

Sliver Cells: The Low Cost PV Electricity Alternative

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ABSTRACT: SLIVER cells are thin, single-crystal silicon solar cells fabricated using standard fabrication technology. SLIVER modules, composed of several thousand individual SLIVER cells, can be efficient, low cost, bifacial, transparent, flexible, shadow-tolerant and lightweight. Compared with current conventional PV technology, mature SLIVER Technology will need less than 10% of the pure silicon, and fewer than 5% of the wafer starts per MW_p of factory output. There are two distinct challenges for SLIVER technology: devising a robust cell fabrication method for high yield, high efficiency SLIVER cells, suitable for transfer to industry; and handling, electrically interconnecting, and encapsulating billions of SLIVER cells at low cost. We have recently fabricated SLIVER cells with efficiencies exceeding 20% using an optimised process. We believe this is the first commercial thin crystalline-type technology to reach 20% efficiency. We believe there is a path to laboratory cell efficiencies of 22% and commercially-produced cell efficiencies of 21%. A 100 MW_p SLIVER factory will produce several billion individual SLIVER cells annually. We have developed a sub-module technology for rapid, reliable, and low-cost assembly of arrays of SLIVER cells to form two main types of conventional solar cell analogues that, because of their appearance, we call "Rafts" and "Sheets". Using our invention, Rafts and Sheets can be reliably produced at high speed using low-cost equipment and entirely conventional materials, and can be assembled into solar power modules using simple adaptations of conventional solar cell handling and stringing equipment.

Keywords: SLIVER, high-efficiency, cost reduction, silicon fabrication, concentrator cells, manufacturing, processing, partial shading.

1. INTRODUCTION

A primary goal of the PV industry is to be cost-competitive with other forms of electricity generation. Cost reductions have largely been achieved via normal growth and maturing of the industry, as demonstrated by the learning curves of Parente *et al* (2002). However, recent rapid growth has caused silicon shortages. One response has been to produce thinner wafers, although ingot sawing technology and wafer handling issues are limitations. Another response has been to focus on methods for reducing the requirements for silicon: such as thin-film technologies under development at Fraunhofer ISE, Reber and Eyer (2005); ISFH, Terheiden (2006); and UNSW, Aberle (2006). Thin-film non-silicon technologies have considerable potential, but are limited by material quality and cell efficiency. SLIVER technology takes the best of both responses: utilising thick crystalline silicon wafers to produce a large area of very thin, high-efficiency, single-crystalline silicon solar cells.

1.1. SLIVER Technology

SLIVER cells, Weber and Blakers (2001); Weber and Blakers (2004); Blakers *et al* (2003); and Weber *et al* (2006), are long, narrow, thin, single-crystalline silicon solar cells, fabricated from wafers in a dramatically different way to conventional wafer-based solar cells. Rather than fabricating one large solar cell on the surface of a wafer, many hundreds of individual SLIVER solar cells are fabricated within a single wafer. A very thin, symmetric, flexible, and perfectly bi-facial SLIVER cell, with typical dimensions shown, is depicted in Figure 1. SLIVER technology aims to simultaneously address three issues to reduce the cost of PV modules: lowering material costs, lowering manufacturing costs, and increasing efficiency. Applying SLIVER technology to wafer processing produces a much larger solar cell area than conventional technology can produce from the same amount of silicon. Consequently, far fewer wafers need to be processed, resulting in a significant reduction in processing cost per unit cell area. SLIVER cells are highly efficient, producing more electrical power for a given cell area compared with conventional solar cells. Compared with conventional PV, mature SLIVER technology will use less than 10% of the silicon and fewer than 5% of the wafers per MW_p, Weber *et al* (2004).

A single 15cm diameter host wafer can contain enough SLIVER cells to populate a module with a rating of up to 100 W_p . For cost reductions to be fully realised, an efficient and robust SLIVER handling and module fabrication method is required to process the several million SLIVER cells produced daily in a commercial-scale manufacturing facility. Everett *et al* (2007) demonstrates that the billions of SLIVER cells produced annually by a 100 MW_p SLIVER cell factory can be extracted, processed, and encapsulated at low cost. Further, this can be performed rapidly and reliably, without vision systems or robotics, using only conventional PV module materials, Everett and Blakers (2004).

Recently, the authors became aware of a paper by Iles and Soclof (1981), which describes a general concept for area multiplication of a silicon wafer, and describes a number of processes for achieving an increase in wafer surface area. However, the processes described in Iles & Soclof (1981), whilst possessing benefits for silicon utilisation, also have a number of significant problems including highly non-uniform groove etching, difficulty in retaining the thin strips of silicon during wafer processing, and an inability to texture, along with difficulty in fabricating solar cells on the thin strips.

