SLIVER® MODULES - A CRYSTALLINE SILICON TECHNOLOGY OF THE FUTURE

A. Blakers, K. Weber, V. Everett, S. Deenapanray, J. Babaei and M. Stocks*
Centre for Sustainable Energy Systems, ANU, Canberra, ACT 0200, Australia
* Now at Origin Energy Solar Pty. Ltd

ABSTRACT: A new technique has been devised for the manufacture of thin (<60µm) highly efficient single crystalline solar cells. Novel methods of encapsulating these Sliver® solar cells have also been devised. Narrow grooves are formed through a 1-2mm thick wafer. Device processing (diffusion, oxidation, deposition) is performed on the wafer, so that each of the narrow strips becomes a solar cell. The strips are then detached from the wafer and laid on their sides, which greatly increases the surface area of solar cell that can be obtained from the wafer. Further gains of a factor of two can be obtained by utilising a simple method of static concentration. Large decreases in processing effort (up to 30-fold) and silicon usage (up to 10-fold) per m^2 of module are possible. The size, thickness and bifacial nature of the cells create the opportunity for a wide variety of module architectures and applications.
Keywords: c-Si, Thin Film, Cost reduction

1 INTRODUCTION

Crystalline silicon wafers remain the material of choice for photovoltaic modules, accounting for 90% of the photovoltaic (PV) market. However, the cost and availability 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 [1,2]. Each has limitations in material quality or yield due to the silicon manufacturing technique.

A new technique for producing thin monocrystalline silicon solar cells was invented [3] and developed [4-6] at the Centre for Sustainable Energy Systems at the Australian National University. The new technology allows for large decreases in silicon usage by up to a factor of 10 (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 30 compared to standard crystalline silicon technology, These factors allow the use of moderate to high quality silicon and more complicated wafer processing that can realise high cell efficiencies while still obtaining significant $/$W_p$ cost savings.

2 THE SLIVER® CELL CONCEPT

Sliver® solar cells are fabricated using 1-2mm thick silicon wafers. The wafers preferably have a high minority carrier lifetime (such as FZ or MCz or Cz:Ga) to take advantage of the high efficiency potential of Sliver® solar cells.

A key step in Sliver® cell processing is to form deep narrow grooves all the way through the wafer (Figure 1). A variety of techniques can be used, including laser scribing, a dicing saw or an anisotropic etching process such as the well-known technique of alkaline etching of (110) wafers. Other methods are also possible.

One etching method is described in detail in the Sliver® patent [3]. 44wt% KOH at 85°C can be used to etch grooves that are initially 10µm openings in an etch mask. The wafers are moved in (5 minutes) and out (5 minutes) of the solution using a mechanical device. This process substantially improves the etch uniformity by dislodging hydrogen bubbles.

Texturing of the sidewalls is possible [3]. Very thin layers of silicon nitride can be deposited, which conformally coats the wafer. The layer is so thin that there are many holes in it. A Si etchant such as 1:50 HF/nitric can be used to etch the Si in these holes, thus covering the surface with shallow etch pits. This acts as a Lambertian scattering surface.

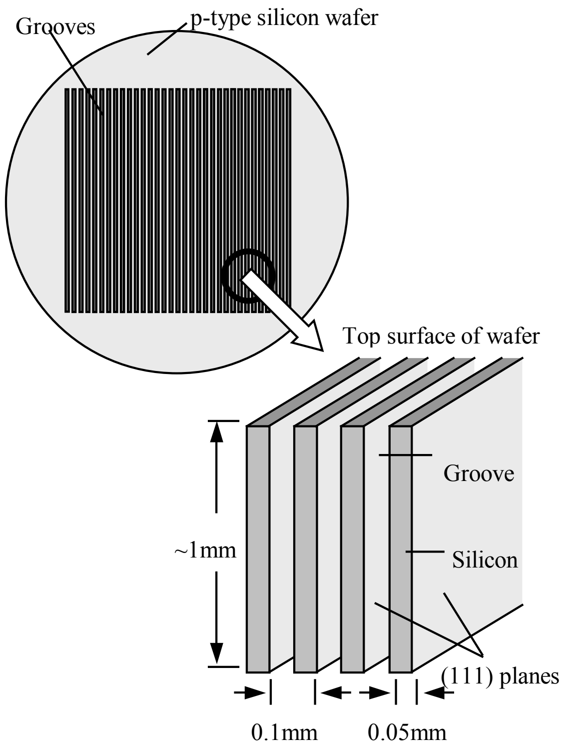

Figure 1: Sliver® wafer. Long thin silicon slices are supported by the wafer frame.

