maps of industrial black silicon wafers.

Light Scatter from Black Silicon Textures

The project enabled wavelength and angle resolved scattering measurements through hardware and software improvements of a custom-built broadband angle resolved optical scatterometer (BAROS) tool. Using updated spectrometers in combination with a high-power white-light laser source the sensitivity and resolution of the measurement technique was able to reach a level in which very low-reflectance surfaces such as black silicon could be characterised. The measurement technique was validated through measurement of more traditional silicon textures for which scattering distributions had previously been published in the literature. The BAROS measurements showed good agreement with published data and were able to expand those previous results into a wider range of angles not previously studied.

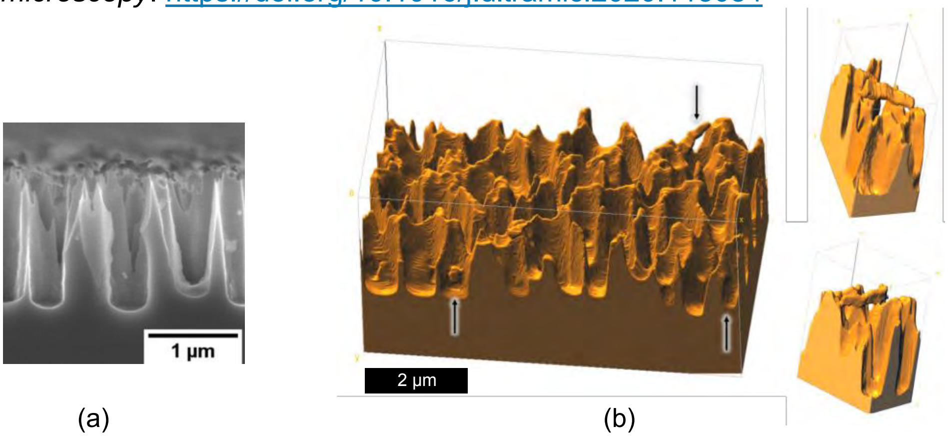
This revealed new features which supported the findings observed during the development of optical modelling techniques carried out within this project. A range of black silicon and conventional textures where characterised with black silicon samples typically found to have an angular distribution like iso-texture but in some cases with a stronger wavelength dependence favouring scattering of shorter wavelength light.

Supporting information

Some technical details pertaining to the key findings are shown below along with references and links to the relevant journal publications from this project.

3D Imaging of Black Silicon

Figure 1-1 highlights the 3-dimensional imaging technique that was developed in this project, which enables quantitative surface characterization of challenging black silicon textures. Figure 1-1 (a) shows the electron microscope image of a black silicon texture with tall, sharp features. Figure 1-1 (b) shows a 3-dimensional rendering of the same texture using an advanced imaging technique developed in this project. This work was reported in a peer-reviewed journal paper published in the journal *Ultramicroscopy*. https://doi.org/10.1016/j.ultramic.2020.113084



(a) (b)

Figure 1-1: (a) Electron microscope image of a Black Silicon texture with tall narrow features, which are very difficult to measure with traditional surface characterisation techniques. (b) A 3-dimensional scan of the same texture using a technique developed in this project. Overhanging features are indicated by arrows and emphasized in the insets. Adapted from [Zhang2020] https://doi.org/10.1016/j.ultramic.2020.113084

Spatial Imaging of Phosphorus in Black Silicon

Figure 1-2 highlights an application of dopant contrast imaging to determine the impact of nano-textures on the distribution of introduced phosphorus atoms. Figure 1-2 (a) shows the contrast image for a pyramid texture. The corresponding contrast images for an industrial black silicon texture and an academic black silicon texture are shown in Figure 1-2 (b) and Figure 1-2 (c), respectively. In this case, all three textures had the same surface area, but the the distribution of phosphorus atoms (the dark band indicated as “n+”) changes significantly for the different texture topographies. This work was reported in a peer-reviewed journal paper entitled, ‘On the Enhanced Phosphorus Doping of Nanotextured Black Silicon’ published in *IEEE Journal of Photovoltaics*. 10.1109/JPHOTOV.2020.3047420

