Australian Government
Australian Renewable Energy Agency

ARENA

Laser Doping Using Laser Chemical Processing Technology for Advanced Silicon Solar Cells *(1-GER006)*

Final Report: Project Results and Lessons Learnt

Lead organisation: The Australian National University (ANU)

Project commencement date: 15 April 2012 **Completion date:** 31 May 2014

Date published: TBA

Contact name: Dr Klaus Weber

Title: Local doping using Laser Chemical Processing technology for advanced silicon solar cells

Email: klaus.weber@anu.edu.au **Phone:** 6125 9734

Website:

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Executive Summary

In Laser Chemical Processing (LCP) technology, a liquid jet with a typical width of that of a human hair is formed by pumping liquid through specially shaped nozzles under high pressure. A laser beam is guided within the liquid jet and used to fabricate the contact regions of solar cells. This project addressed key challenges in LCP technology that created significant hurdles to its commercial application, particularly the laser beam size and uniformity when it reaches the solar cell. Typically, the beam intensity is highly non-uniform. In addition, the beam size is equal to the size of the liquid jet.

To overcome these limitations, the optics of the laser beam was studied in detail and the way in which the laser beam is introduced into the beam was radically modified. By using advanced techniques to couple the laser beam into the liquid jet, it was possible to obtain a much smaller beam size. The excellent quality of the contact regions that can be realised from the modified process were demonstrated using different measurement techniques. To demonstrate the full potential of the advanced LCP technology, solar cells were fabricated using LCP technology for both solar cell contacts. In a first attempt with not yet optimised processing parameters, a conversion efficiency of 20.4% was realised, significantly higher than the efficiency of most currently produced commercial solar cells. This result confirms the excellent properties obtained from the advanced LCP process and means that significant hurdles to the commercial application of LCP technology for solar cell fabrication have been addressed.

Project Overview

Project summary

In this ARENA funded project, substantial improvements were made to LCP technology, a laser-based technology that can be used to create the contact openings and simultaneously introduce dopants (beneficial impurity atoms) into the regions beneath the contacts.

LCP stands for Laser Chemical Processing. In LCP technology, a liquid jet with a typical width of that of a human hair is formed using specially shaped nozzles and pumping the liquid through the nozzle under high pressure. The solar cell to be processed is placed under the liquid jet. A laser beam is then coupled into this jet and remains confined by the jet. In this way, it is possible to create a fine laser beam that is stable over many centimetres and guide this beam to the solar cell. The liquid in which the laser beam travels contains the right impurities needed to dope the cell. When the laser beam reaches the solar cell surface, it temporarily heats the cell surface in the region of the beam to sufficiently high temperatures to melt the silicon and remove the surface coating. The molten silicon then readily incorporates the dopant impurities from the liquid jet. In this way, it is possible to dope the contact regions and create the contact openings in a single step. The process is therefore simple, elegant and cost effective.

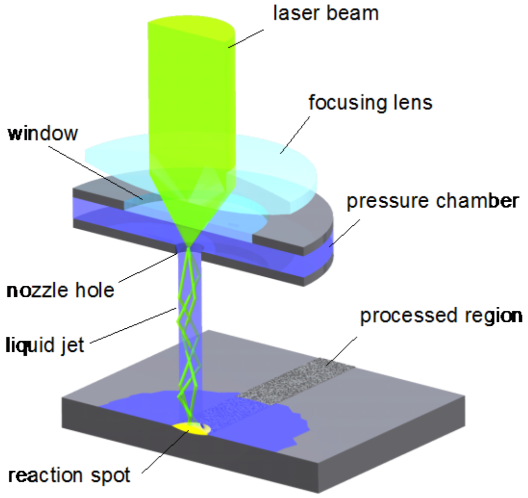

Figure 1: Left: A schematic illustration of LCP technology

Figure 2: Right: LCP technology in action

The project addressed key challenges in LCP technology that create significant hurdles to commercial application. The most significant of these concerns is the laser beam size and uniformity when it reaches the solar cell. Typically, the beam intensity is highly non-uniform. In addition, the beam size is equal to the size of the liquid jet. While the width of a human hair may not appear to be very wide, it is actually still much wider than ideal for application to solar cells. Hence, both the non-uniformity of the beam and its size will create limitations on the solar cell efficiency.

To overcome these limitations, the optics of the laser beam was studied in detail and the way in which the laser beam is introduced into the beam was modified. The performance with the modified arrangement was then analysed in depth to understand exactly how the new system behaved, including its performance potential and limitations. For this, a range of sophisticated modelling and analysis techniques were employed.