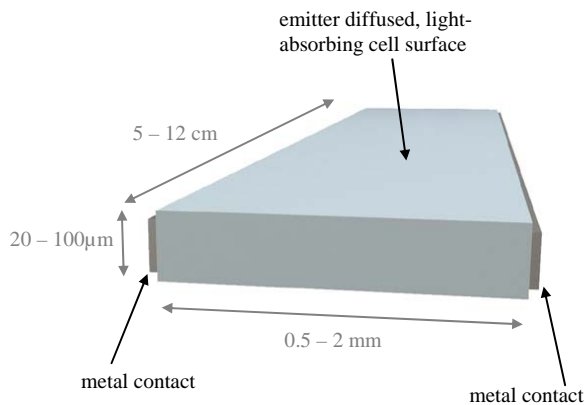


Figure 1: An individual SLIVER cell with typical dimensions shown.

Weber and Blakers (2001) at the Australian National University (ANU), with financial support from the Australian company Origin Energy and the Australian Research Council, independently re-invented the concepts described by Iles and Soclof (1981). Along with others, they have substantially improved upon this earlier work, including solving the above-listed problems; Blakers *et al* (2003), Weber *et al* (2004), and Franklin *et al* (2007). Recent work at The Centre for Sustainable Energy Systems at ANU has resulted in the development of a 2nd generation of SLIVER technology, comprising a high-performance, low-cost SLIVER solar cell

fabrication technology, Franklin *et al* (2007), and handling, separation, assembly, and electrical interconnection processes, Everett and Blakers (2004), and Everett and Blakers (2005).

2. SLIVER CELL FABRICATION

SLIVER solar cells are long, narrow, thin mono-crystalline silicon solar cells, fabricated in a dramatically different way to conventional wafer-based solar cells, yet the substrate formation and cell processing use no procedures unknown in the PV or micro-electronics industry. SLIVER cells are radically different, yet there is nothing new. In fact, the unique, elegant, and innovative combination of using the old to construct the new is perhaps the greatest feature of SLIVER technology.

2.1. SLIVER cell fabrication: an overview

Figure 2 depicts a wafer with, for simplicity, just a few SLIVER cells represented. The essential step in forming SLIVER cells is producing deep narrow grooves right through the wafer. A variety of techniques, including narrow focus laser, narrow blade dicing saw, anisotropic alkaline etching, and high-speed plasma etching can be used. At ANU, we have reliably created grooves less than 50 μm wide through 1mm thick wafers, at a pitch of 100 μm , leaving SLIVER substrates approximately 50 μm thick and 1 mm deep secured at their ends by the intact wafer frame. Individual SLIVER solar cells are constructed on the narrow strips. All cell processing steps are completed while the silicon strips are retained within the wafer frame. All cell processing steps are based on standard silicon solar cell processing technologies. The cell electrical contacts are also formed while the SLIVER cells are retained in the wafer. Following extraction from the wafer, the SLIVER cells are rotated about their long axis so that the sidewall formed by grooving becomes the sun-facing surface of the cell. Since cell processing on both sidewalls is identical, the cell is, by default, perfectly bifacial. Because the SLIVER cell is very thin, and has lightly diffused pn-junctions on both faces, good surface passivation ensures that the internal quantum efficiency is almost unity across the entire spectrum.

In contrast with conventional solar cells, except for rear-contact solar cells, there is no shading of the cell from front surface metallisation since the electrodes, only 1-2 μm thick, are on the edges of the SLIVER cell. The edge occupies only a small fraction of the total surface area, so doping below the

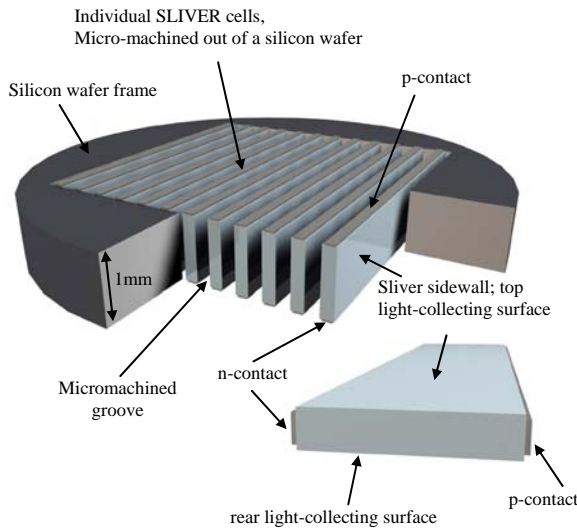


Figure 2: A wafer containing SLIVER cells. The diffused pn junction is located below each of the large, light-collecting surfaces.

metal contacts can be heavy, providing excellent, low-resistivity contacts and minimal recombination. Good short-circuit currents, high open-circuit voltages, and high cell efficiencies are observed as a result. SLIVER cells ideally require texturing. Although standard texturing techniques cannot be applied to anisotropically etched SLIVER cell sidewalls, which have $\langle 111 \rangle$ orientation, texturing and light-trapping can be achieved via an acid etch technique through a very thin deposited silicon nitride layer, Weber and Blakers (2005).