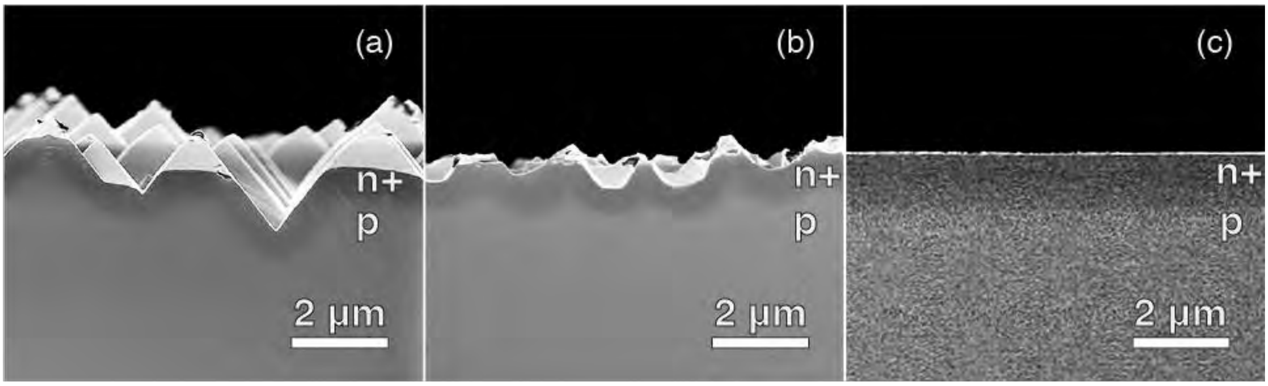


Figure 1-2: Dopant contrast images for (a) pyramid texture, (b) industrial Black Silicon texture and (c) an academic Black Silicon texture. The dark bands indicate that the distribution of phosphorus atoms (indicated as “n+”) changes significantly for the different texture topographies. Adapted from [Scardera2021] DOI: 10.1109/JPHOTOV.2020.3047420

Spatial Mapping of Black Silicon Surface Area

Figure 1-3 highlights a spatial mapping technique developed in this project to monitor black silicon texture surface area. Figure 1-3 (a) show a schematic of a simple texture feature indicating the lateral surface area and the underlying projected area. The ratio of these two areas is a typical metric for characterising black silicon textures. Figure 1-3 (b) shows a height scan for a black silicon texture measured using a traditional microscopy technique with the limited scan size indicated. A surface area value can be extracted from this scan. Figure 1-3 (c) shows a high resolution, full-wafer, surface area map for the same black silicon texture. Our technique is able to detect spatial variations in texture with significant statistics. This work is reported in a journal paper entitled ‘Silicon Nanotexture Surface Area Mapping using Ultraviolet Reflectance’, published in *IEEE Journal of Photovoltaics: 10.1109/JPHOTOV.2021.3086439*.

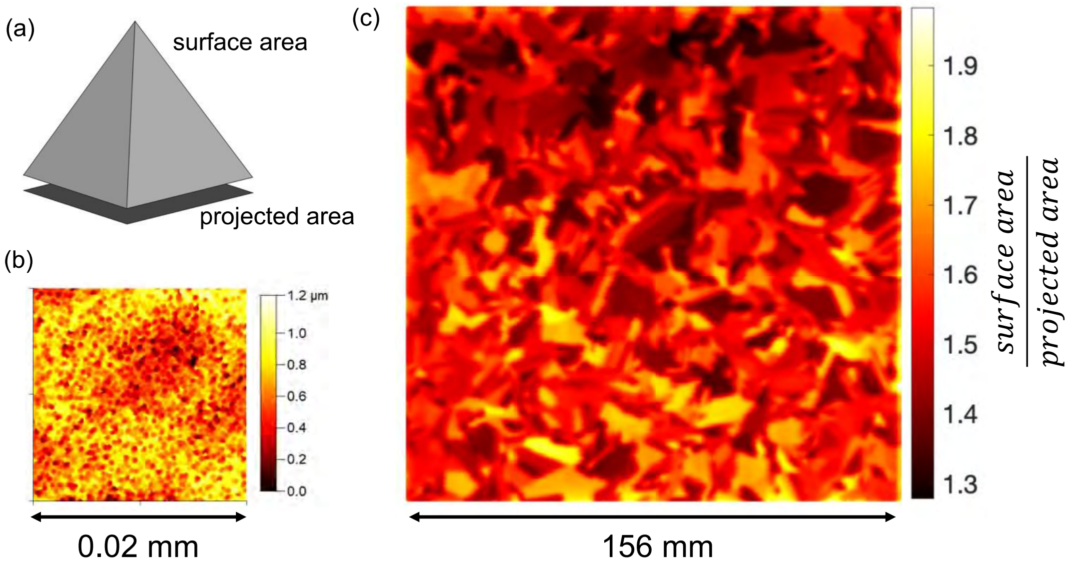


Figure 1-3: (a) Schematic of a simple texture feature illustrating its surface area and projected surface area. (b) Height scan of a Black Silicon texture measured using a traditional microscopy technique with the size of the scan area indicated. A surface area value can be calculated for this scan. (c) A high-resolution surface area map of a full-sized wafer with Black Silicon texture measured using a new technique developed in this project. Adapted, in part, from [Scardera2021b] 10.1109/JPHOTOV.2021.3086439

Light Scatter from Black Silicon Textures

Figure 1-4 shows an illustration of the BAROS tool and scattering measurement technique along with a range of wavelength and angle resolved scattering results. Figure 1-4 (a) shows a 3D CAD drawing of the scattering measurement tool. Figure 1-4 (b) shows a scattering distribution result for a typical random pyramid textured monocrystalline silicon sample. Figure 1-4 (c) shows a scattering distribution result for a typical iso-textured multicrystalline silicon sample. Figure 1-4 (d) shows a scattering distribution result for an MCCE black silicon textured multicrystalline silicon sample. This work was presented at the 2019 European PV Solar Energy Conference (EUPVSEC).

