SCHOOL OF ENGINEERING
Faculty of Science and Engineering

MACQUARIE University

Public Report

Substitution of niche-market PV production tools with cost-effective consumer-electronics technology

Organization
Macquarie University (MQ)
School of Engineering

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Executive Summary

This Project aims to reduce the cost of current silicon solar photovoltaics (PV) manufacturing technology through the development and application of novel production line equipment based on low-cost consumer electronics technology. These low-cost tools will work as direct, drop-in replacements to conventional higher cost niche PV production equipment.

The Project identifies three forms of consumer electronics technology that will be optimised with the aim of reducing the cost of solar PV device fabrication processes and quality control. These form the three technology streams of the Project:

(a) Microwave heating, using the same technology as found in most kitchens, will be investigated as a low-cost and more energy efficient replacement of various thermal processes in PV production, such as dopant diffusion, contact formation, and hydrogenation.

(b) Flatbed scanner technology, used in most office environments, will be used to enable rapid yet comprehensive measurement of silicon texturing processes.

(c) Thermal imagers, such as devices now available as mobile phone attachments, will be adapted for the detection of silicon wafer defects.

This report is the interim public dissemination report, submitted at the midway point of the project. It provides an updated overview of the project's progress along with details of the key highlights and lessons learnt so far.

Project Overview

The Project intends to leverage the substantial cost-savings of mass-produced consumer electronics, to create drop-in replacements for specific production line tools. The end-goal is to improve the cost-effectiveness of current mass-market solar PV panels by a reduction of manufacturing processing costs through improved overall equipment efficiency and automated, cheap and rapid quality control (QC) monitoring.

These alternative tools will have up-front costs in the order of 5 to 100 times cheaper than conventional tools. The Project technology will not only propose to lower the cost of setting up new production lines, but also has strong potential to lower operating costs of both new and existing lines, particularly for microwave processing which can lead to more energy efficient thermal processes, with less electricity required to achieve comparable or superior results. Improved QC though flatbed-scanner and consumer thermal imaging technology may also lead to improved module reliability, reducing the costs and liability associated with warranty returns. Finally, these QC improvements will also enable rapid and detailed determination of production line defects and provide useful data for process optimisation, thus improving overall yield and potentially leading to further production line optimisation

Project Update

Progress Against Outcomes

The project aims to achieve the following outcomes at completion:

a) Progression in technology readiness (from TRL 3 to 6) for at least one of the following technologies: microwave processing, flat-bed scanner technology and thermal imaging, for potential use in production line equipment for the manufacture of silicon solar PV cells and modules.

b) Increased knowledge and understanding of the technical capabilities and cost reduction opportunities for microwave processing, flat-bed scanner technology and thermal imaging as drop-in technologies to replace conventional CAPEX and OPEX intensive equipment currently used in the manufacture of silicon solar PV.

c) Dissemination of key research findings to the photovoltaic research community, industry and the public to encourage and advance commercialisation of the most promising of the three technologies outlined above.

Each of these outcomes have been progressed and all are on track towards full achievement by the end of the project. Specific progress against each outcome is detailed below.

a) All project technology streams have been advanced from TRL of 3 (proof-of-concept) to at least TRL level 4 (validation in lab environment) during this first phase of the project with working lab tools now developed and used for investigation of each technology's potential. Economic and technological capability have been analysed for each case and the outcome of that analysis indicates Flatbed scanner technology is most promising for advancement into the second phase of the project where it is on-track to progressing to TRL 6 (proto-type demonstration in relevant environment).

b) Investigations of each technology stream through experimentation using the aforementioned newly developed laboratory tools has led to increased knowledge and understanding for all three streams. This new information has formed part of the input for detailed cost-benefit modelling, a thorough analysis of which has been carried out for each technology in collaboration with industry expert consultants *Solinno Pty Ltd*. This analysis has revealed that whilst each technology stream has some merit the most promising and most feasible is the flatbed scanner technology due to its extremely low cost and variety of use cases. This technology will be further developed in phase 2 of the project with additional use cases investigated and further economic modelling for commercialisation applied.

c) The first phase of the project has primarily involved the establishment and development of new laboratory tools and experiments required to investigate each of the project technology streams. As such, findings have not yet been published and disseminated throughout the research community. However, a significant amount of new data has been gathered and analysed and this analysis is now in the process of being formed into multiple research papers as well as at least one patent application. This outcome is therefore on-track to be achieved in the upcoming second phase of the project.

