

PLANK CELLS: ULTRA THIN AND FLEXIBLE SOLAR CELL

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ABSTRACT: The design, development and performance of a flexible mono-crystalline silicon solar cell is presented. The mentioned solar cell design is 18~25 μm thick, elongated in shape, and can be rolled up around a 6mm diameter. The design of the solar cell is presented in detail and discussed in the paper. Preparation of the solar cell is done on free standing thin mono-crystalline silicon wafers, and standard manufacturing processes and handling techniques are used for all parts of the cell preparation. Several batches of Plank solar cells has been successfully fabricated and tested. Initial results are promising, and prove the possibility of producing highly flexible solar cells using mono-crystalline silicon solar cells. The structure is then evaluation using 2-D modelling to examine the ideal performance of Plank Solar cells at thicknesses that allow high flexibility.

Keywords: Solar Cell, Flexible, Crystalline.

1 INTRODUCTION

The technology for wafer based crystalline silicon solar cells is relatively matured. Modules are stable over an extended lifespan, are non-toxic and have the potential for high energy conversion efficiency. However, most silicon solar cells, are above 200 μm thick, and are therefore inflexible. This imposes a requirement on the module packaging to be strong and rigid to protect the silicon cells, thus making the module heavy and non-mobile.

For a solar cell to be suitable as a mobile power source, it preferably should be efficient, light weight, robust, and have high tolerance to shadow losses. Thin-film technologies are potentially capable of meeting those requirements, although most have low conversion efficiency, and/or are not suitable for flexing [1]. On the other hand, thin crystalline silicon solar cells are highly efficient, and have the potential to be flexible.

This paper presents the development of a very flexible thin mono-crystalline silicon solar cell fabricated from Float Zone grown silicon wafers. The solar cell is very thin, elongated in shape, and can be rolled up around a 6mm diameter. Figure 1 shows a 24 μm thick, 45mm long Plank solar cell having extremely high flexibility.



Figure 1: Plank Solar Cell

It is well known that mono-crystalline silicon below 100 μm can flex and bend. Taking that further, research work in the Australian National University (ANU) showed that solar cells fabricated on thin silicon can be flexed at 1.5x fracture limit repetitively over many cycles without significant degradation of the cell performance [2]. Based on this, it is possible to make flexible solar cell modules with the assurance that the performance will

not degrade with repetitive usage. The applications of such a module would be suitable for mobile and high power/weight ratio applications.

2 PLANK CELL DESIGN AND PROCESSING

2.1 Cell Design

The general geometry of the solar cell is 45~100mm long, 18~50 μm thick, and 0.5~1.0mm wide. An illustration of the cell cross section is shown in Figure 2.

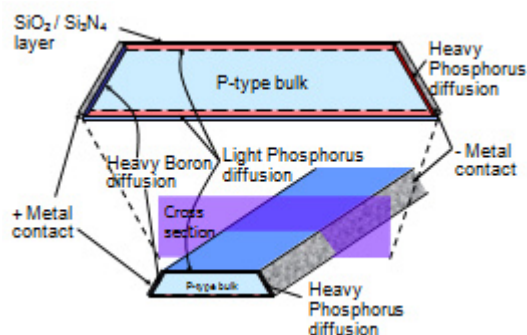


Figure 2: Plank solar cell design

The cell is bifacial, and the negative and positive contacts are on the sidewalls. The front and back surfaces of the cell is diffused with phosphorus with sheet resistance of 100 Ohm/square as the cell emitter. For good surface passivation, a thin layer of dry SiO_2 layer is thermally grown. The surfaces are coated with silicon nitride as the anti-reflection coating.

The sidewalls of the solar cell are the contact points, with a heavy boron diffusion on one side and heavy phosphorus on the other. Metal is deposited on both sidewalls as the metal contacts of the cell.