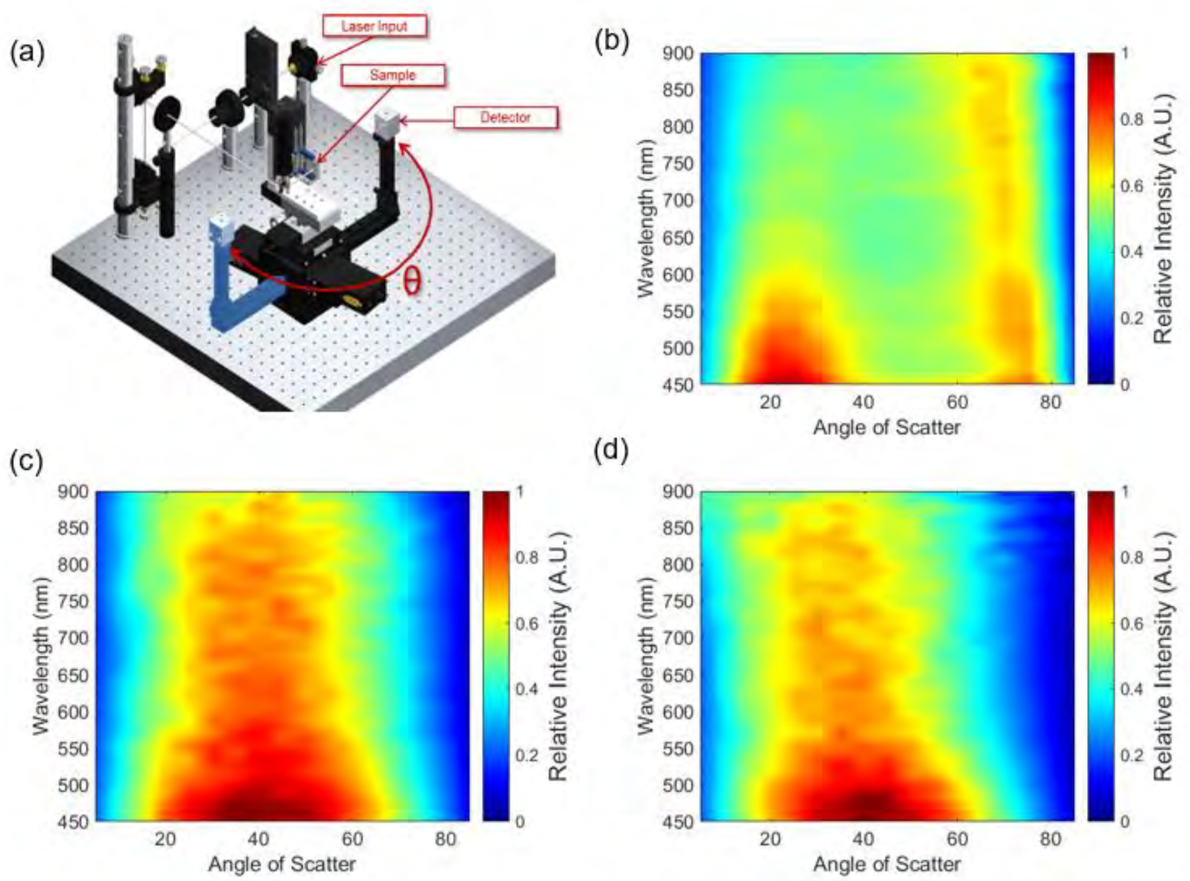


Figure 1-4: (a) 3D CAD drawing of the scattering measurement tool (b) Wavelength and angle resolved scattering result for random-pyramid textured monocrystalline silicon sample (c) Wavelength and angle resolved scattering result for iso-textured multicrystalline silicon sample (d) Wavelength and angle resolved scattering result for MCCE black silicon textured multicrystalline silicon sample.

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

Simulations of photovoltaic technologies should be done on the system level to correctly predict the true impact on energy yield.

The project thoroughly explored a range of topics related to the use of computer modelling to predict the optical performance of textured solar cells. A key learning was the importance of assessing performance as part of a complete system deployed in the field rather than as a sub-part of that system. Optical simulations on a wafer and cell level were found to be useful to validate the inputs used in the larger simulations. However, the predicted performance gain, and the optimal design point, were found to be different when technology was encapsulated into a solar panel (i.e., the texture was covered in glass) and even more so when deployed in a real-world scenario.

Accurate system level simulations required improved models

To support these types of simulations it was necessary to develop and validate rapid techniques to simulate the optical performance of solar cell textures. It was found that there were significant errors already present in the best-known techniques for the incumbent textures. A summary of some of the detailed findings are presented below:

- Random pyramid texture (the incumbent technology on high-efficiency cells) results in more complex scattering of light that can be explained by the pyramid shape itself. To simulate accurately the absorption of light in such textures it is necessary to include an additional scattering model that implements a Gaussian distribution of exit angles [Fung2019]. Failure to include such a model can result in errors on the order of 0.7% in energy yield [Abbott2019].
- Industrial black silicon formed using the metal-assisted chemical etching (MACE) approach can be simulated using random inverted spherical caps [Payne2018]. The angular distribution of scattering from this model is not very accurate, however the specific interaction with glass means that this does not induce significant errors in energy yield simulations [Payne2019].
- Black silicon formed via reactive-ion-etching (RIE) tends to result in features with an average height and/or width that means that geometric optics cannot be used to predict optical performance. A combination of an effective medium and ray tracing of a geometric shape can be used to approximate the performance [Abbott2018].
- Nanotextures that are very small do not significantly scatter light and behave optically as a thin film based on a mixture of silicon and superstrate material (i.e., air or EVA). These

can be simulated using graded-refractive-index stacks of thin layers calculated via the effective-medium techniques [Fung2019b].