SLIVER technology offers large reductions in wafer processing per W_p , so longer cell processes and good process control can be afforded. However, the original SLIVER cell process contained many more processing steps than industry-standard high efficiency silicon solar cells. To be successful in an industrial context, a SLIVER cell manufacturing process must achieve high cell efficiencies and high process yields reliably at low cost; preferably using standard semiconductor processes and

equipment in order to capitalise on existing knowledge and experience. As part of the 2nd generation of SLIVER technology developed by ANU, cell fabrication has been considerably simplified.

2.2. A robust, optimised processing sequence

A significant challenge for any new technology is ensuring the process conceived in the laboratory can be transferred to the commercial environment with minimal loss in product quality. For SLIVER technology this is particularly important since it differs markedly from the dominant commercial processes. Hence, a successful SLIVER cell manufacturing process must be robust and reliable, with broad process windows. The process should be optimised, as far as practicable, in the laboratory. Reliance on non-standard cell manufacturing techniques and equipment should be minimised. Successful transfer of SLIVER technology to industry hinges on meeting these requirements.

The original SLIVER cell processing sequence was longer by a factor of about 3 than that required to produce conventional high-efficiency one-sun cells, Blakers (2005). Additional costs can be compensated by large gains in efficiency and module area. However, manufacturing costs could be substantially reduced, and reliability increased, by judicious re-design of the manufacturing process. Complex wafer processing is more expensive because it entails a larger fabrication facility, more processing equipment, higher maintenance costs, and larger consumables and waste disposal costs. Furthermore, manufacturing yield depends on the product of the yields associated with each step of a process, so a longer solar cell manufacturing process generally results in a lower net yield. Another disadvantage of a long process is that development and refinement of the process is more difficult: the feedback process is longer and the level of predictability of outcomes is decreased.

One method for measuring the complexity of solar cell fabrication is simply to count the number of steps in the process. A processing step can be defined as a set of operations using a particular piece of equipment, such as a phosphorus diffusion; or which are similar and occur sequentially, such as a wafer-washing sequence. Using such a bench-marking method, the original SLIVER cell processing sequence developed at ANU and transferred to Origin Energy consisted of 59 separate processing steps. For comparison, only 24 steps are required to produce a buried contact cell, Blakers (2005). Research at ANU has focused on developing a robust, optimised processing sequence capable of consistently delivering high efficiency cells, at a high yield. The simplified processing sequence used to produce our 20% efficient SLIVER cells contains only 32 processing steps; a little more than half that of the original processing sequence. It also utilises fewer pieces of equipment.

2.3. SLIVER cell efficiency loss mechanisms

During the development of the optimised cell processing sequence, several issues were identified that required refinements or modifications in order to address specific problems. In particular, two significant SLIVER cell performance problems directly related to subtle intricacies of the cell design and fabrication were identified. The first issue was associated with the resistance of the emitter regions; while the second issue related to heavily cross-doped compensated regions of silicon at the SLIVER cell corners, directly adjacent to the metallised contact terminals.

The emitter resistance losses arise from the fact that collected majority carriers have to travel a distance of up to 1mm in the diffused emitter of a 1mm wide SLIVER cell. For high efficiency cells, the emitter doping should be light enough to ensure excellent surface passivation and high transparency for photo-generated minority carriers, but heavy enough to avoid significant series resistance losses. Due to SLIVER cell design, these emitter losses appear as distributed series resistance losses, Franklin *et al* (2004), reducing fill-factor and cell efficiency. This loss mechanism dominates for wide SLIVER cells, or for SLIVER cells operating under concentration, where the current is proportionally higher. Even at 1-Sun with 1mm wide cells, the series resistance of the emitter can account for 3 or 4 fill-factor points. The losses can be even greater for very light or poorly controlled emitter diffusions. Careful investigation of emitter diffusions has revealed that, owing largely to the topology of the grooved wafer, doping levels of SLIVER sidewalls are considerably lower than normal wafer surfaces. Measured sheet resistance is about double that of the sheet resistance on a planar wafer exposed to the same diffusion. More detailed measurements of sidewall doping profiles, using laser-isolated channels, revealed that the doping is reasonably consistent but marginally heavier at SLIVER cell edges, corresponding to proximity to the normal wafer surface. The final dopant density is a function of the ability of the diffusion reaction products to travel through the narrow grooves.

