SLIVER™ SOLAR CELLS

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Thin (<70 micron) single crystal silicon cell solar cells have been manufactured through the use of a novel process. Narrow grooves are formed through the wafer. Cells are manufactured on the resulting silicon strips. These cells have a much greater surface area than the original wafer, leading to large decreases in processing effort and silicon usage. The size, thickness and bifacial nature of the cells create the opportunity for a wide variety of module architectures and applications.

INTRODUCTION
Crystalline silicon wafers remain the material of choice for photovoltaic modules, accounting for 90% of the photovoltaic (PV) market. However, the cost of the silicon remains a major barrier to reducing the cost of crystalline silicon photovoltaics.

Improvements in silicon usage in conventional ingot based technology have arisen through improved wafer sawing to reduce kerf losses and decrease wafer thickness. These changes are incremental and are limited by processing yield.

Substantial decreases in silicon usage requires a different approach. A variety of techniques for growing or harvesting thin layers of monocrystalline silicon have been developed (Weber 1999, Tayanaka 1998). Each has limitations in material quality or yield due to the silicon manufacturing technique.

A new technique for producing thin monocrystalline silicon solar cells has been developed at the Centre for Sustainable Energy Systems at the Australian National University, in conjunction with Origin Energy. The new technology allows for large decreases in silicon usage by up to a factor of 12 (including kerf losses). In addition, it allows for a large reduction in the numbers of wafers processed per module by up to a factor of 35 compared to standard crystalline silicon technology. These factors allow the use of moderate to high quality silicon and more complicated wafer processing that enables high cell efficiencies while still obtaining significant $/Wp cost savings.

THE SLIVER™ CELL CONCEPT
Solar cell texturing and micromachining technologies have used for many years the excellent selectivity of anisotropic etches for (111) surfaces. The new sliver cell process uses a micromachining technique to form deep narrow grooves in suitably masked wafers oriented such that the (111) plane is perpendicular to the wafer surface. Long narrow slots are opened perpendicular to the (111) plane in a masking layer on the wafer surface. Micromachining of the sliver cells commences at the surface of these narrow slots.

Trenches form vertically into the wafer. The base of the trench forms relatively rapidly compared to the (111) sidewalls. The micromachining continues until the trench extends the entire thickness of the wafer. The result is a large number of thin silicon strips in the centre of the wafer, held together by the unetched surrounds of the wafer (Figure 1). On 1mm thick 150mm wafers, these strips would typically be 100mm long, 1mm wide (wafer thickness) and 50-65 microns thick.

Cells are constructed on the narrow strips of silicon formed during the micromachining. Cell processing is completed while the silicon strips are still supported by the silicon substrate at the edge of the wafer.

The wafers are processed to produce solar cells (figure 2) using methods borrowed from the fabrication of high performance solar cells, such as heavy doping under the contacts, lightly doped emitter with good surface passivation and surface texturing. Heavy phosphorous and boron diffusions are applied to top and bottom surfaces of the wafer. These wafer surfaces become the long narrow edges of the silicon strips and therefore of the cells. The edges are subsequently metallised to form
the p-type and n-type contacts. The sides of the grooves are textured using a novel texturing technique for (111) surfaces that offers near Lambertian light trapping properties. The grooves are then phosphorus diffused and passivated.

![Grooves](image)

**Figure 1: Selectively etched wafer. Long thin silicon slices are supported by the wafer frame.**

After processing, the cells are removed from the wafer frame. The resulting cells are long, narrow and thin. Typical Sliver™ cell dimensions are 50-100mm long, approximately 1-1.5mm wide and 50-65microns thick. Since the cell processing is symmetric, the cells are perfectly bifacial.

The cell structure has the potential for excellent cell efficiencies. The cell is thin and there are collecting junctions on both sides of the cell. The emitter is lightly doped and the surface is well passivated. Therefore the cell has unity collection efficiency, even with low quality silicon.

The cell structure offers the opportunity for high cell voltages. The n and p contacts each cover only ~3% of the cell surface (at the edge) and can be independently doped for optimal passivation of the metal contacts.

The best cells produced to date have an efficiency of 19.5%. Open circuit voltages between 680mV and 690mV are regularly achieved. These cells are textured and have an oxide antireflection (AR) coating. The oxide AR coating limited cell efficiency due to reflection losses. Efficiencies exceeding 20% are expected with SiN AR coating and further technology optimisation.

**SLIVER™ MODULES**

Sliver™ cells differ radically from conventional cells in size and shape, being long, narrow, thin and flexible. Unlike conventional cells, Sliver™ cells have a width that is smaller than the thickness of the module. In addition, the cells are perfectly bifacial. This allows further silicon reductions by a factor of 2 to 3 through the use of a novel module design. A simple design approach is to introduce a Lambertian reflector at the rear of a bi-glass module. The cells are positioned between the two layers of glass, spaced by a multiple of their width (typically from 1.5 to 3) (figure 3).

Some of the light scattered from the rear reflector is directed onto the rear surface of the bifacial Sliver™ cell while a fraction of the light is reflected onto the glass where it is totally internally reflected back into the module. The remainder of the light is lost through the front glass. Conventional cells cannot have significant spacing (compared to the cell dimensions) without compromising greatly on efficiency due to their large size.
For cells spaced at double their width, about 84% of the light entering the module is captured in return for a 50% decrease in the silicon used per square metre. With 3 times spacing 74% of the light in the module is captured for a 67% reduction in silicon. Even better optical performance is possible with geometric designs. However, the cost of machining appropriate shapes and accurately aligning cells currently outweighs the performance benefits compared to the Lambertian reflector.