In addition to the learnings on modelling techniques there were a number of findings that relate to the predicted performance of textures.

- Optimal performance of solar cell textures occurs when they are large enough to scatter all wavelengths of light. For this reason, many industrial solar cell textures are compatible with ray tracing since the optimisation process has naturally selected the larger textures.
- Very small nanotextures should be combined with larger scale texture to improve the absorption of the light. It is not necessary for the larger scale texture to be very extreme and even substrate waviness can provide a significant advantage.
- The most important property of a texture is the reduction in reflection and the internal trapping of light. The angular distribution of the reflected and transmitted light is secondary since the actual escape angle from the glass is quite narrow.
- The angular performance of black silicon, as it relates to the angle of incoming light, is superior to other textures. This advantage is greatly reduced in a module since the first reflection of the glass is not significantly impacted by this and it tends to dominate module performance.
- Nanotextures provide an improvement to the uniformity of the appearance of a solar cell. However, this improvement is almost entirely negated once the cell is encapsulated under glass.

Implications for future projects

Future projects should incorporate the proposed improvements to the models developed for solar cell textures. This will result in more accurate simulations. Those projects should also consider the use of total energy yield simulations as opposed to simulations just on a cell level. This extends to where simulations are being used as part of an optimisation process. In the real-world solar panels are subject to a diverse range of off-angle light and how that is used becomes critical to finding the optimal point. The encapsulation of textures under a piece of glass also results in dramatic changes in the optical performance which should be accounted for.

The findings related to the importance of internally trapping absorbed light should be considered when developing nanotextures. Reduction in front surface reflection is important, but if that light is not properly absorbed then the texture will not be superior to the incumbent technology. It is likely that the nanotextures should not be used as the only texture on the surface and that a texture-on-texture approach should be employed. Noting that the underlying texture need not be very extreme to be effective.

The performance of industrial forms of black silicon explored in the project were in some cases superior to the incumbent texture on mono-crystalline silicon. Historically black silicon has been developed as a texturing solution for multi-crystalline substrates. However, it should be explored to further improve the power output of monocrystalline wafers.

Knowledge gap

The work addressed a lack of cohesive studies into how a broad range of black silicon textures should be simulated. Specifically, what rapid techniques could be used to complement techniques based on more rigorous approaches which, although accurate, are too slow for integration into large scale simulations. Some work had been presented on the use of effective medium techniques to predict the performance, but there was limited discussion on the details of how it is best implemented and for what textures is it valid. A key motivation for the project was the rapid increase in the popularity of MACE based black silicon in production. For other production textures (random pyramids and iso-texture) there were clear publications on the model and its validation in terms of reflection reduction. That did not exist for MACE textures. Specifically for random pyramid texture it had been identified that the existing models did not accurately reproduce the absorption in silicon substrates. No solution to that had been proposed. Furthermore, for all textures there was little study into the angular dependence of the performance and how well the models replicated that.

Background

Objectives or project requirements

A key 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 on a cell and module level as well as in the determination of the annual energy output of a solar power plant. The project seeks to identify the limitations in existing models and the gaps in the existing knowledge, particularly as it relates to comparison to experimental measurements. The project seeks to address this by developing new modelling techniques and comparing them to highly accurate optical measurements.

The requirement of the new models is that they be solved in seconds and provide an accurate enough approximation of the optical performance to not cause significant error in yield predictions.

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 rigorous solving on a supercomputer). These models have been integrated into ray tracing software that can be used on a cell, module, and system level. Simulations of different models have been run to determine the impact on the final energy yield.

Lessons Learnt Report: Solar 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

This project assessed the feasibility of solar cell integration for two different classes of textures: (1) industrial black silicon textures, which achieve lower reflectance than industry-standard texturing used for multi-crystalline silicon, and (2) more advanced black silicon textures, which provide ultra-low reflectance. This project validated the integration of industrial black silicon textures into stable, high efficiency industrial solar cells. A significant reduction in electrical losses, referred to as recombination losses, was also demonstrated for ultra-low reflectance black silicon. Fundamental studies carried out in this project revealed new insights into the altered behaviour of black silicon compared to planar silicon, and its interaction with key solar cell process steps.

This project demonstrated that industrial black silicon textures are highly compatible with critical standard solar cell processing steps. While such textures do not achieve the ultra-low reflectance of more advanced, or ‘academic’, black silicon textures, they do approach the optical performance of the state-of-the art industrial textures used for monocrystalline silicon wafers. More importantly industrial black silicon textures enable the use of the latest multi-crystalline silicon wafer technology. This project showed that industrial black silicon solar cells made with this latest wafer technology exhibited high energy conversion efficiencies and were also shown to be very stable when subjected to standard degradation testing. It was also found that for lower quality silicon wafers industrial black silicon textures suppressed degradation associated with light and heat exposure.