Project scope

High Efficiency silicon solar cells – used to make the next generation of Photovoltaic panels – require relatively complicated structures. A typical structure is shown below. Key features are a textured front surface and an antireflection coating to reduce reflection losses; a diffused impurity region which is essential to collect electrical charge carriers – generated by sunlight – from the cell; a rear surface coating; openings through the front and rear coatings; and metal on the front and rear of the cell to carry electrical current produced by the cell.

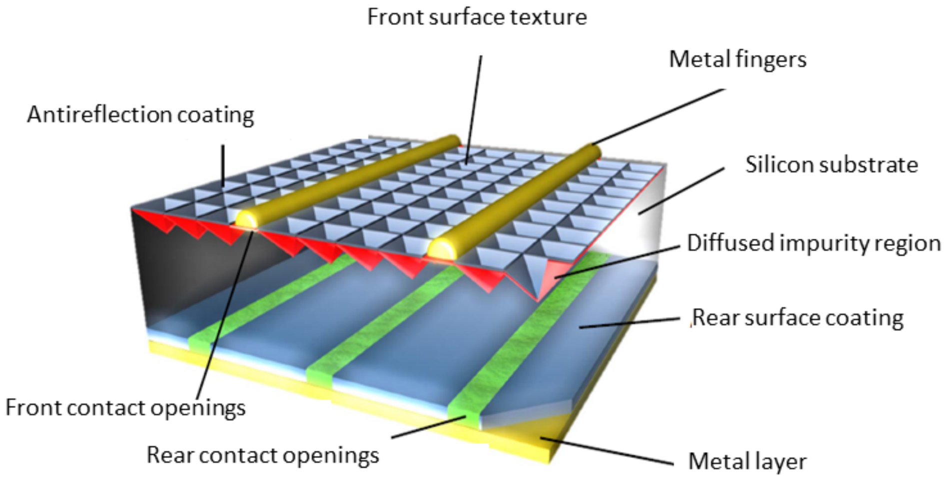

Figure 3: An illustration of a typical high efficiency solar cell structure

The openings through the front and rear side coatings must be created in a way that is cheap and allows the ready formation of the metal contacts on both sides. For high efficiency cells, it is also important that additional impurities (dopants) are introduced into the regions beneath the metal contacts. This helps to ensure excellent electrical contact and reduces losses in the solar cell.

Laser doping is a particularly attractive process for the creation of suitable contact regions. In laser doping, a laser beam temporarily melts a shallow and small, precisely defined region of the wafer surface, in the process removing any overlying insulting layers. If a source of dopant atoms is present whilst the surface is molten, these dopant atoms will be incorporated into the surface.

The LCP process is an attractive method of achieving laser doping, because the source of the dopant atoms is the liquid jet. This means that in just one process step it is possible to open and dope the contact regions. Other techniques usually require a separate step to deposit a film on the wafer surface which contains the dopant atoms. In addition, the LCP process allows very small contact openings to be created. Generally, the smaller the contact openings, the higher the solar cell conversion efficiency – the efficiency of conversion of solar to electrical energy - that can be realised.

The aim of this project was to significantly improve LCP technology, so that the technique becomes commercially attractive and can ultimately contribute to lowering the cost of electricity generated by solar cells. This was to be achieved by improving the laser beam size and shape, as well as optimising the variation of the laser pulse intensity with time. This allows narrower, higher quality laser doped contacts to be realised. Importantly, such contacts were to be achieved at high laser speeds, so that throughput rates can be sufficiently high for industrial application. In industrial solar cell fabrication, a process step for each solar cell must not take longer than 5s, and ideally should be 2s or less.

Outcomes

By using advanced techniques to couple the laser beam into the liquid jet, it was possible to obtain a much smaller beam size. The CCD images below show the improvement that was obtained. The colours in these images give an indication of the intensity of the laser light, with the intensity in the red areas being up to 100 times greater than in the light blue areas. The greater intensity will result in deeper melting of the solar cell material, and in much heavier doping.

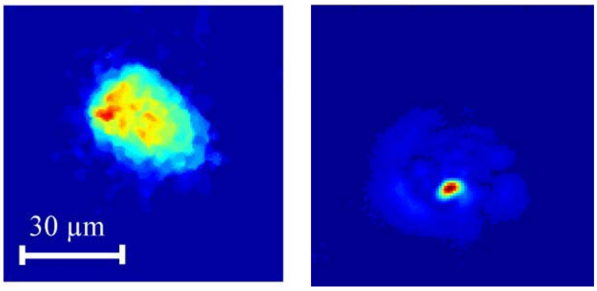

Figure 4: CCD camera images of laser beam intensity profiles. Left: state-of-the-art profile at the start of the project. Right: profile achieved with advanced coupling techniques

These results were then demonstrated to translate to improved laser processed contact regions. The electrical contact of metal to the contact openings could be shown to be excellent. The new process also did not introduce significant damage into the silicon crystal. This is important as such damage can reduce the efficiency of the silicon solar cell.