In addition to the emitter-diffusion series resistance losses a significant recombination loss, characterised by high n-factor recombination on a J_{SC} - V_{OC} curve and a reduced fill-factor on a standard IV curve, has been observed. By investigating a range of cells with varying boron and sidewall phosphorus diffusions the non-ideal recombination has been identified in the heavily compensated silicon regions in the corners where boron and phosphorus diffusions overlap. Careful monitoring and control of both of these diffusions is required to ensure that associated recombination losses are minimised. However, low reverse breakdown voltage arises due to tunneling in this compensated region; providing robust tolerance of partial shading without the need for bypass diodes. Careful selection of the diffusion conditions can minimise the recombination problem, while at the same time retaining the beneficial effects of tunneling, thereby offering further efficiency gains.

2.4. Further improvements to SLIVER cells

Despite major recent improvements to SLIVER cell fabrication, there is still room for further development. The area-related advantage of SLIVER technology is inversely proportional to groove pitch. The approximate area multiplication factor M for the SLIVER process, $M = U * W/P * 1/C$, where U is the proportion of the wafer that is utilised, W is the wafer thickness, P is the groove pitch, and C is the proportion of a SLIVER module covered by SLIVER cells. With mature SLIVER technology the values of these parameters could be 80%, 1500 microns, 40 microns and 50% respectively, yielding an area multiplication factor M of 60. Thus, a 15 cm wafer could contain enough SLIVER cells for a 1m² module, compared with 60 conventional wafers. On-going research in groove formation is aimed at reducing the pitch to maximise the active area of solar cell coverage per wafer. Groove pitch is the single greatest cost driver; halving the pitch doubles the surface area at virtually no process cost.

3. SLIVER CELL PERFORMANCE

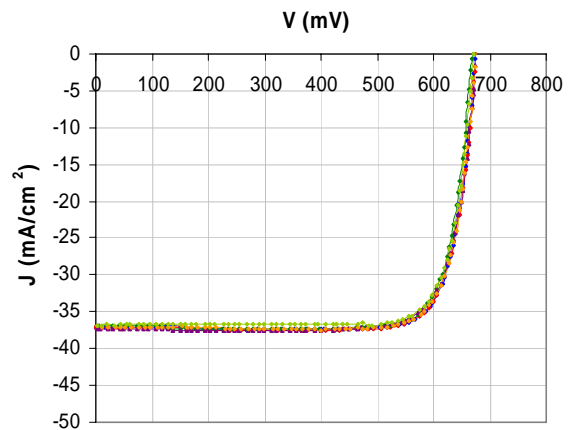
Optimised fabrication sequences have consistently produced cells with high open-circuit voltage and high fill-factor, and equally importantly, in terms of transferability of the technology to industry, a very high yield and excellent consistency between cells. Testing 10 to 20 cells each from numerous wafers revealed cell performances range within a few percent. High yield and performance consistency is crucial to a cheap, high through-put module construction method suitable for industrial environments.

Table 1: Measured data for six SLIVER cells fabricated with the optimised processing sequence.

Median values for tested cells	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF	Eff
@ 1 sun	666	37.0	0.82	20.1%
Std Dev	3.3	0.18	0.008	0.2%

The highest efficiency SLIVER solar cells fabricated at ANU were made from 1mm thick wafers with an anti-reflection coating, no surface texturing, and a post-process rear-surface lambertian coating. The coating does not provide light-trapping, which can be as effective as surface texturing, but it does produce a very good short-circuit current in SLIVER cells.

Data for six cells, with the lambertian coating, are shown in Table 1, and corresponding IV curves in Figure 3. The measurements are calibrated against reference cells under the AM1.5G spectrum.

**Figure 3:** Measured IV curves for six SLIVER cells fabricated using the simplified processing sequence.

4. EARLIER HANDLING AND ASSEMBLY TECHNIQUES

Earlier SLIVER cell handling and assembly was based on a modified pick-and-place technique, Wong *et al* (2004). Individual SLIVER cells were sequentially removed from the wafer, individually electrically tested, and binned using a binary pass/fail classification. The surviving cells were individually assembled in a temporary array, with cell location referenced relative to adjacent cells. The assembled, referenced array was then transferred via a vacuum transfer head on an x-y-z-θ gantry, placed and bonded to a substrate. The substrate defined the size of the finished module array; which was in turn limited by the bounds of the placement gantry. This was essentially a linear process with limited scope for modularity and limited opportunity for process-line intermediate-stage buffering.