The lowest electrical losses ever reported in the literature for advanced, ultra-low reflectance black silicon were achieved in this project via optimization of the key solar cell processing steps referred to as diffusion and surface passivation. Studies carried out in this project also revealed how aspects of the 3-dimensional form, or morphology, of nano-texture features play important roles in black silicon’s interaction with both process steps.

Implications for future projects

This project has uncovered new aspects of black silicon’s altered behaviour, compared to planar or standard textures, when subjected to solar cell processing. Understanding such behaviour will be critical for the integration of ultra-low reflectance black silicon into industrial solar cells. Black silicon studies have typically relied on limited surface metrics, like surface area, which do not fully capture morphology changes. This project has found that the form and volume of a texture feature play a critical role in process interaction. Future studies will need to consider the 3-dimensional form of texture features more carefully when investigating electrical performance. Local 3-dimensional variations in texture features will also need to be considered.

Knowledge gap

Validating Industrial Black Silicon

Nanotextures are known to interact with standard solar cell processing which can lead to unwanted performance losses. Furthermore, processes are continually optimized to achieve higher solar cell efficiencies. However, the extent of industrial black silicon interaction with process optimization was unclear. This project found that industrial black silicon is compatible with standard solar cell processing and exhibited marginal interaction effects, which allowed for cell optimization.

Degradation Suppression with Industrial Black Silicon

Ultra-low reflectance black silicon was recently reported to suppress an electrical degradation signal, triggered by light and heat exposure, which is detrimental for solar cells. This project has demonstrated that more industry-relevant black silicon textures also exhibit this effect. We have also provided further insight into this new effect by showing that it is sensitive to a nano-texture's changing surface morphology. The underlying mechanism for this behaviour still requires further investigation.

Influence of Nanotexture on Surface Charge Performance

Black silicon often exhibits increased electrical losses which is attributed to increased surface area. Advanced surface coatings, referred to as 'passivation layers', with tuneable embedded charge are often proposed for mitigating such losses. However, the impact of nano-scale texture features on the performance of such charged layers is not well understood. This project has addressed this knowledge gap by conducting a fundamental simulation study looking into this interaction.

Electrical Performance of Advanced Black Silicon

Studies on improving electrical performance of black silicon have primarily focused on optimizing post-texturing surface treatments. As mentioned previously, 'dopant diffusion' is a critical process that determines the electrical behaviour of solar cells. However, diffusion optimization for black silicon has not been adequately addressed in the literature. This project has addressed this gap by applying known diffusion optimization approaches to black silicon in conjunction with highly optimized surface treatments. Despite matching the desired processing metrics used for industrial cells, advanced black silicon still exhibited unexplained losses that were too high for solar cell integration. The underlying mechanisms of these remaining losses require further investigation. Simulation studies in this area are already underway.

Influence of Nanotexture on Doping Behaviour

Solar cells require the introduction of so-called 'dopant atoms' into the silicon via a 'doping' or 'diffusion' process. Black silicon textures often enhance this process which negatively impacts electrical performance. This effect is typically attributed, in a cursory manner, to increased surface area, but no systematic study of the underlying mechanism was previously reported. This project has addressed this gap by conducting a fundamental study into the doping behaviour of black silicon. We extended surface characterisation to include surface-to-volume ratio, which is directly related to surface reactivity. Whilst this metric is common for nanoparticle or nano-wire studies, it has not been readily used for black silicon. Our study found that surface-to-volume ratio plays a fundamental role in the doping behaviour of black silicon. This metric is currently being evaluated for other black silicon solar cell parameters.

Background

Objectives or project requirements

This project set out to identify any limitations to integrating black silicon into solar cell production. For industrial black silicon textures, studies were focused on determining compatibility with industry-standard processes and optimization. For advanced black silicon, one approach was to optimize key processing steps required for high efficiency solar cells which were not previously demonstrated in the literature, and then identify any remaining performance limitations. In parallel, fundamental studies were carried out focusing on specific black silicon behaviour and process interaction aimed at understanding the underlying mechanisms.

Process undertaken

Validating Industrial Black Silicon

Industrial black silicon textures were subjected to key processing step variations in order to monitor the extent of any interaction effects. Unlike for more nano-scale textures, these industrial textures exhibited marginal interaction with a key process referred to as ‘diffusion’, which allowed for optimization over a wide range of processing parameters. These textures were also found to be compatible with the industry-standard surface coating technique, allowing for conformal coverage of texture features. This compatibility also allowed for coatings with multiple layers, which provided greater flexibility for performance optimization.

Degradation Suppression with Industrial Black Silicon

Test samples designed to detect degradation associated with light and heat exposure were prepared using industrial black silicon textures. Standard ‘light soak’ tests showed that black silicon textures exhibited a reduced degradation signal compared to a reference planar texture. Furthermore, the extent of the degradation signal also decreased with increasing black silicon surface roughness.

Influence of Nanotexture on Surface Charge Performance

We conducted a simulation study on the effect of nano-texture features on the performance of front side coatings designed to minimise inherent electrical losses, referred to as ‘surface recombination’. These ‘passivation’ layers contain embedded charges which play a critical role in their performance. We found that the passivation performance offset between a nano-texture and a planar surface does not simply track with increasing charge. We found that the nano-scale features impact the effectiveness of charge due to short range effects. Follow-up studies are currently underway to gain more insight into this behaviour.