Key Highlights

- New laboratory tools based on the project's consumer electronics technology streams have been developed and are now fully operational at Macquarie university
- The technical capability of each of the project's technology streams has been experimentally investigated for a selection of key use cases
- New, unanticipated uses for some technology streams have been identified with proof-of-concept tests carried out and patenting of these novel uses now underway
- A detailed cost modelling analysis has been carried out for all likely use-cases of each project technology stream and the most promising technologies have been identified
- Improved understanding of each technology stream has been gained through experimental investigation using the project's custom-made lab tools. Multiple scientific journal publications are currently in progress.

Lessons Learnt

Lesson Learnt 1: Absorption of microwaves in silicon

Category: Technical

Detail: Microwave absorption in materials happens by two different mechanisms, one is dielectric loss because of the polarisation loss of atomic dipoles, and the other is ohmic loss because of eddy current generation. Crystalline silicon in its natural intrinsic form does not absorb microwaves at room temperature. This is because of the rigid crystallinity and non-polar nature of silicon crystals.

The absorption of microwaves in silicon solar cells was assumed to be taking place in the silicon nitride anti-reflection coating (ARC) layer which is deposited on top of the silicon, this is a polar structure that can absorb microwaves through dielectric absorption. During the course of the project, we found that rapid heating rates as high as 250°C/s to 300°C/s are achievable also through ohmic absorption in silicon wafers. This ohmic loss is due to the rapid movement of free carriers along the silicon which has a finite sheet resistance. We were able to heat up raw silicon wafers, silicon wafers with an emitter diffusion (the doped layer required for solar cell operation), and silicon wafer with both an emitter diffusion and ARC coating, all at fairly similar heating rates.

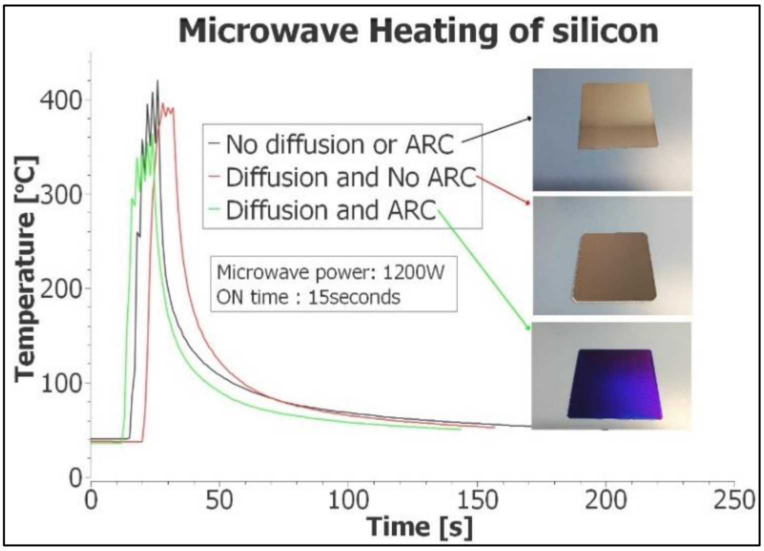

Figure 1: Microwave heating of silicon
wafers in various stages of processing.

Knowledge Gap: As we progressed the project work we also found that microwave processing presents a unique challenge in the accurate measurement of temperature. In conventional heating, heat flows from the outside to the inside of the sample. Measuring temperature in this case is fairly straightforward as an infrared (IR) thermometer can be used. However, during microwave processing, the outside of the sample is at a lower temperature than the inside of the sample. As IR thermometry only captures the temperature at the surface, this measurement technique leads to an underestimation of the temperature. This problem becomes more severe when there are insulating layers on the sample, e.g. glass plates on a silicon solar cell. This is a common problem when working with microwaves and has resulted in several research groups wrongly reporting 'non-thermal effects' in microwave processing.

To make the temperature measurement more accurate, especially under insulating layers, we have been developing mathematical models to estimate the transient temperature of the cell under a glass plate. We envisage that this model will be helpful in other microwave-based areas of research where accurate temperature measurements are needed.

Implications for future projects: These findings open up more possibilities for silicon solar cells to be heated by microwaves in the earlier stages of processing which do not require the silicon wafer to have a diffusion or anti-reflection coating process already applied. This becomes significant if microwave heating techniques are to be developed for solar cells that do not have an anti-reflection coating, such as advanced black silicon solar cells.