The grooves typically have a pitch of 100µm and a width of 40µm, which allows the Sliver® cells to have a thickness of 60µm. A 1.5mm thick 150mm diameter wafer would have about 1000 Sliver® solar cells with a combined surface area of about 1,500 cm^2, compared with the area of a conventional solar cell fabricated using the wafer of 177cm^2. Careful attention to detail allows the number of imperfections resulting from the grooving to be kept below ten for an entire wafer.

Cells are constructed on the narrow strips of silicon formed during the grooving process. Cell processing (diffusion, oxidation, deposition) 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, a 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 sidewalls of the grooves are textured using a novel texturing technique for (111) surfaces that offers near Lambertian light trapping properties. The grooves are then lightly phosphorus diffused, passivated and coated with an antireflection coating.

After processing, the cells are removed from the wafer frame and laid on their sides (the groove sidewalls) (Figure 2). The resulting cells are long, narrow and thin. Typical Sliver® cell dimensions are 50-100mm long, 1-2mm wide and 40-60μm thick. Since the cell processing is symmetric, the cells are perfectly bifacial.

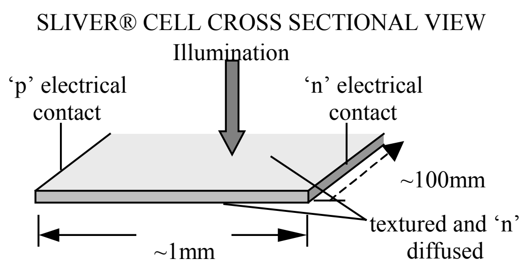

Figure 2: Schematic of the Sliver® cell design.

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 surfaces are 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 two edges) and can be heavily doped for optimal passivation and contact resistance of the metal contacts.

On cells processed on FZ wafers, the highest open circuit voltage measured to date has been 686mV at 25^{o}C, while the highest efficiency has been measured at 19.4% at 25^{o}C, and the highest I_{sc} was 37.1mA/cm^2. These cells were approximately 50μm thick, 1mm wide and 56mm long. This corresponds to a power to weight ratio greater than 1,500 W/kg. These cells had been textured on both sides but did not have an optimal antireflection coating. Further improvements have the potential to push the efficiency above 20%.

3 STATIC CONCENTRATION

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 incorporating a simple static (non-tracking) concentrator. 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 or other suitable material, spaced by a multiple of their width (typically from 1.5 to 3) (Figure 3).

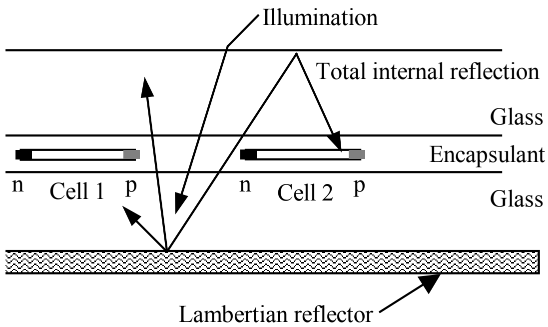

Figure 3: Lambertian reflector module design. The small width and bifacial nature of the Sliver® cell enables the cells to be spaced out (in this case double cell width, halving silicon use).

Some of the light scattered from the rear reflector is directed onto the rear surface of the bifacial Sliver® cell while another 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 use this technique because it relies upon the cell width being similar to the thickness of the rear glass layer.