Electrical Performance of Advanced Black Silicon

This project applied multiple solar cell process optimizations to an ultra-low reflectance black silicon texture to demonstrate improved electrical performance. By achieving desired process metrics, we demonstrated the lowest electrical losses ever reported for ultra-low reflectance black silicon in the literature. However, despite these impressive results, we also found that the losses were still significantly higher than for an industry-standard pyramid texture condition. Studies looking into the remaining performance limitations have started and will continue beyond this project.

Influence of Nanotexture on Doping Behaviour

We conducted a fundamental study looking into how black silicon alters the standard process of introducing so-called dopant atoms into silicon. We demonstrated with experiments and simulations that the texture surface-to-volume ratio, a metric not commonly applied to black silicon, plays a key role in a texture's 'doping' behaviour. We also believe this metric will prove useful for other nanotexture properties and for other applications beyond solar cells.

Supporting information

Some technical details pertaining to the key findings are shown below along with references and links to the relevant journal publications from this project.

Validation of Industrial Black Silicon

Figure 3-1 highlights the successful integration of black silicon texture into a stable, high efficiency, industrial solar cell. The image in Figure 3-1 (a) indicates the spatial electrical quality of an industrial black silicon solar cell made with the latest multi-crystalline silicon wafer technology. Yellow regions indicate high material quality and excellent electrical properties. Such lower cost wafers are difficult to texture with the state-of-the-art industrial texturing process but are well suited to industrial black silicon texturing. The corresponding electrical results (JV curves) before and after a 500-hour stress test, employing constant illumination and heating, are presented in Figure 3-1 (b). These results indicate the excellent stability of this cell. Figure 3-1 (c) shows a cross-sectional electron microscope image of the industrial black silicon texture covered with an industry standard coating layer. Excellent conformal coverage is demonstrated, which highlights the ability to use such textures as drop-in solutions for industrial manufacturing lines.

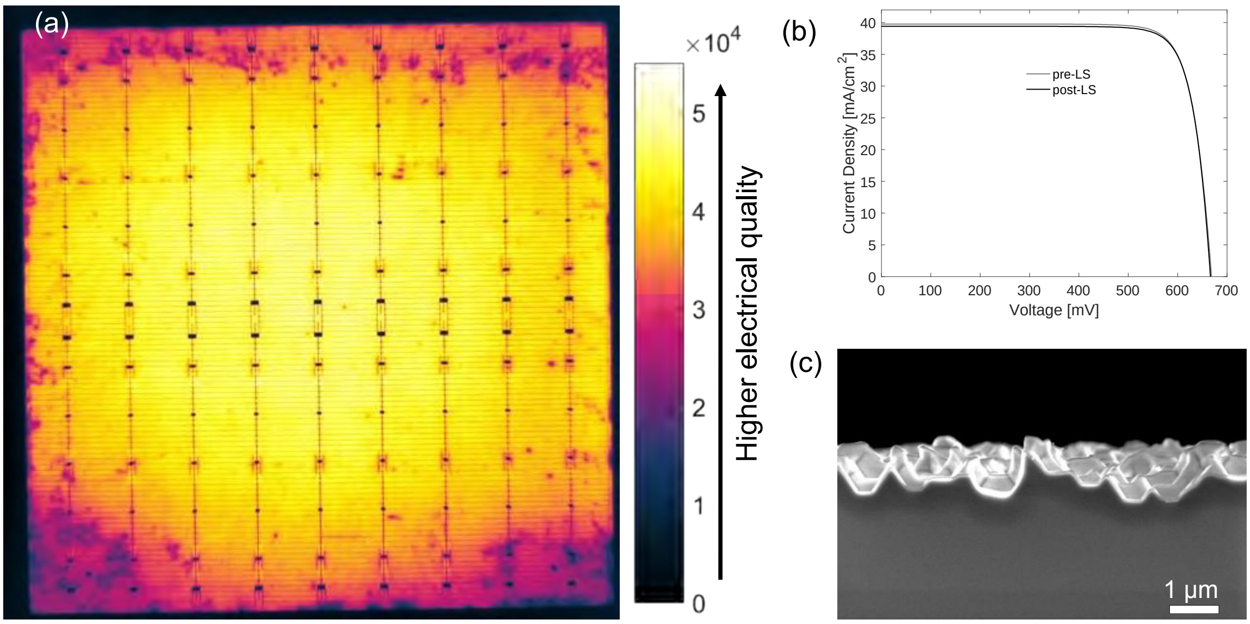


Figure 3-1: (a) Spatial electrical quality map of a high efficiency industrial solar cell (21.6% conversion efficiency) made with black silicon texture at the Canadian Solar facility. (b) The corresponding electrical performance (current-voltage curves) before and after a 500-hours light soak (LS) test. (c) Cross-sectional electron microscope image of the texture with conformal coverage of an industry standard coating layer.

