SLIVER® Solar Cells: A High-efficiency, Low-cost, Climate Change Solution.

Corresponding author: Vernie Everett, ph 61 2 6125 8872. vernie.everett@anu.edu.au
Andrew Blakers, ph 61 2 6125 5905. andrew.blakers@anu.edu.au
Klaus Weber, ph 61 2 6125 9734. klaus.weber@anu.edu.au
Evan Franklin, ph 61 2 6125, 4883. evan.franklin@anu.edu.au
Centre for Sustainable Energy Systems, Australian National University
Canberra, 0200, Australia. Fax 61 2 6125 8873

SUMMARY: Sliver® Solar Cells are thin single-crystal silicon solar cells fabricated using standard fabrication technology. Sliver® modules can be efficient, low cost, bifacial, transparent, flexible, shadow-tolerant, and lightweight, requiring only 5 to 10% of the pure silicon and less than 5% of the wafer starts per MW of factory output when compared with conventional PV. We have recently produced 20% efficient Sliver® Solar Cells using a significantly simplified cell process, demonstrating that high Sliver® cell efficiencies can be reached at low cost. This paper provides an overview of the simplified, high-efficiency Sliver® cell process, and the path to further cell improvements. A 100 MW Sliver® factory will produce several billion individual Sliver® cells annually. A key remaining question, "can Sliver® cells can be handled and assembled at low cost?" is answered in this paper with a description of a modularised Sliver® cell sub-assembly, methods of extracting Sliver® cells from the host wafer to form these sub-assemblies, methods of rapidly forming reliable electrical interconnections, and assembling and encapsulating the Sliver cell sub-assemblies into a range of module designs at low cost.

1. INTRODUCTION

Sliver® cells are long, narrow, thin mono-crystalline silicon solar cells capable of high efficiencies. Sliver® cells are fabricated from wafers in a dramatically different way to conventional wafer-based solar cells: rather than fabricating a single solar cell on the surface of a wafer, many hundreds, up to several thousands, of individual Sliver® solar cells are fabricated within a single wafer. Sliver® cell dimensions depend upon wafer size, wafer thickness and sliver formation or patterning method; they typically have a length of 5 – 12cm, a width of 0.5 – 2mm, and a thickness of 20 – 100µm. The very thin Sliver® cells are symmetrical, perfectly bi-facial, and quite fragile.

The technology allows for a tenfold decrease in silicon usage, and a 20- to 40-fold reduction in the number of wafers processed per MW, compared to standard crystalline silicon wafer-based PV technology. Sliver Technology is aimed at simultaneously reducing three of the four main cost areas in the production of solar modules: material costs, manufacturing costs, and module efficiency. Encapsulation costs for Sliver® modules are similar to conventional modules. Applying Sliver Technology to the processing of wafers to form sliver cells produces a significantly larger solar cell area than can be obtained from the same amount of silicon using conventional solar cell processing technology, significantly reducing silicon feedstock consumption. Consequently, far fewer Sliver® wafers need to be processed in order to obtain the same solar cell area as that produced by conventional wafer processing methods, significantly reducing processing cost per unit area of cell produced using the Sliver® process. Lastly, Sliver® cells are highly efficient and therefore capable of producing more electrical power for a given cell area when compared with conventional solar cells.

Insofar as the technology is capable of realising substantial reductions in silicon consumption, Sliver Technology can be compared to thin-film silicon technologies such as those under development at Fraunhofer ISE [1], ISFH [2] and UNSW [3]. However, unlike the majority of thin-film technologies, Sliver Technology has the major advantage of yielding high efficiency solar cells. Yet further reductions in material and manufacturing costs can be achieved by innovative module designs, which are made possible by the unique size, shape, and operating characteristics of Sliver® cells. For example, a module with rear Lambertian reflector and evenly spaced Sliver® cells can capture over 80% of incident light with only 50% of the module area being covered by cells. Compared with standard wafer technology, mature Sliver Technology allows for decreases in silicon usage by a factor of 10 to 20, and a reduction in the number of wafers processed per unit area by a factor of 20 to 40. Such large reductions in silicon usage and wafers processed per MW_p capacity justifies the extra expense associated with the use of moderate- to high-quality silicon and wafer processing methods directed towards optimising high efficiency cells. The result of this approach is that high cell efficiencies can be obtained at a significantly reduced $\$/W_p$ process cost.