For cells spaced at double their width, about 79% of the light entering the module is captured relative to a module with 100% cell coverage, in return for using only 50% coverage of silicon [7]. With 3-times spacing 65% of the light in the module is captured in return for using only 33% coverage of 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.

4 SLIVER® MODULES

The small size of each cell means thousands of cells are required per square metre of module. These can be 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. Sliver® strings with 200-400V output only require lengths of a few tens of centimetres. 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.

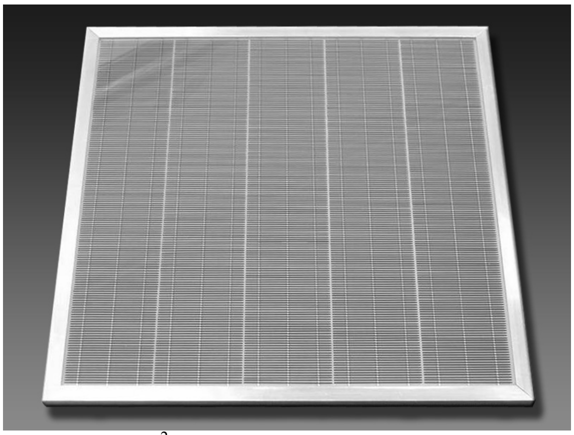

Figure 5: 1000cm^2 Sliver® module. The cells are spaced at double their width and the module has a rear Lambertian reflector.

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. Modules containing strings of Sliver® cells have passed hot spot tests without by-pass diodes.

5 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 perfect 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® cell 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 perfect bifacial response of a Sliver® cell allows for novel applications of Sliver® modules. For example, highway round barriers can utilise Sliver® modules that are mounted vertically facing east-west [8].

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 grooving is determined by the pitch of the grooving, the thickness of the wafer and the fraction of the wafer that can be grooved 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 apart the Sliver® cells in the module. There is also a large reduction in the mass of silicon required per m^2 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/kW$_p$. Per kW rating, there is a reduction in silicon usage of 8-12 times and a reduction in the number of wafers that need to be processed of 16-35 times.

Table I: Silicon mass and manufacturing savings possible with Sliver® modules compared with conventional Cz modules.

Wafer thick. (mm)	Gap size in module	Silicon savings kg/kW	Process reduction Wafer/kW	Model Effic. (%)
1.0	No gap	4 fold	10 fold	16.8
1.0	1x cell width	8 fold	16 fold	14.1
1.5	2x cell width	12 fold	35 fold	12.2

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. Fabrication of Sliver® wafers has more in common with concentrator solar cells than conventional screen-printed cells.

Sliver® modules operate at slightly lower temperatures than comparable conventional modules because of the escape of ~20% of the light. The Sliver® cells are considerably more efficient than conventional cells which further reduces module temperature. Sliver® modules have lower temperature coefficients than conventional modules, partly due to the high cell open circuit voltage [9]. Measurements at Sandia show a low temperature sensitivity of -0.3% per degree.

The energy payback time of a Sliver® module is short because the quantity of energy-intensive silicon is sharply reduced. We estimate that the energy payback time will be only 1.5 years [10], two thirds of which is due to standard module components (glass, Al frame, encapsulant, etc). This compares with about 4 years for a conventional module.

Sliver® cells have important potential applications as concentrator cells in the range 10-80 suns [11]. Reasons for this include the fact that the concentrator cells can come from large production runs, high cell efficiency, cell bifacial response and the high voltage capability.

The capital cost of a Sliver® factory per MW of output capability is substantially less than that of a conventional PV factory because the number of wafer required per kW is reduced 30-fold. On the other hand, Sliver® technology is new and therefore the risk of unforeseen problems is higher.

6. RESULTS

To date all Sliver® test structures, cells, and modules have been fabricated and tested at ANU (or Sandia).

A 1190cm^2 module in which the cell coverage is 50% has been measured by Sandia to have an efficiency of 13% under standard test conditions. A 104cm^2 module in which the cells are close-packed has been measured by Sandia to have an efficiency of 17.7% under standard test conditions. Efficiency can be easily traded for cost reductions by varying the spacing between the cells.

