SLIVER CELLS – A COMPLETE PHOTOVOLTAIC SOLUTION

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ABSTRACT

Sliver technology was invented and developed at the Australian National University [1-3], with support from the Australian company Origin Energy. The Sliver process uses standard materials and techniques in novel ways to create thin single crystalline solar cells with superior performance and reduced cost. Sliver cells are made from very thin single crystalline silicon, and are highly efficient. Sliver technology offers reductions in silicon consumption by a factor of 10-15 and reductions in wafer throughput per Megawatt by a factor of 20-50. This paper examines the economic potential of Sliver cells. We show that, with careful engineering, a reduction in the cost of PV modules of up to three quarters is possible in the medium term, without the need for any breakthroughs. Sliver technology, with its low cost and multiple attributes, could be a long-term solution for photovoltaics.

SLIVER SOLAR CELL TECHNOLOGY

Standard Si wafers (~1mm thick) are used as the starting material for the Sliver cell process. Low cost micromachining is used to create thousands of narrow grooves that extend through the wafer. The grooves lead to the creation of a series of thin silicon strips ("Slivers"). The grooves do not extend all the way to the wafer edges so that a frame of uncut silicon remains, which holds the Slivers in place.

The wafer is then processed using standard techniques to turn each of the slivers into a solar cell. At the end of the process, the Slivers are cut out of the wafer frame, laid flat, and electrically connected. The rotation of each Sliver through 90 degrees generates a large gain in the active surface area – "area multiplication" – compared with the starting wafer.

Area multiplication is a valuable attribute of Sliver technology, allowing a single wafer containing the equivalent solar cell surface area of around thirty conventional wafers to be processed at not much greater handling cost than a single conventional wafer.

The key to understanding the significance of Sliver technology from the cell processing perspective is to recognise the fundamental difference between conventional cell processing and Sliver cell processing. In the conventional cell process, cells are formed on the wafer surface – essentially a 2-dimensional process. In the Sliver cell process, cells are formed in the wafer volume – essentially a 3-dimensional process, which produces a dramatic increase in the active surface area of solar cells per unit volume of silicon consumed and per wafer that is processed.

Sliver modules can be manufactured using techniques adapted from conventional module manufacture, using only conventional PV materials. Sliver modules can be efficient, low cost, bifacial, transparent, flexible, shadow-tolerant and lightweight.

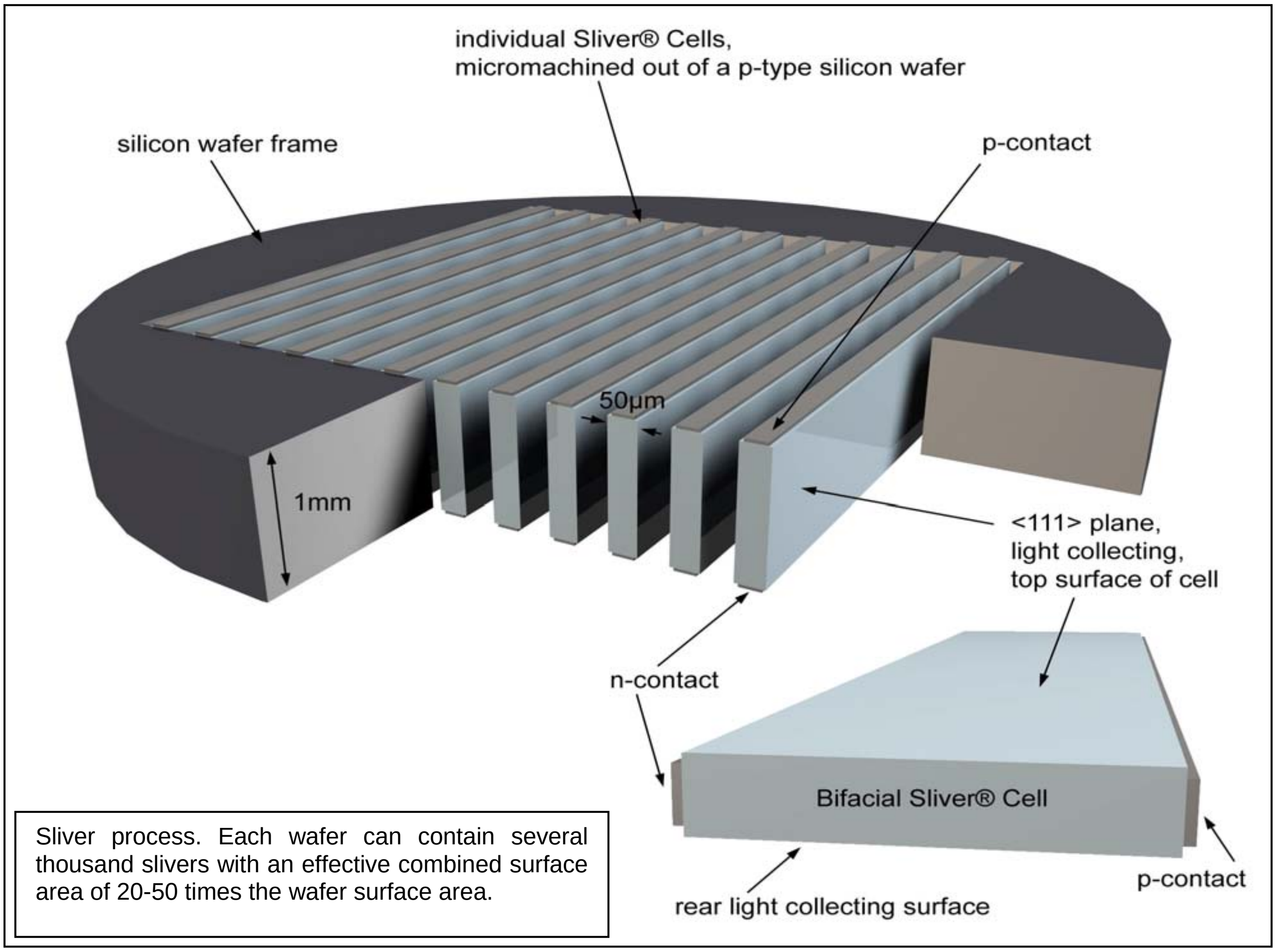
Sliver technology allows for large reductions in the cost of silicon and the cost of cell processing. Applications for Sliver cells span the PV industry, as shown in Table 1.