Lesson Learnt 2: Arcing and potential damage from microwave processes is avoidable

Category: Technical

Detail: Arcing is a commonly known issue in that can occur in microwave cavities. It happens when the electric field intensity is very high at the sharp edges of an object within a microwave field. This results in a discharge to the surroundings by breaking down the air, creating a plasma resulting in arcing, which appears as a bright spark. Arcing is detrimental to a silicon heating processes as (i) it creates a non-uniform distribution of heating as extreme heat will be localised in the part of the sample near the arc (ii) it is difficult to control the temperature during the arcing process (iii) this can damage and crack the samples because of the extreme heat and temperature gradient and (iv) arcing reduces the lifetime of the microwave source, the magnetron, because of sudden dips in the load.

During the project, we observed plasma arcing in the samples when we used smaller rectangular samples. We were able to reduce the arcing by using circular samples. Further, we learned that the full-size wafers (6 inches and more) do not have the problem of arcing in the microwave, even with the rectangular shape and sharp edges. To achieve this, the sample needs to be lifted at least 5 cm above the base of the microwave cavity by a non-absorbing and non-conductive material as shown in the picture below.

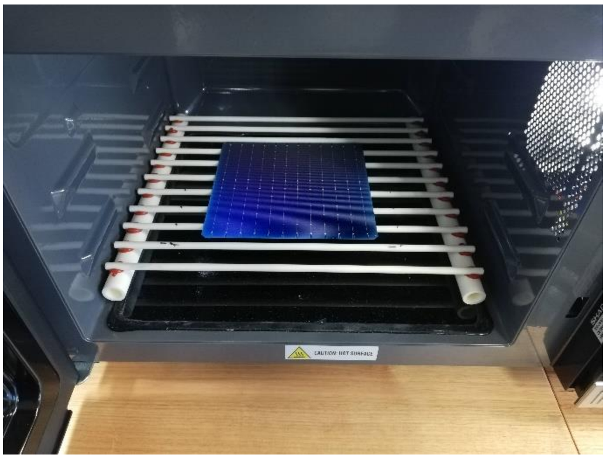

Figure 2: Full- sized silicon solar cell in the microwave cavity

After the elimination of arcing, the next focus was on avoiding any performance degradation of microwave processed solar cells as this determines the range of thermal processes which can be replaced by microwave processes. One of the main concerns for microwave processing is for any damage to the deposited device structures due to the high heating rate or by the high electric field inside the microwave cavity. We investigated the performance degradation on passivated-contact bifacial cells from Hanwha Q-cell processed in the microwave cavity for 20 seconds at 1000W. Visual inspection and Open circuit voltage measurements were performed on the solar cell before and after microwave processing. We found no visible damage or decrease in the open-circuit voltage, leading us to the conclusion that microwave field effects- within the range that we used- do not degrade the solar cell performance.

Lesson Learnt 3: Flatbed Scanners are not all equal

Category: Technical

Detail: There are two main types of flatbed scanners on the market, and throughout our investigations we have found that it makes a big difference which type you use to scan solar cells. Solar cells are a high-volume-mass-produced product, and so have processes to make sure the thousands of cells that are made are within specification. We are looking at the use of these ultra-low-cost mass-produced flatbed scanners to replace much more boutique expensive equipment when monitoring some of these specifications, and it turns out that making the correct choice of scanner type is essential.

There are two types of imaging systems used in consumer-market scanners; one which uses a large lens and a charge-coupled device (CCD), much like a digital camera, and ones which use contact image sensors. Contact image sensors are different because they have an image sensor that is as big as the object you are taking the image of. While this might be an issue for normal camera technology it turns out it's a great thing when measuring solar cells.

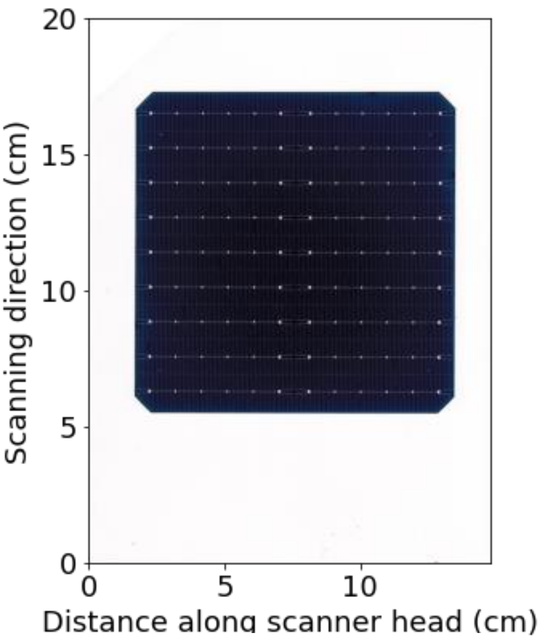

Figure 3: Example scan of a solar cell.