An important feature of mature Sliver Technology in respect of the large reduction in silicon usage per MW is that a single 15cm diameter host wafer can contain enough cells to populate a module with a rating of up to 100W. This means that a longer wafer process and good process control can easily be afforded.

The first generation Sliver® cell fabrication process contained many more processing steps than the industry standard for high efficiency silicon solar cells. To be successful in an industrial context, and produce reliable results at low cost, a commercial Sliver® cell manufacturing process must achieve high cell efficiencies and high process yields; preferably using standard semiconductor processes and equipment in order to capitalise on existing knowledge and experience.

Recent Sliver Technology research in cell-processing at the ANU has been directed towards a 2nd Generation process with a greatly simplified processing sequence, capable of producing high efficiency cells at higher manufacturing yield than the 1st Generation process. This research has produced a reliable and robust 2nd Generation fabrication process that contains around half the number of separate processing steps compared to the original Sliver® cell fabrication process. This dramatically simplified process, with fewer complex steps, has the advantage of providing faster turnaround, and uses fewer pieces of expensive equipment and fewer consumables. A shorter, simpler process sequence has the inherent advantage of introducing fewer processing errors and defects, leading to a significantly higher process yield. The fabrication process is described in some detail in this paper, with areas for potential improvements also indicated.

At ANU, we have recently fabricated Sliver® cells with efficiencies exceeding 20% using the optimised processing sequence. Production cell efficiencies of 21% are clearly possible, given the care that can be afforded, even in a production environment, because of the low per-unit-area costs arising from the large effective cell surface area contained in each wafer.

Consideration of optimisation strategies for cell fabrication and module production processes cannot be made independently or in isolation, since the most cost-effective module production methods also rely upon a cell fabrication sequence which delivers high-efficiency cells with high yield and uniform, or low-variance, cell performance spreads. A high yield reduces per unit cost, and a consistent performance in turn avoids the necessity of measuring and binning every cell. Some details of handling and assembly technology will be provided in this paper. In particular, one example solution to the problem using a simplified modular approach will be treated in some depth as a means of understanding the significance of the problem and the importance of a workable solution.

Iles & Soclof [4] describe a general concept for area multiplication of a silicon wafer, and describe a number of processes for achieving an increase in wafer surface area. The processes described by Iles & Soclof, whilst possessing benefits for silicon utilisation, also have a number of significant problems including non-uniform etching of the grooves, difficulty in holding the slivers of silicon in place during wafer processing, inability to texture the hidden (sunward) faces in the grooves, and difficulty in fabricating cells.

Blakers and Weber [5] at The Australian National University (ANU), with financial support from the Australian company Origin Energy, independently invented the concepts described in Iles & Soclof and have significantly improved upon their work, including solving all of the above-listed problems, culminating in the high performance and low cost solar cell technology [6 - 8] summarized in this paper.

2. SLIVER® CELLS AND APPLICATIONS

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 processed.

2.1 Sliver® cells

Figure 1 is a depiction of a wafer with, for the sake of simplicity and ease of discussion, just a few slivers represented. The essential step in forming the sliver substrates is to form deep narrow grooves all the way through the wafer.

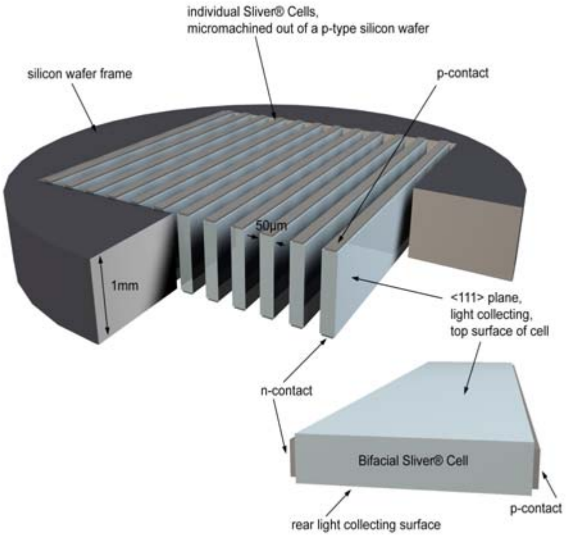

Figure 1. A wafer containing Sliver® cells. The pn junction is located beneath each large, light-collecting surface.