The electrical interconnections in the earlier method were established by printing or dispensing pads of electrically conductive material on the substrate. Depending on the material and application process, the conductive material could be placed on the substrate before or after the cell array was bonded in place. The establishment of module electrical interconnections spans inter-cell connections on a large scale: both in number – tens of thousands of connections per square metre, and in scope - very small interconnections spanning the entire module area. As well as the inter-cell connections, bus-bar interconnections between groups of cells are also required. The magnitude of the challenge of establishing electrical connections in a SLIVER module should not be under-estimated. Depending on module design there are typically 40,000 to 60,000 electrical connections per square metre. Not all these connections are critical: a significant fraction provide reliability and robustness through redundant interconnections. However, establishing electrical interconnections this way may require batch processing, large accumulation-storage area, and possibly a large-volume curing oven.

From a manufacturing perspective, a linear assembly approach introduces yield compromise due to tolerance accumulation; limits the choice of substrate material; limits the substrate size due to placement range capability; limits the product design and layout flexibility; restricts the ability to introduce input/output buffers - a factor that can severely compromise throughput expectations; and generally requires frequent manual intervention, increasing cost, reducing yield and throughput. In order to avoid the above difficulties, a simplified modular approach to SLIVER cell separation, handling, assembly, and electrical interconnection has been developed.

5. THE SLIVER SUB-MODULE CONCEPT

The majority of challenging problems, whether they be theoretical or practical, become more tractable upon division into a sequence of logically related modules or tasks. In the case of a manufacturing problem, these tasks should be physically separated and, preferably, procedurally independent. In

devising a 2nd generation cell handling, assembly, and electrical connection process low-cost, easily-automated, reliable and robust, procedurally-independent solutions were developed for performing each of the handling and assembly process stages, commencing with the separation of the SLIVER cells from the wafer, and proceeding right through to the finished SLIVER module.

Rather than handling individual SLIVER cells using expensive, high-speed, automated processes, the 2nd generation technology developed at ANU constructs modular sub-assemblies forming conventional solar cell analogues in a simple, low-speed, low-precision, low cost, but high-throughput process. The sub-module approach implements low-cost separation, handling, and assembly techniques, Everett and Blakers (2004), and rapid electrical interconnection, Everett and Blakers (2005), of groups of SLIVER cells to form a conventional solar cell analogue that, because of its appearance, we call a "Raft". Origin Energy subsequently published a sub-module approach, Kerr and Verlinden (2005). The Raft modular sub-assemblies comprise planar arrays, comparable in size to a conventional solar cell, of SLIVER cells fixed to a supporting medium. A high-efficiency form of the modular sub-assembly structure, referred to as a "Sheet", which may or may not require a supporting medium, constitutes SLIVER cells abutting adjacent cells in the array, providing 100% area cover sub-modules for use in high efficiency SLIVER solar power modules, Everett and Blakers (2004).

5.1. SLIVER cell separation



Figure 4. Transfer of SLIVER cells to a single-stack cassette.

Since SLIVER cells are perfectly bifacial and perfectly symmetrical, it is only possible to determine their orientation by electrical testing. The 2nd generation handling process developed at ANU retains control of the entire array of SLIVER cells contained within a wafer, or sections of an array, using simple and cheap methods. In one method, a block of cells is secured on one or both sides of the SLIVER array. The cells are released from the wafer frame by dicing saw or laser scribing. The released array is then stored in a cassette or other buffer storage device until required, as shown in Figure 4.

5.2. SLIVER cell storage

The bundle of secured SLIVER cells is placed in a cassette where the the cells are released as shown in Figure 5. The cassette, now containing sufficient SLIVER cells for a module with a rating of up to 100W, is stored until required. Alternatively, the array of retained SLIVER cells can be loaded into a multi-stack cassette. The spacing of individual cassette stacks, or stacks within a multi-stack cassette, can be arranged to suit the SLIVER cell spacing in sub-module arrays formed from these devices.

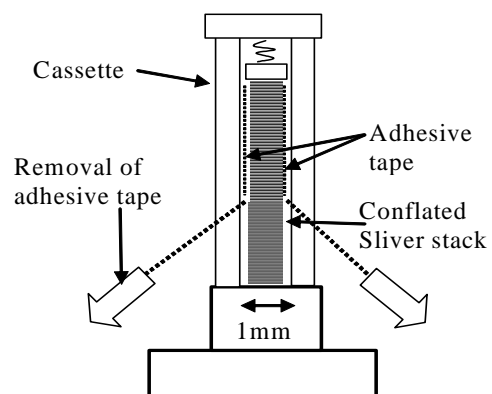


Figure 5. Transfer of SLIVER cells.