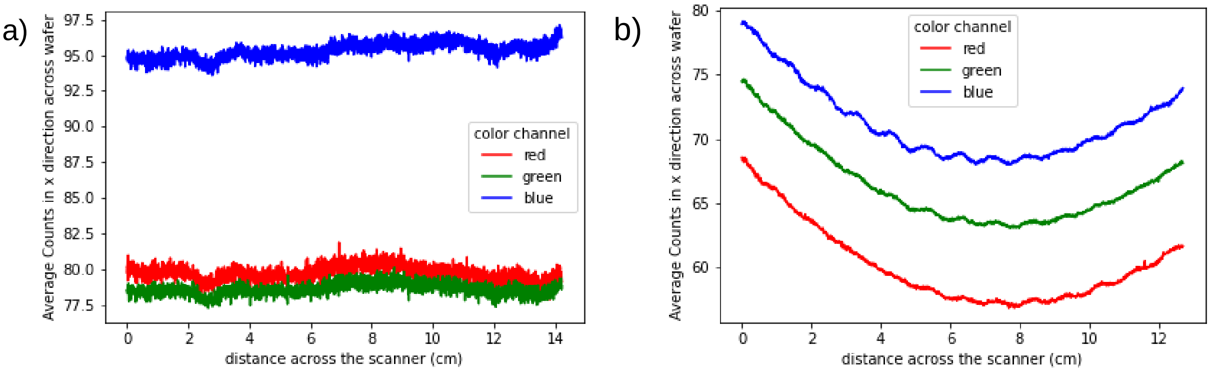

Figure 4: Comparison of line-profile across a scan with a) contact image sensor and b) standard scanner

To show the difference the type of scanner has on the data, we measured the same solar cell with the two different types of scanners. From these scans we then extracted a single row of pixels from the cells area, with the results shown in Figure 4. The contact image sensor shows what we expect, a constant intensity right across the solar cell, while the more standard scanner shows us a big change across the solar cell. This is because a standard scanner has to perform corrections to what it images, this process is called flat-field correction or vignetting correction. This is needed because this type of imaging system does not have the same sensitivity across its width. The built-in correction is optimised to work well for documents and photos which have very different characteristics to solar cells, so this leads to inaccurate data when imaging our devices. While it may be possible to find a new calibration procedure for these more standard scanners, the contact image senor-based scanners readily provide more reliable data and they are typically lighter, smaller and cheaper.

Implications for future projects: Future projects will consequently focus on contact image sensor technology for monitoring solar cells.

Lesson Learnt 4: Solar cells interact with light very differently in the 7 -14 µm wavelength range

Category: Technical

Detail: Low-cost thermal cameras are now widely available, now even available as attachments for mobile phones. We are testing if these low-cost cameras can be used for solar cell process monitoring instead of the much more expensive thermal cameras ($10,000-100,000 range) that are currently used in production. The low-cost thermal cameras measure light in a longer wavelength range relative to their more expensive counterparts. The conventional more expensive cameras operate at a 3-5 µm range while the low-cost cameras work in the 7 to 14 µm range. Both of these measure at longer wavelengths than the wavelength range solar cells are designed to operate; solar cells operate at wavelengths < 2 µm. But it turns out that the optical response of solar cells still changes dramatically when switching from 5 µm to over 7 µm.

The difference between a normal photo and thermal image can easily be seen using a SeekShot Pro camera from Seek Thermal, as this device has both a visual camera and a low-cost thermal camera. In Figure 5 we have taken a photo of a solar cell with both these cameras and displayed the images side-by-side. In Figure 5a, the normal photo, the solar cell is the blue object with white lines across it. The white lines are the metal contact fingers used to get the electrons out of the silicon. There is also a white object behind the solar cell, this is a power supply, used here to act as a heat source. In this regular photo, the solar cell appears as a relatively uniform blue colour. In contrast, Figure 5b shows an image taken with the thermal camera. Now we can see that the power supply is hot (38 ºC), and we can also see another hot object that at first glance appears to be within the solar cell. However, this second object is a hot block (near 50 ºC), that is in front of the solar cell, but out of frame. In the 7 to 14 µm wavelength range a solar cell behaves as a mirror, and so we can see a well-defined reflection of this hot block. This mirror-like behaviour is because the typical feature size of the texture on a solar cell is now much smaller than the wavelengths of light we are observing (7 to 14 µm) meaning geometric optics no longer apply and the photons of light effectively cannot distinguish the texture features, and instead experience it as a smooth planar surface. The hot block is at 50 ºC but it appears as a lower temperature in the thermal reflection image because the solar cell is not a great mirror and only reflects around half of the light at these wavelengths.