Application	Salient features
Power modules	Low cost, efficient
Architectural applications	Bifacial, low-cost flexible, efficient, shadow-tolerant, transparent
Small power supplies (eg toys, phones)	Flexible, efficient, high voltage from small area module
Parabolic trough concentrators	Low cost, efficient, shadow-tolerant
Transportable panels	Flexible, efficient, shadow-tolerant
Line-focus microconcentrators	Bifacial, low cost, efficient, shadow-tolerant, the right shape
Aerospace	Bifacial, lightweight, radiation tolerant, shadow-tolerant

Table 1: Applications for Sliver solar cells

THE COST OF SLIVER MODULES

Sliver technology has the potential, over the next few years, to reach very low costs per square metre for the crystalline silicon energy-converting material. This will happen as the technology matures. Costs may become so low that the cost of encapsulation, which is much the same for any PV technology, dominates the finished module cost. In the longer term, Sliver technology has a decisive advantage over competing low cost technologies because it is likely to be substantially more efficient (~20%) in commercial production than alternatives. In addition, there are no issues of toxicity or scarcity of raw materials, and the supply and cost of hyperpure silicon will not be a serious issue.



Sliver process. Each wafer can contain several thousand slivers with an effective combined surface area of 20-50 times the wafer surface area.

We present here a cost model for mature Sliver technology. “Mature” means the technology that we expect to be available within few years of thorough process engineering of existing laboratory-based Sliver technology. It is important to note that Sliver modules are composed of single crystal silicon cells fabricated with standard technology using standard equipment, which will allow rapid scale-up and learning-curve cost reductions.

The kerf loss arises from slicing of a silicon ingot to form wafers. The fractional kerf loss for Sliver wafers is lower than for conventional solar wafers because the Sliver wafer is thicker. In this analysis a kerf loss of 260μm per wafer is assumed, including the removal of saw damage.

Wafer thickness translates to Sliver width following rotation of each Sliver through 90° when it is removed from the wafer. The optimum wafer thickness is in the range 0.5 to 2mm. Smaller thicknesses will require the handling of larger numbers of Sliver cells per module. On the other hand, the minimum groove width will be larger in thicker wafers, which will limit the number of Sliver cells that can be harvested from the wafer. In addition, the resistance loss in the Sliver emitter is proportional to the square of the Sliver cell width, and becomes substantial for widths greater than 2mm. Our analysis suggests that a wafer thickness of around 1mm is optimum, but that module costs depend only weakly on the wafer thickness.