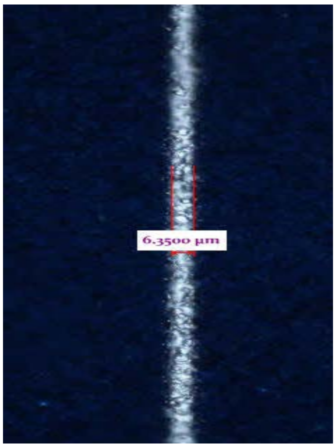

Figure 5: Optical microscope image of an extremely narrow (<7µm wide) line created using advanced LCP processing on a textured solar cell surface

To demonstrate the full potential of the advanced LCP technology, solar cells were fabricated at ANU and Fraunhofer ISE where both front and rear contacts were opened and doped using LCP technology. In a first attempt with not yet optimised processing parameters, a conversion efficiency of 20.4% was realised, significantly higher than the efficiency of most currently produced commercial solar cells. This result confirms the excellent properties obtained from the advanced LCP process and means that significant hurdles to the commercial application of LCP technology for solar cell fabrication have been addressed.

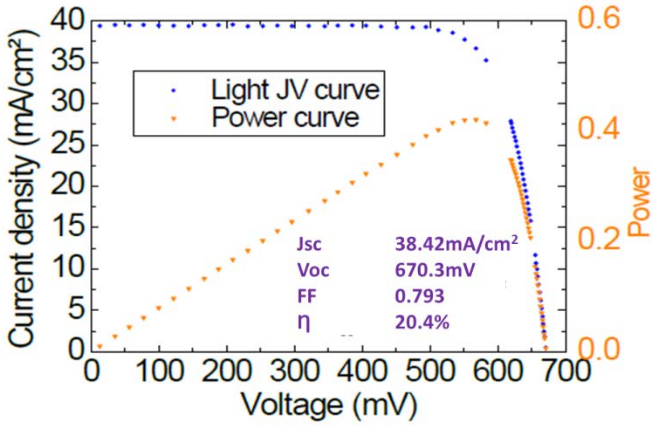

Figure 6: The current-voltage and power-voltage curves of one of the solar cells processed using advanced LCP technology

Discussions are now under way with equipment manufacturers to commercially exploit this technology.

Transferability

An important aspect of the project was the development of advanced measurement and modelling techniques. The interpretation of measurements on laser processed features is challenging due to the highly non-uniform nature of these features. The new techniques both accelerate the collection of data and improve the accuracy of the values extracted from these measurements.

These techniques are already finding application in other areas. Several have been published in international journals and conference proceedings. As a specific example, the modelling program Quokka was developed chiefly by Dr. Andreas Fell, with input from other researchers. This is an extremely flexible, fast and powerful program that allows both the modelling of complex solar cell structures, and the interpretation of measurement results of complicated test samples, to allow the accurate and reliable determination of the most important sample properties. This program is freely available through the PV Lighthouse website.

The work carried out in the project is supporting ongoing work on LCP technology carried out through a postdoctoral fellowship awarded by ARENA to Dr. Xinbo Yang, which aims to develop and demonstrate LCP technology on even more sophisticated solar cell structures with higher efficiency.

This project was one of a suite of projects focused on the development of advanced laser processing techniques and associated measurement/modelling techniques, as listed below. There is substantial synergy between all these projects which helps to accelerate research and ensure top quality research outcomes.

- 3-GER002 “High quality laser doping for solar cells through improved characterisation techniques” (ARENA funded Australia-Germany project with partner The Institute for Solar Energy Research (ISFH), Hameln)
- L. Xu “Advanced Laser Doping for Solar Cell Applications” PhD project
- D. Walter “Characterisation and Development of Laser Processing for High Efficiency Silicon Solar Cells, PhD thesis (submitted)
- Y. Han, “Laser Doping for Manufacturing of High Efficiency Silicon Solar Cells”
- A. Fell, 5-F007, "High efficiency very low thermal budget silicon solar cells by laser processing" (ARENA funded Fellowship)
- X. Yang, 6 - F007, “High Efficiency N-type Silicon Solar Cells with Local Laser Doping by Laser Chemical Processing (LCP)” (ARENA funded Fellowship)

Conclusion and next steps

We aim to commercialise the project outcomes in order to realise the full benefit of the project results. The most prospective route to commercialisation of the Intellectual Property is through partnership a large equipment manufacturer who makes a range of industrial processing equipment for the PV industry and possibilities are being explored.

Project outcomes are also feeding directly into other continuing projects, including the postdoctoral LCP project by X. Yang. Further, the outcomes from this project as well as the suite of other laser projects is feeding directly into projects aiming to take the commercialisation of laser processing technology to the next stage with solar cell manufacturers.