2.2 Sidewall Structure

Sidewalls of the solar cell are formed using a combination of Nd:Yag laser cut and taking advantage of the anisotropic etch profile of heated Tetraethylammonium hydroxide (TMAH). TMAH solution at 100 degrees will etch (100) silicon planes two orders of magnitude faster than (111) silicon planes. By varying the wafer crystal orientation, cut depth and TMAH etching times, the sidewalls can either be sloped, vertical, or inverted. Graphical illustration of the three techniques is shown in Figure 3.

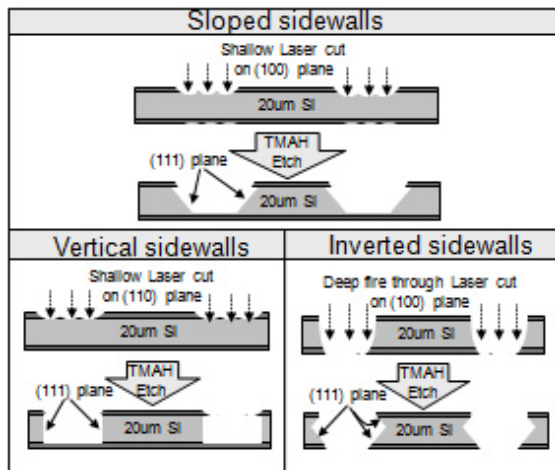


Figure 3: Plank Sidewall structure formation

A sloped sidewall can be achieved using a wafer with (100) surface crystal orientation, where the laser cuts are done parallel to the wafer flat. This creates a sloped sidewall of approximately 54.7 degrees. This structure allows easy one step metallization technique to be applied to the metal contact. However, the cell is not fully bifacial.

A vertical sidewall is achieved by using a silicon wafer with (110) surface crystal orientation and using laser scribe to remove the dielectric layers followed by a TMAH etch. The etching will propagate vertically through the wafer, while etching into the (111) sidewalls at a much slower rate. This gives a perfect bifacial cell, but requires a two step angled metal evaporation

followed by metal etch back for contact formation.

An inverted sidewall is a more complicated technique which can be created using a (100) wafer by removing the dielectrics on both sides followed by a TMAH etch. This structure allows a full back surface reflector to be deposited on the rear surface of the cell as the inverted structure isolates the rear reflector from the contact fingers.