Wafer diameter: Sliver cells are not constrained by series resistance losses relating to wafer diameter. The optimum diameter is mainly a function of the cost of the process equipment and wafer throughput. The optimum diameter may be one generation behind the IC industry in order to take advantage of the low cost of reconditioned second hand equipment. A wafer diameter of 15cm has been used in this analysis, but diameters of 20-30cm may eventually be preferred.

Groove pitch is the centre-to-centre spacing of the slivers during wafer processing. Halving the pitch of the grooves will double the yield of silicon area from a wafer. Not only will this halve silicon consumption (in terms of kg/kW), but also it will halve the number of wafers that need to be processed to produce 1m^2 of PV module. Therefore the groove pitch is a strong cost driver.
One method of creating grooves is the etching of deep grooves in (110) oriented silicon wafers using alkaline etches, as has been practised for many decades [4]. Alternative grooving techniques may also be used. (110) to (111) etch ratios above 500 have been reported using KOH. Such ratios would allow 10μm wide grooves to be etched through a 1mm thick wafer. A groove pitch of as

little as 20μm would be possible, resulting in Sliver thickness of 10μm. In this analysis, a groove pitch of 40μm is assumed, resulting in Sliver thickness of 20μm.

Sliver cell efficiencies are currently in the range 18-20%, depending on cell design. Given that open circuit voltages approaching 700mV have been observed, it is likely that efficiencies around 22% will eventually be obtained. Since few wafers need to be processed per kW of module, a sophisticated and costly process can be afforded, as can expensive float zone wafers. This will ensure high cell efficiency. In this analysis an average cell efficiency of 20% is assumed.

The Module coverage fraction refers to the fraction of the module that is covered with Sliver solar cells. If the solar cells are butted up against each other then the coverage fraction is 100%. This will yield the most efficient module. However, if every second Sliver cells is "left out" (50% coverage fraction), and if a scattering rear reflector is included, then the number of Sliver cells required per module is halved. With this arrangement an additional ~20% of the sunlight will escape from the module compared with a module with 100% coverage fraction [5]. However, for a given annual wafer throughput, the output (MW/year) of the Sliver cell factory will be increased by ~60%. There will also be a reduction in the number of Slivers that need to be encapsulated. Set against this is reduced module efficiency, which increases the cost of the encapsulation materials & process as well as the balance of systems costs.

It is a simple matter to change coverage fraction. A Sliver module factory is likely to have a range of modules ranging from lower cost and lower efficiency (low coverage fraction) to premium modules with 100% Sliver coverage. Transparent modules for architectural applications will have the Slivers spaced apart without a rear reflector.

Our analysis suggests that 100% coverage factor is preferred in the long term. One reason for this is that the cost per cm^2 of each Sliver cell will be quite small, and so the loss of light from the module for lower coverage fractions will outweigh the savings in Sliver cell manufacturing and handling. Another is that the deletion of the rear surface reflector coupled with the perfect bifacial response of Sliver cells allows advantage to be taken of reflected light entering the rear of the modules, causing a significant boost in capacity factor.

Mounting, interconnection and encapsulation of the Sliver cells to form modules will result in efficiency losses, including from series resistance, "dead" slivers, cell mismatch, optical reflection at the air-glass interface and absorption in module materials. In this analysis a combined electrical and optical loss of 10% is assumed upon encapsulation.

Yield of a manufacturing process usually rises as the process matures. The yield of Sliver modules (starting wafer to finished module) is likely to be high for a mature sequence because relatively expensive process technology can be afforded due to the high value of a Sliver wafer. In this analysis, yields of 90% are assumed.

Wafer cost: The cost of a specialist silicon wafer is high when purchased in small quantities. In the longer term, prices can be expected to fall sharply as the production volume increases and long-term purchase agreements with wafer manufacturers are arranged. Because a Sliver wafer is thick, the wafer cost will be higher than for an equivalent thin wafer. However, the cost ratio will be smaller than the ratio of the thicknesses because of the constant value of kerf loss, sawing cost, damage removal cost and wafer handling cost. In this analysis it is assumed that the cost of a Sliver wafer (1mm thick, 15cm diameter) will fall to $10 in the long term.

Wafer processing costs for Sliver wafers are higher than for conventional cells. We estimate that the process length of Sliver wafers will be about 1.5 times longer than the buried contact process [3]. Process steps and equipment are similar, and so the relative process length will translate loosely to relative process cost. In this analysis it is assumed that the process cost per Sliver wafer is $5.