Degradation Suppression with Industrial Black Silicon

Figure 3-2 (a) shows the degradation signal observed for test samples with industrial black silicon texture along with a planar reference subjected to a prolonged heat and light soak test. The height of the peak indicates the extent of degradation. The extent of the degradation signal decreased for the black silicon conditions with increasing surface area. The corresponding electron microscope images of the black silicon textures are shown in Figure 3-2 (b) – (d). This work was reported in a peer-reviewed journal paper published in *Journal of Photovoltaics:* 10.1109/JPHOTOV.2021.3059426

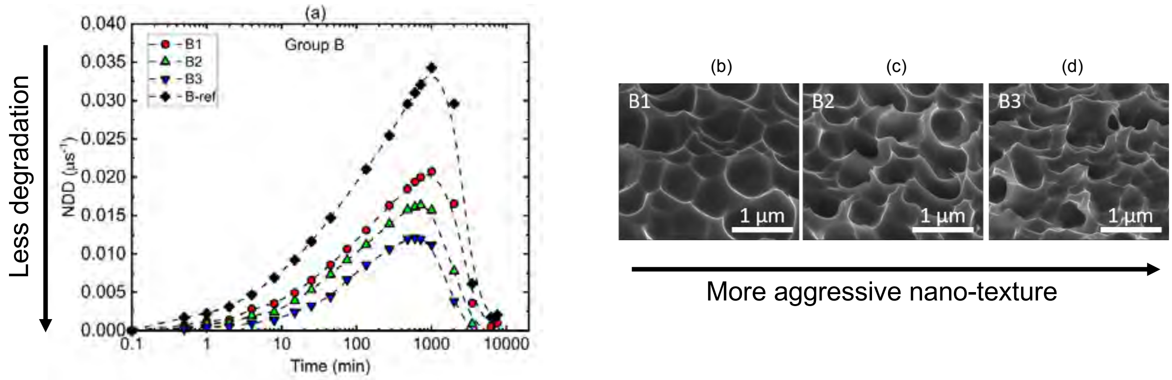


Figure 3-2: (a) Degradation signal for test samples subjected to prolonged light and heat exposure. A taller peak in the signal corresponds to more degradation. (b) – (d): Electron microscope images of the black silicon textures with surface roughness (surface area) increasing from left to right. Adapted from [Khan2021] DOI: 10.1109/JPHOTOV.2021.3059426

Influence of Nanotexture on Surface Charge Performance

Figure 3-3 shows the simulation results for passivation tests of a nano-cone texture feature and a reference planar condition where the amount of embedded charge in the layer is increasing from (a) to (c). The colour scale indicates the amounts of electrical carriers. Less carriers at a surface result in reduced recombination losses. The changes in the nano-cone carrier concentrations relative to the planar reference condition showed unexpected offsets with varying charge compared to assumptions previously made in the literature. This work was reported in a peer-reviewed journal paper published in *Journal of Photovoltaics*. 10.1109/JPHOTOV.2021.3069124

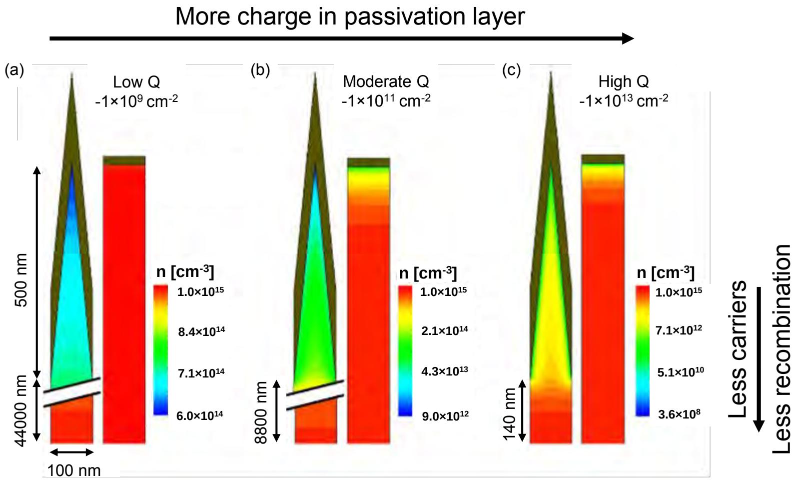


Figure 3-3: Simulation results for a nano-cone texture feature and a planar reference covered with a passivation layer with three different amounts of imbedded charge. The colour scale indicates the amounts of electrical carriers. Adapted from [Wang2021] DOI: 10.1109/JPHOTOV.2021.3069124

Electrical Performance of Advanced Black Silicon

Figure 3-4 shows the dopant contrast images of (a) standard pyramid texture and (b) RIE black silicon after a phosphorus diffusion process. The dark bands (indicated as ‘n+’) corresponds to phosphorus distribution. The black silicon texture enhances the amount of phosphorus that gets incorporated into the wafer. Figure 3-4 (c) shows the recombination performance of different phosphorus diffusion processes for black silicon and reference polished and pyramid texture conditions. Despite significant diffusion process optimization, the recombination is still significantly higher for the black silicon texture compared to the references. This work was reported in a peer-reviewed journal paper published in *Solar Energy Materials and Solar Cells*. https://doi.org/10.1016/j.solmat.2020.110480