2.3 Overview Fabrication Sequence

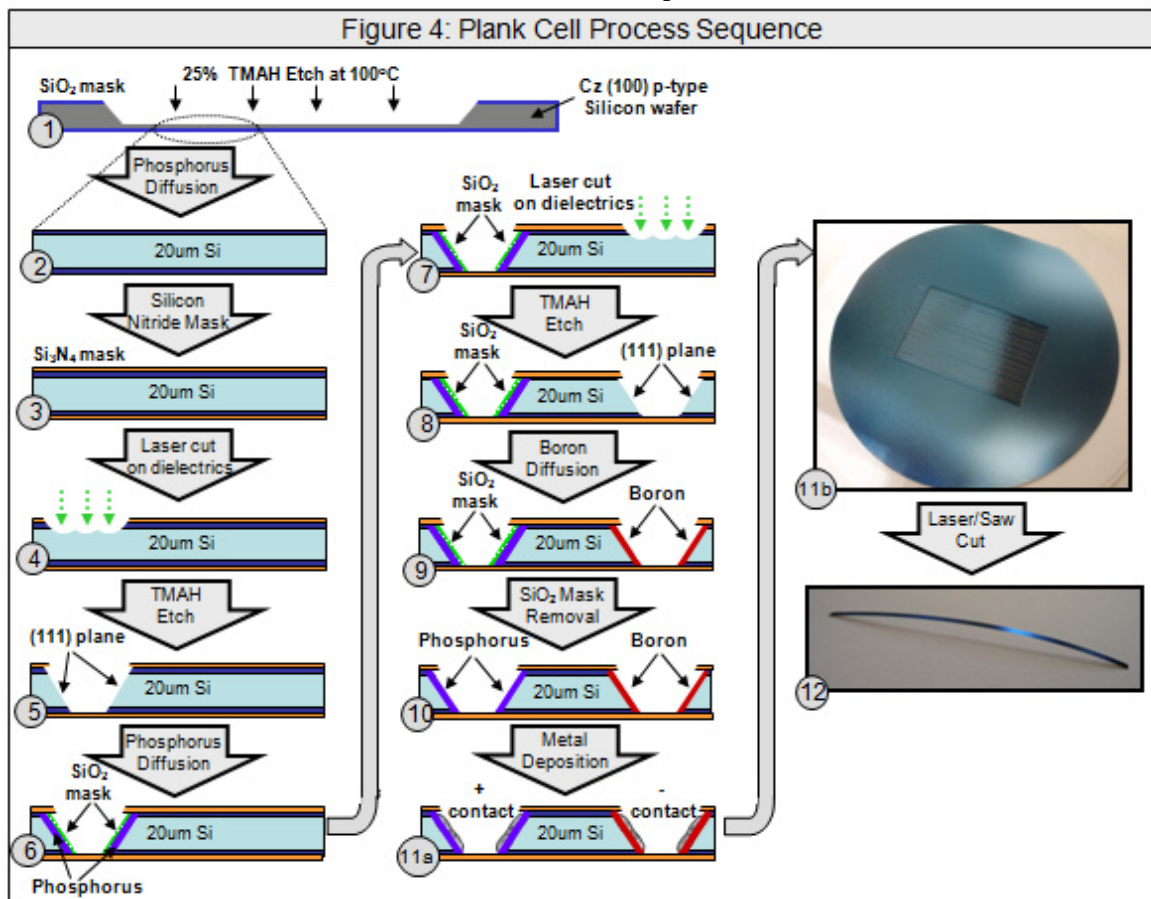
The processing of a batch of Plank solar cell requires 21 individual steps. For the sake of illustration, Figure 4 simplifies the processes into 12 distinct process steps.

Step 1: 4 Inch (100) crystal orientation FZ p-type wafer of thickness 300µm is used as the starting substrate. A Silicon dioxide (SiO_2) mask is grown thermally. A rectangular window on the top side of the wafer is opened using Hydrofluoric Acid (HF) vapor. The wafer is then etched in heated TMAH solution to achieve ~20 µm thickness in the middle section of the wafer. This will be the area which the cells will be fabricated. It is important to note that the cell fabrication does not have to begin from a thick substrate, which wastes silicon material through the thinning process. The reason this is done is to allow ease of handling due to manual fabrication of the cells in laboratories.

Step 2: Initial SiO_2 mask is removed entirely via a HF etch step. A light phosphorus diffusion is then made into both sides of the wafer.

Step 3: A very thin (20nm) layer of SiO_2 is grown for surface passivation, followed by a Silicon Nitride (Si_3N_4) deposition via LPCVD as an anti-reflection coating.

Step4: A shallow laser scribe is used to remove the



dielectric layer, exposing the bare silicon for TMAH etching for the formation of the cell sidewalls.

Step 5: Hot TMAH etching for 30~40 minutes forms the sloped sidewalls.

Step 6: Heavy phosphorus doping is diffused onto the exposed sidewalls. Following the diffusion step, a thermal oxide of approximately 200nm is grown to mask the surface against subsequent TMAH etching and boron depositions.

Step 7: A light laser scribe is performed to remove dielectric layers midway between the two phosphorus sidewalls

Step 8: Similar to step 5, TMAH etching for 30~40 minutes forms sloped sidewalls.

Step 9: Heavy doping of boron is diffused into the exposed silicon surfaces

Step 10: HF etching is used to totally remove any oxide masks, exposing metal contact areas, whilst preserving the Si_3N_4 .

Step 11a: Metal deposition of aluminum, followed by a low temperature anneal is performed to achieve electrical contact. Shadow masking is used to confine the metal to the sloped sidewalls

Step 11b: Image of an actual Plank cell wafer at this stage. The cells are still intact on the host wafer.