![Figure 2: Lambertian reflector module design. The small width and bifacial nature of the Sliver\textsuperscript{TM} cell enables the cells to be spaced out (in this case double cell width, halving silicon use).](image)

The small size of each cell means thousands of cells are required per square metre of module. These are assembled into modules at modest cost using high-speed assembling equipment similar to those developed for the microelectronics and opto-electronics industry. This automated cell placement allows great flexibility in cell layout and interconnection.

By connecting cells in series, it is easier to build voltage than in conventional modules where the economies of scale favour large cells. Module output can be tuned from standard 12V applications to several hundred volts for grid-connected applications. Strings of Sliver\textsuperscript{TM} cells with 200-400V output only require lengths of a few tens of centimetres. Series strings can be connected in parallel to increase current. These high voltage modules could allow for direct conversion from DC to AC without the requirement for voltage up-conversion.

![Figure 3: 1000cm\textsuperscript{2} Sliver\textsuperscript{TM} module. The cells are spaced at double their width and the module has a rear Lambertian reflector.](image)

Since the cells are relatively small in area, so are the cell currents. This decreases the reverse current that any cell needs to tolerate during shading events. Cells can be designed which can reversibly breakdown to 100mA or more, alleviating the need for diode protection in the module. Modules containing strings of Sliver\textsuperscript{TM} cells have passed hot spot tests without by-pass diodes.

A 580cm\textsuperscript{2} prototype module was constructed with 500 0.56cm\textsuperscript{2} Sliver\textsuperscript{TM} solar cells. An efficiency of 12.3% was independently measured by Sandia National Laboratories. The cells were connected in four strings and were spaced with a gap between cells equal to their width. The cells were fabricated from 100mm wafers and had a SiN AR coat and no texturing. The voltage output of this module with the strings in parallel was 80V. With the strings connected in series the $V_{oc}$ was 320V.
Texturing offers large gains after encapsulation and should push this efficiency over 14%. An equivalent module with no gaps would have an efficiency of about 17%, but would cost more.

**ADVANTAGES OF SLIVER™ CELLS**

In addition to direct competition with conventional PV modules for power production, Sliver™ technology is well suited to other applications.

The high power-to-weight ratio is of interest for satellites and solar-powered aircraft, as is the bifacial response (to take advantage of the Earth’s albedo). The cells are likely to be radiation tolerant because of their small thickness and the fact that there is a collecting junction on each surface. Building integrated Sliver™ modules take advantage of the fact that any degree of module transparency can be easily achieved by adjusting the Sliver™ spacing. Flexible modules can be created by suitable encapsulation of the Sliver™ cells (which are flexible due to their thinness). The ability to obtain high voltages in very small modules allows Sliver™ cells to be used to power small consumer items.

The combination of the novel cell processing and the module design flexibility provides Sliver™ cells with the potential for large savings in the amount of silicon required and the number of wafers used per MW of module production.

The gain in surface area from etching is determined by the pitch of the etching, the thickness of the wafer and the fraction of the wafer that can be etched to form silicon slices. Not all the wafer can be used due to the need for the edge of the wafer to form a frame to hold the cells. Additional area gains can be made by spacing the Sliver™ cells in the module. There is also a large reduction in the mass of silicon required per m² of module. In Table 1 a comparison is made with conventional pseudosquare Cz wafers with thickness 320µm, kerf 260µm and module efficiency of 13.5% yielding around 13kg/kWp. Per kW rating, there is a reduction in silicon usage of 812 times and a reduction in the number of wafers that need to be processed of 16-35 times.

<table>
<thead>
<tr>
<th>Wafer thick. (mm)</th>
<th>Gap size in module</th>
<th>Silicon savings kg/kW</th>
<th>Processing reduction</th>
<th>Model Effic. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 No gap</td>
<td>4 fold</td>
<td>10 fold</td>
<td>16.8</td>
<td></td>
</tr>
<tr>
<td>1.0 1x cell width</td>
<td>8 fold</td>
<td>16 fold</td>
<td>14.1</td>
<td></td>
</tr>
<tr>
<td>1.5 2x cell width</td>
<td>12 fold</td>
<td>35 fold</td>
<td>12.2</td>
<td></td>
</tr>
</tbody>
</table>

Due to the silicon savings, better quality silicon can be used to maintain higher efficiency or lower quality material can be substituted to save costs. The saving in manufacturing is particular attractive as it allows for relatively expensive processing to be undertaken (e.g. photolithography, tube furnaces, evaporated and plated contacts) which help maintain high performance.

Sliver™ modules operate at slightly lower temperatures and have lower temperature coefficients than conventional modules. Temperature coefficients are reduced to 2.0mV because of the high Voc.

Preliminary estimates show that the energy payback time of a Sliver™ module is only 1.7 years, two thirds of which is due to standard module components (glass, Al frame, encapsulant, etc).

**CONCLUSIONS**

Sliver™ PV technology offers large reductions in silicon consumption and wafer processing, together with other important advantages, while maintaining all of the advantages of single crystalline silicon.

**REFERENCES**