5.3. SLIVER sub-module assembly

Raft modular sub-assemblies comprise planar arrays, comparable in size to a conventional solar cell, of SLIVER cells fixed to a supporting medium. The supporting medium can be a collection of long, thin material in the form of ribbons or a tracks, or it may be quite wide, up to slightly larger than the size and shape of the SLIVER cell array. It can be transparent or opaque and, depending on the sub-

assembly application, may be flexible or rigid. A simple method has been developed to extract the SLIVER cells from their host wafer and to subsequently lay them out in a planar array format, either on supporting beams, planar substrates, or even in free-standing contiguous arrays in a bulk handling approach, Everett and Blakers (2004). The cell arrays so formed can be fixed to the supporting medium to form Rafts, or to adjacent SLIVER cells to form Sheets, using adhesive, electrically conductive adhesive, or solder. Similarly to Rafts, Sheet modular sub-assemblies comprise planar arrays of SLIVER cells, comparable in size to a conventional solar cell, but with the additional feature that a separate structural supporting medium is not essential for these contiguous arrays.

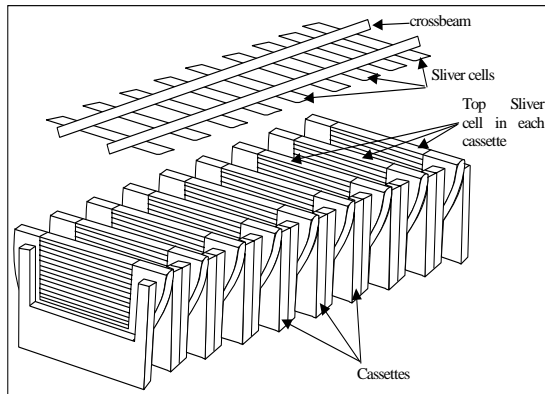


Figure 6. SLIVER Raft formation using an array of spaced, SLIVER cell cassettes.

A pair of pre-metallised crossbeams is adhered to the top (or bottom) SLIVER cell of each cassette and the secured planar array is then withdrawn, with the 50 SLIVER cells arranged and secured in a Raft format. Alternatively, a vacuum device and clamp arrangement can be used, with solder forming the electrical interconnections as well as establishing the physical structure of the Raft, as shown in Figure 7. A low-cost solder process has been devised to electrically interconnect each cell to the intermittent metal track on each crossbeam, and via these tracks to adjacent cells, forming a series-connected string of 50 SLIVER cells in a 100 x 100mm Raft. The process is repeated several thousand times until the SLIVER cells in the cassettes are exhausted, creating Rafts with a rating of several kW_p. Sheets, high-efficiency SLIVER analogues of conventional cells, are modular sub-assemblies of cells abutting adjacent cells, providing SLIVER sub-assemblies with 100% area cover. Rafts and Sheets produce high voltage, up to 60V or more, and correspondingly low current, typically a few tens of milli-amps.

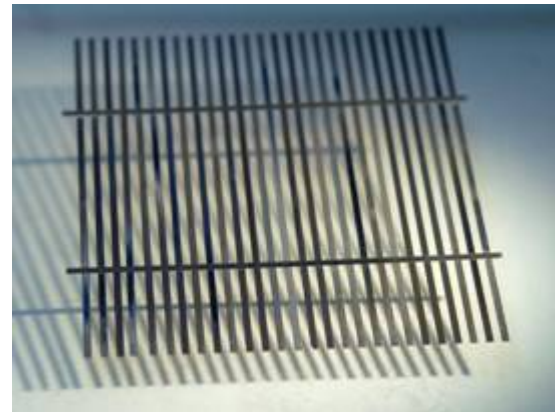


Figure 7. A Raft sub-module: an array of cells interconnected by thin, narrow supports.

5.4. SLIVER sub-module electrical interconnections

Having successfully devised a high-throughput, low-cost, reliable assembly method the remaining task is to rapidly and reliably form a large number of electrical interconnections within the Raft or Sheet sub-assembly. For large-scale manufacturing applications, it is preferable to reduce the number of process steps, as well as the number of iterations, for forming electrical connections. With the constraint that only conventional PV module materials can be used in 2nd generation modules, the second of these two considerations makes dispensing unattractive, whilst the first makes stenciling or dispensing and subsequent solder reflow unattractive.