Several test modules have been constructed and a range of accelerated lifetime tests have been conducted (IEEE 1262-1995). These include

* 5.1 Visual inspection procedure,
* 5.2 Electrical performance test,
* 5.4 Electrical isolation test (dry hipot),
* 5.5 Wet insulation resistance test,
* 5.6 Electrical isolation test (wet hipot),
* 5.7 Thermal cycle test,
* 5.8 Humidity freeze cycle test
* 5.13 Damp Heat test,
* 5.14 Hail impact test,
* 5.16 Hot spot endurance test,
* 5.17 Ultraviolet conditioning test, and
* 5.18 Outdoor exposure test.

The modules passed all tests with no visible deterioration. The IEEE 1262-1995 standard requires final performance of not less than 90% baseline electrical performance, the modules' final performance was within the uncertainty of efficiency measurement, which we estimate to be +-3%. The efficiency of some modules, particularly during thermal cycling tests, increased slightly over time. This could be due to improved conductivity of the electrical interconnections.

7 CONCLUSIONS

Sliver® PV technology offers large reductions in silicon consumption (10-fold) and wafer processing (30-fold) while maintaining all of the advantages of single crystalline silicon, including efficiency, reliability, market acceptance and the ability to borrow skills and infrastructure from the conventional IC and PV industries. Sliver® modules can be transparent, flexible, high voltage and perfectly bifacial, and can have a high power-to-weight ratio and a sharply reduced energy payback time. Sliver® concentrator cells have important advantages over conventional 10-50 sun concentrator cells.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge fruitful discussions with people at Origin Energy, and Dr Pierre Verlinden in particular.

Financial support from Origin Energy and the Australian Research Council is gratefully acknowledged.

Thanks are also due to David King and colleagues at Sandia for measurements of Sliver® modules.

REFERENCES

[1] K.J. Weber, A.W. Blakers and K.R. Catchpole, Applied Physics A 69, 195 (1999)

[2] Hiroshi Tayanaka, Kazushi Yamauchi, and Takeshi Matsushita, 2nd World Conference on PV Solar Energy Conversion, Vienna, 1998.

[3] Weber & Blakers, Semiconductor Processing PCT/AU01/01546 (2001)

[4] K.J. Weber, A.W. Blakers, M.J. Stocks, J. H. Babaei, V.A. Everett, A.J Neuendorf, and P.J. Verlinden, "A Novel Low Cost, High Efficiency Micromachined Silicon Solar Cell", Electron Device Letters 25, 37 (2004)

[5] M.J. Stocks, K.J. Weber, A.W. Blakers, J. Babaei, V. Everett, A. Neuendorf, Mark Kerr and P.J. Verlinden, "65-Micron Thin Monocrystalline Silicon Solar Cell Technology allowing 12 Fold Reduction in Si Usage", 3rd World Conference on Photovoltaic Solar Energy Conversion, May 2003, Osaka, Japan

[6] A.W. Blakers, M.J. Stocks, K.J. Weber, V. Everett, J. Babaei, P. Verlinden, M. Kerr, M. Stuckings and P. Mackey, "Sliver Solar Cells", 13th NREL workshop on Crystalline Si Materials and Processing, Vail Colorado, August 2003

[7] K.J. Weber, J. MacDonald, V.A. Everett, P.N.K. Deenapanray, M.J. Stocks and A.W. Blakers, Modelling of Sliver® Modules incorporating a lambertian rear reflector, this conference

[8] P.N.K. Deenapanray, A.W. Blakers, K.J. Weber and V. Everett, The effect of bifacial Sliver® module orientation on energy production, this conference

[9] V. Everett, P.N.K. Deenapanray, K.J. Weber and A.W. Blakers, Characterisation of the temperature response of Sliver® cells and modules, this conference

[10] A.W. Blakers, P.N.K. Deenapanray, K.J. Weber and V. Everett, Embodied Energy of Sliver® Modules, this conference

[11] Evan Franklin and Andrew Blakers, Sliver® Cells for concentrator systems, this conference