a) b)

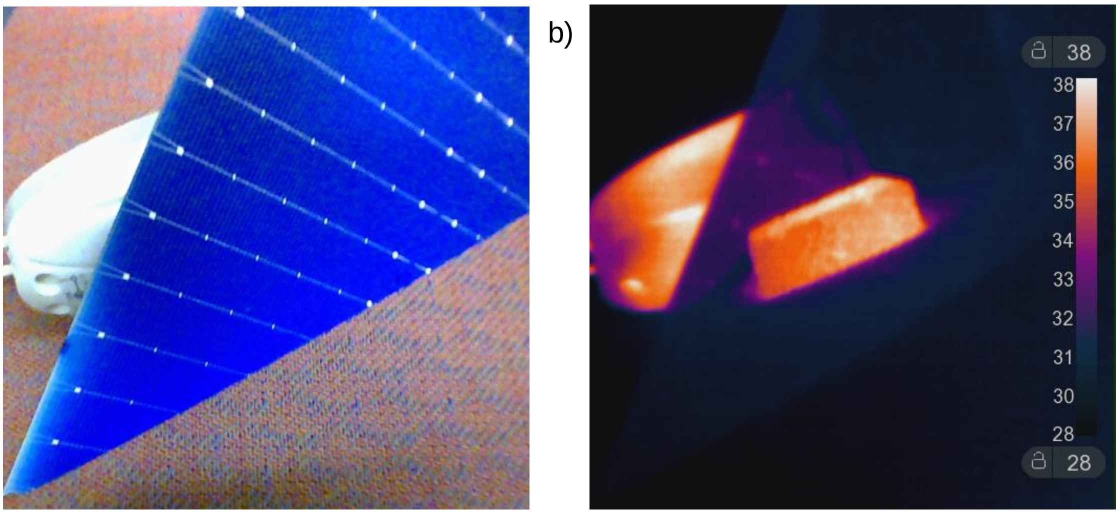

Figure 5: Images showing a solar cell with a heat source behind it and a hot block in front of it positioned out of frame, taken with a) normal camera and b) low-cost thermal camera.

A similar change occurs with light that passes through a solar cell rather than reflecting from it. In the 7-14 µm range a silicon solar wafer (a solar cell without the metal contacts) behaves like a tinted window. An example is shown in Figure 6, where a wafer is suspended over a hot plate by two insulating blocks. In Figure 6, the large hot square (~100 ºC) is a hotplate and the two labelled darker squares are insulating blocks. The silicon wafer is placed on top of these blocks and appears to be at a temperature of 65 ºC. The real temperature of the wafer is less than 30 ºC, but some of the thermal radiation from the hotplate is able to pass through the wafer and get to the camera. Since the wafer acts as a tinted window, not all of the light makes it to the camera, though it lets enough light through to clearly see the insulating cubes holding the silicon wafer off the hot plate.

Implications for future projects: Changing from thermal cameras that operate in the 3-5 µm range to the 7-14 µm range has significant implications for the application of monitoring solar cells. In the 3-5 µm range the light is heavily scattered from the solar cell, while in the 7-14 µm range the cell's transmission and reflection are completely specular (mirror like).

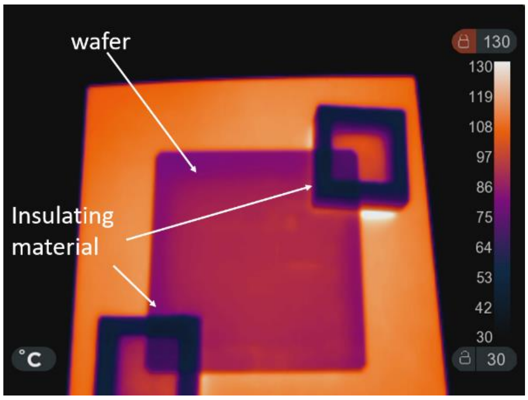

Figure 6: Thermal image show that silicon wafers are transparent like tinted windows in the 7 to 14 µm wavelength range.