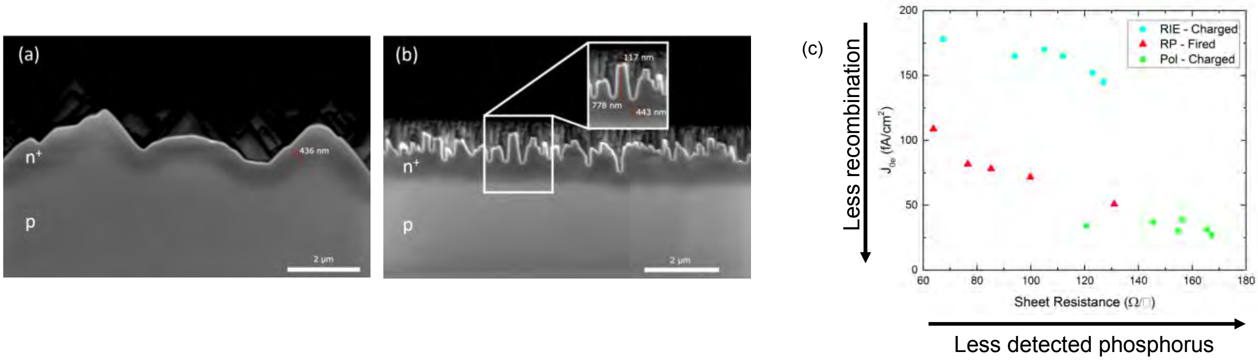


Figure 3-4: Dopant contrast images for (a) standard pyramid texture and (b) RIE black silicon texture. (c) Recombination performance versus phosphorus conditions for RIE, pyramid (Rp) and polished (Pol) textures. Adapted from [Fung2020] https://doi.org/10.1016/j.solmat.2020.110480

Influence of Nanotexture on Doping Behaviour

Figure 3-5 shows a schematic representation of silicon nano-texture behaviour when subjected to a phosphorus diffusion process. As the texture feature gets smaller, its surface-to-volume ratio (or specific surface area) increases along with the surface reactivity. As a result, smaller nano-cones are more fully doped, and doping extends more deeply into the underlying substrate. Diffusion simulations confirmed this behaviour. Figure 3-6 (a) shows schematics of nano-cone conditions used for diffusion simulations. Figure 3-6 (b) shows the simulation results for the nano-cones along with a reference planar condition. The colour scale indicates the amount of phosphorus. The transition from light blue to dark blue indicates the extent of phosphorus penetration into the underlying wafer. This work was reported in a peer-reviewed journal paper published in *Journal of Photovoltaics.* 10.1109/JPHOTOV.2020.3047420

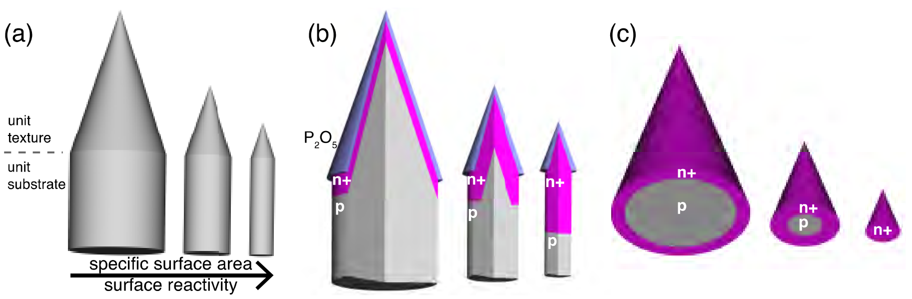


Figure 3-5: (a) Schematic of nano-cone texture features with increasing surface-to-volume ratio from left to right. (b) Corresponding post-diffusion cross-sectional views with the distribution of phosphorus indicated in purple (‘n+’). (c) Corresponding bottom-up view of the nano-cones. Source [Scardera2021] DOI: 10.1109/JPHOTOV.2020.3047420

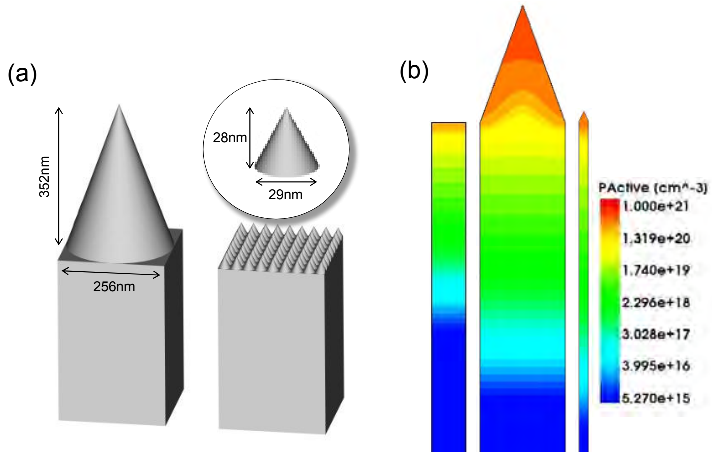


Figure 3-6: (a) Schematics of nano-cone texture features used for diffusion simulations. (b) Simulation results showing the distribution of phosphorus for the two nano-cone conditions and a planar reference. Adapted from [Scardera2021] DOI: 10.1109/JPHOTOV.2020.3047420

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Below is the complete list of papers published during the project.

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