A selective wave solder process has been developed to rapidly and reliably form low-cost sub-module electrical interconnections. This process is a single-step, in-line, modular approach requiring no materials measuring, no accurate registration of components, and no dispensing, cleaning, or waste disposal. Eliminating handling and materials requirements reduces costs and increases yield. The selective wave solder process uses low-cost, available equipment, with no material wastage. Further,

throughput can easily be increased, up to a factor of eight, with a simple, very low-cost modification. Because the solder quantity and location applied with this method is “automatically” controlled by the process, there is no additional complexity such as registration and control, or machine vision requirements as may be the case, say, where additional dispense heads are attached to a dispense gantry to increase throughput for alternative methods of establishing electrical interconnections.

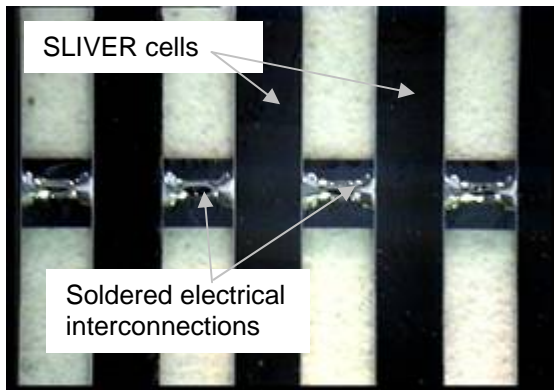


Figure 8. Detail of a selective wave-soldered SLIVER Raft, formed with a multi-stack cassette.

A plan view of a section of a selective wave-soldered Raft is shown in Figure 8. The location of the solder joint is determined by the metallisation on the Raft cross beam. The quantity and distribution of the solder can be controlled using the shape of the metallisation and solder process parameters such as speed, temperature, flux control, and fountain-workpiece separation. Because the Raft thermal mass is small, the solder process can be very rapid. Prototype soldering has been demonstrated at speeds up to 400 mm/sec, establishing reliable electrical. This compares favourably with perhaps 5 to 10 electrical connections per second achieved with expensive, high-speed dispensing. The use of solder to establish electrical connections as well as to maintain the physical sub-assembly structure is an important feature of this process.

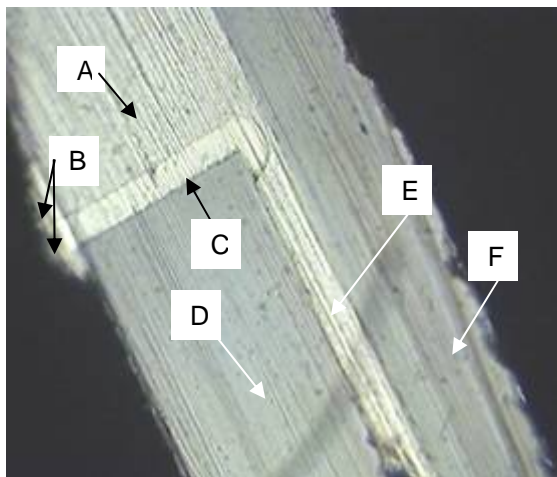


Figure 9. Cross-section detail along a cross beam of a SLIVER Raft sub-module.

Figure 9 shows a cross-section along a selective wave-soldered Raft cross-beam. Label ‘A’ shows the solder joint, with the solder wetting the silver SLIVER electrode, ‘C’, and beading in the region ‘B’ to provide extra strength to the joint. The SLIVER electrode ‘C’ shows no structural damage from the solder process; either by dissolving in the solder, electrode delamination from stress in the solder joint, or warping of the structure. The solder, ‘E’, shows very good wetting of the metallisation, wicking under the SLIVER cell along the metallisation that extends slightly under the cell along the cross-beam ‘F’.

joint is such that it imposes no appreciable shading, or reduction in SLIVER cell coverage to Sheet area surface ratio, thereby substantially maintaining a valuable attribute of SLIVER cells; no electrode shading of the cell surface.

Selective wave solder can be used to establish electrical interconnections in high-efficiency Sheet sub-modules. An image of a selective wave soldered joint is shown in Figure 10. The width of the solder

The Raft and Sheet SLIVER sub-modules described above can be flexible or rigid, semi-transparent or full-cover, high-efficiency, and bifacial or mono-facial. They form the versatile building blocks for a very broad range of PV modules ranging from large-scale solar power modules suitable for solar farms to micro-modules for powering portable electronic devices; from building-integrated PV to remote power supply; and from bifacial PV noise barriers to flexible and rollable portable PV power supplies. The list also extends to concentrator PV applications.