The encapsulation cost: A Sliver module can be constructed using similar materials, techniques and equipment to a conventional module. Good engineering allows for low cost extraction of slivers from the Sliver wafer, and handling and encapsulation of the Sliver cells. We foresee opportunities for cost savings in module assembly compared with current practice for conventional modules, arising from particular features of Sliver cells, such as the location of contacts on the cell edge (eliminating copper tabs from front to rear) and thinness (reducing EVA thickness). This is despite the fact that Sliver cells are each only 1-2 cm^2 in area. We estimate that the encapsulation cost of a mature Sliver module will be around $\$100/m^2$.

Financial parameters: American dollars are used in this analysis. The levellised energy cost calculation assumes an 8% discount rate, 3% inflation rate, 30-year module life, 18% average capacity factor (representative of a reasonably good site with 5% rear surface albedo collection) and the provision of 0.5% per year of the initial capital cost to cover operations and maintenance. A markup of 30% by the manufacturer is assumed. That is, the selling price is 30% above the cost of manufacturing. The balance of systems (BOS) costs are assumed to be $\$100/m^2$ and $0.25/Watt.

SUMMARY AND RESULTS OF THE ANALYSIS

Table 2 summaries the assumptions and results of our study.

PARAMETER	**Mature Sliver**
Wafer cost	$10
Process cost per wafer	$5
Encapsulation cost	$\$100/m^2$
Yield	90%
Grooving Pitch	40μm

Cell efficiency	20%
Wafer thickness	1mm
Module coverage	100%
RESULTS	
Module efficiency	18.0%
Si usage (kg/kW)	0.9
Watts per wafer start	61
Wafer cost	\$0.16/W (21%)
Wafer processing cost	\$0.08/W (10%)
Encapsulation cost	\$0.55/W (69%)
Module cost	\$0.8/W
Electricity price	\$0.09/kWh

Table 2: Summary and results

Module manufacturing costs (before any markup) below US\$0.8/W are within reach. This translates to an electricity price of US\$0.09/kWh, which is below the retail price everywhere, and is in the same range as wind energy and zero-emission coal (with geosequestration of CO_2). It should be noted that commercial considerations mean that reduced cost does not necessarily translate to reduced prices compared with conventional technology.

There are three distinct phases in PV module manufacturing: (i) the production of silicon wafers (ii) the processing of the wafers to form solar cells and (iii) the electrical interconnection and packaging of the solar cells to form PV modules. The ratio of costs for each of the above manufacturing phases using conventional solar cell technology is roughly half, quarter and quarter respectively. Essentially a mature Sliver technology reduces the 50% cost of the silicon wafers and the 25% cost of the wafer processing to small values. This leaves the 25% cost of interconnection and packaging, which is roughly comparable to conventional solar cell technology cost.

Since the silicon wafer cost and the solar cell process cost is reduced to small values, the cost of encapsulation is the major cost of a Sliver module. Sliver encapsulation technology can take advantage of any improvements in conventional encapsulation technology, such as will be required if an alternative thin film PV technology is to reach very low costs. This means that a hypothetical thin film PV technology in which the deposition & processing of the energy converting material is nearly free will still be more expensive than mature Sliver technology unless the thin film matches the ~20% efficiency of Sliver cells.

As cost structures for various technologies converge to the packaging cost, PV choices will ultimately be made on the basis of efficiency alone. The efficiency of mature Sliver cells in commercial production is likely to be around 20%.

Compared with current PV technology, mature generation Sliver technology will need 5-10% of the pure silicon and 2-5% of the wafer starts per MW of factory output. The cost (and associated risk) of a Sliver factory will therefore be much lower than for an equivalent factory running conventional technology.

Heroic assumptions are not required to reach the costs suggested in this paper. What is required is careful silicon processing, micromachining and packaging engineering to transfer laboratory-based Sliver technology into methods and processes for the commercial manufacture of mature Sliver PV modules. This contrasts with the leap of faith required for advanced thin film technologies.

Sliver cells are fabricated on well-understood and accepted single crystal silicon. Sliver modules are manufactured using standard techniques & materials. They can be efficient, low cost, bifacial, transparent, flexible, shadow-tolerant and lightweight. Sliver technology could be a complete long-term solution for PV.

ACKNOWLEDGEMENTS

Support from Origin Energy for the development of Sliver technology at ANU, particularly in the period 1998-2003, is gratefully acknowledged. Origin Energy is now undertaking commercialisation of Sliver technology at its new factory in Adelaide [http://sliver.com.au].

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