Step 12: Individual Plank solar cells are removed from the wafer.

3 2-D SIMULATION OF PLANK CELLS

In order to examine the potential of Plank Solar Cells as a flexible structure, a 2-dimensional (2-D) simulation is performed to simulate the maximum efficiency of the cell at thickness below $120\mu\text{m}$. The simulated plank solar cell has a polished surface, good surface passivation, and with a Si_3N_4 anti-reflection coating.

By combining the simulation results with the findings of previous work [2] on flexible solar cells, we were able to obtain a correlation between flexing at $1.5x$ fracture diameter and the associated maximum efficiency (Figure 5). As an example, with a requirement of 20 mm maximum bending diameter, one would ideally expect to be able to utilize polished surface Plank solar cells of 19% efficiency.

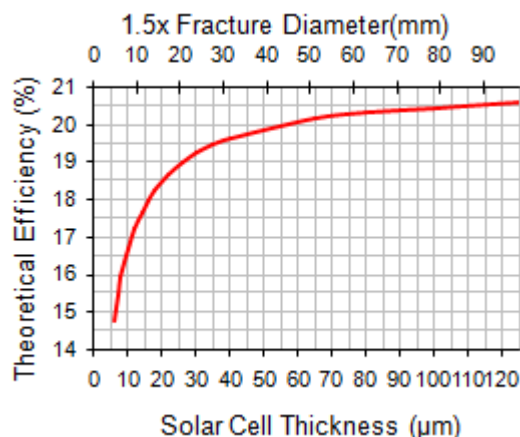


Figure 5: 2-D Simulation results showing maximum efficiency of Plank Solar Cells as a function of cell thickness. Also shown is the $1.5x$ fracture diameter at the top x-axis [2].

The efficiency of polished surface Plank cells deteriorate

quickly going below $20\mu\text{m}$, mainly due to poor light trapping, as well as increasing series resistance in the bulk. Incorporation of light trapping would address this problem. This structure of dual sided emitter Plank solar cells ceases to function below $5\mu\text{m}$ due to the front and back emitter diffusions consuming all of the bulk.

4 RESULTS AND DISCUSSION

Several working batches of Plank solar cells have been fabricated at the ANU below $25\mu\text{m}$ thickness. The best performing batch of $18\mu\text{m}$ thick cells demonstrated an efficiency of 11.9%, with an open circuit voltage of 605mV, and a short circuit current density of $26.8\text{mA}/\text{cm}^2$. Figure 6 shows the Current Voltage response of the cell at one sun intensity.

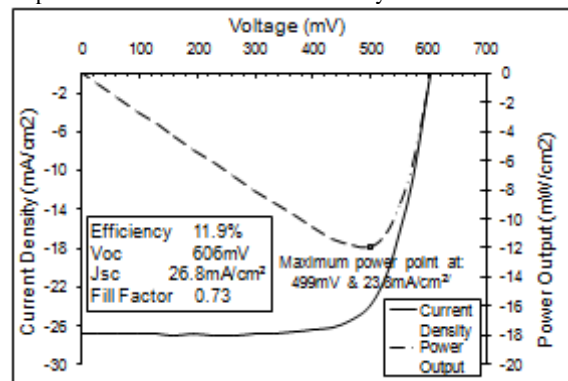


Figure 6: I-V performance of $18\mu\text{m}$ thick Plank Solar Cell at 1 sun intensity.

The examined solar cell does not have surface texturing, and implements a 70nm thick Si_3N_4 anti reflection coating. At the thickness of $18\mu\text{m}$, samples from this batch were able to flex to a diameter of 6mm. All reported measurements are calibrated in-house measurements, calibrated against known silicon reference cells and measured using a constant voltage I-V flash tester [3].

5. SUMMARY

The design, and fabrication technique of Plank Solar Cells have been discussed, and a 2-D simulation have been performed to 18~19% efficiency is achievable without surface texturing. The best performing Plank solar cell fabricated at the Australian National University is 11.9% efficient.

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