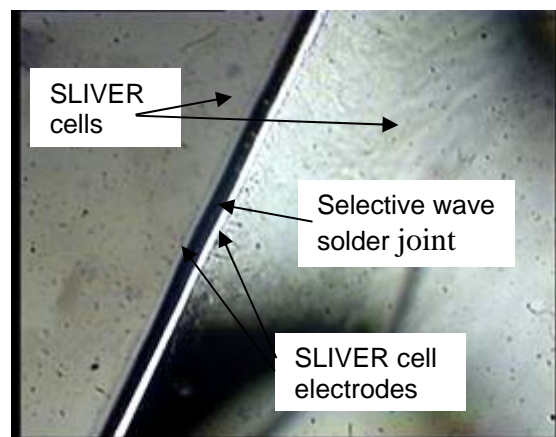


Figure 10. Detail of a selective wave-soldered joint of a SLIVER Sheet sub-module.

6. SLIVER MODULES

Rafts and Sheets eliminate requirements for handling individual SLIVER cells. Sub-modules can be formed in sizes similar to conventional solar cells, typically 10x10 to 12x12 cm², treated as conventional solar cell analogues, allowing techniques similar to those used for conventional cells and modules to be adapted for testing, binning, handling, assembling, electrically connecting and encapsulating SLIVER Raft and Sheet sub-modules.



Figure 11. A SLIVER module constructed using Raft sub-modules.

They can be deployed to form SLIVER modules of any shape, area, current and voltage characteristics, and associated output power. A sample SLIVER module, constructed using Raft sub-modules is shown in Figure 11. A critical advantage of the ANU Raft and Sheet sub-module approaches is that SLIVER cell solar power modules can be manufactured using entirely conventional PV module materials: SLIVER cells, solder, conventional bus-bars, EVA, and glass. Efficiency measurement of large numbers of individual small SLIVER solar cells is inconvenient and expensive but the characteristics of sub-modules can be directly measured, allowing many cells to be efficiently measured in a single operation.

SLIVER Raft and Sheet modules can be constructed to provide high voltage outputs. For example, the module shown in Figure 11 has an output voltage of 45V_{mpp}, with twelve 45V-strings connected in parallel. Alternatively, each string could be connected in series to provide a module output of 540V. Many other intermediate arrangements are readily implemented, for example allowing the voltage up-conversion stage of an inverter to be eliminated. Alternatively, sub-modules connected in parallel can greatly reduce the effect on module output of non-uniformities in illumination, in addition to inherent shadow tolerance of the individual SLIVER cells arising from reverse conduction allowed by the adjacent boron and phosphorus diffusions.

IRaft sub-modules fabricated using thin and flexible SLIVER solar cells and substrate supports can be mounted conformally on curved structures. Optional semi-transparency tcan be “dialled up”, selecting appropriate spacing for the SLIVER cells. It is difficult to achieve such outcomes using conventional solar cells, but the Raft and Sheet sub-module approach lends itself readily to the fabrication of flexible modules, such as the example in Figure 12.



Figure 12. A flexible SLIVER module constructed from flexible Raft sub-

7. CONCLUSION

In this paper, we have demonstrated the broad framework for a complete 2nd generation of SLIVER technology. High-efficiency SLIVER cells can be reliably produced using a simplified, high yield cell fabrication process, which, using the 2nd generation Rafts and Sheets process developed at ANU can:

- Cut the cost of SLIVER technology handling and assembly equipment by an order of magnitude with respect to earlier processes;
- Increase SLIVER cell throughput by an order of magnitude with respect to earlier methods;
- Modularise the process-line, enable easy line balancing, establish buffered line input and output, eliminate critical line-blockage, and eliminate requirements for manual intervention;
- Form electrical connections at least two orders of magnitude faster than prior art methods, using a dramatically simplified low-cost process, at dramatically reduced cost per connection.

In addition to the potential for providing a source of cheap, high-efficiency, low-concentration solar cells, the 2nd generation of SLIVER technology developed at ANU also provides a means for significantly reducing serious performance-compromising difficulties caused by non-uniform

illumination in concentrator systems when using conventional concentrator cells. By using a smart configuration of SLIVER cells the requirement for by-pass diodes, and reductions in receiver performance arising from partial shading of series-connected strings can be avoided. A typical SLIVER concentrator sub-module, formed by a series-connected string of 50-100 SLIVER cells, occupies an area comparable to a conventional concentrator cell yet has a much lower current and much higher voltage output; as high as a conventional concentrator receiver, or even as high as system voltage. With each short, sub-module string of series-connected concentrator SLIVER cells connected in parallel, rather than in series as is generally the requirement for conventional cells in a linear concentrator receiver, the receiver output is no longer limited by the cell receiving the lowest illumination. A sub-module approach incorporating SLIVER cells in linear concentrator receivers introduces many significant advantages.

8. ACKNOWLEDGEMENTS

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