A variety of techniques can be used including, but not limited to, narrow focus laser, narrow blade dicing saw, anisotropic alkaline etching, or high-speed plasma etching. Several of these methods, separately and in combination, have been used at ANU to reliably create multiple narrow (<50μm) grooves through 1mm thick wafers on a pitch of 100μm, leaving sliver substrates approximately 50μm thick and 1 mm wide secured at their ends by the remaining wafer frame.

Individual Sliver® solar cells are constructed on the narrow substrates, or strips, of silicon formed during the grooving process. Most cell processing steps are completed while the silicon strips are still supported by the silicon substrate at the edge of the wafer. All cell processing steps are based on standard silicon solar cell processing technologies. The solar cell electrodes are also formed while the Sliver® cells are retained in the wafer. The surfaces of the wafer, now corresponding to the long narrow edges of the cells, are metallised to form p-type and n-type contacts on either side of the wafer. Following extraction from the wafer, the Sliver® cells are rotated about their long axis. The large face of the Sliver® cell, corresponding to the sidewall formed by grooving, becomes the sun-facing surface of the cell. Since the processing treatment of both sidewalls on a Sliver® cell is identical, the cell is, by default, perfectly bifacial. Because the Sliver® cell is very thin and has pn-junctions on both large faces, corresponding to the sidewalls of each groove, good surface passivation ensures that internal quantum efficiency is essentially unity across the spectrum.

In contrast to all conventional solar cells, with the exception of rear-contact solar cells, there is virtually no shading of the cell due to metallisation since the metal contacts, only 1-2 μm thick, are on the edges of the Sliver® cell rather than the sunward facing surface. The edges of each cell occupy only a small fraction of the total surface of the cells, and doping can be very heavy below the metal contacts. Excellent, low resistivity contacts and minimal recombination are thus easily achieved. Good short-circuit currents, high open-circuit voltages, and high cell efficiencies are observed as a result.

2.2 Sliver® cell applications

The unique shape of Sliver® cells means that they can be used to produce novel module designs. One such design developed at ANU utilises a very simple Lambertian reflector and has cells occupying only a fraction (typically half) of the module surface area [9], as depicted in the diagram of Figure 2. This allows for a further reduction in silicon usage: the number of required Sliver® cells can be halved, while high optical efficiency is retained via the rear surface light-trapping regime.

An alternative module design has a similar arrangement of Sliver® cells but a transparent rear glass sheet rather than a Lambertian reflective surface. This design produces a semi-transparent module, with considerable architectural potential. Another module type utilises thin, flexible plastic sheeting to encapsulate Sliver® cells, thereby creating flexible, rollable, or wearable solar modules. An example of a small flexible module is given in Figure 3.

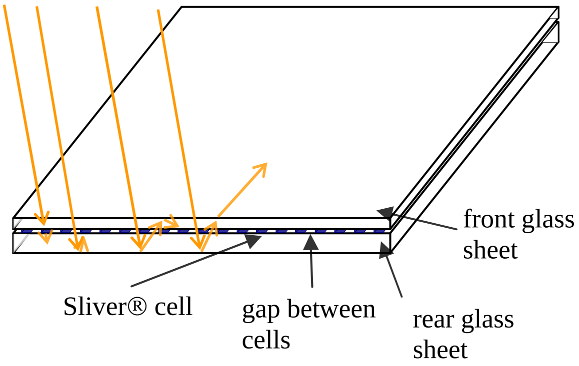

Figure 2. Sliver® cell module with 50% cell coverage, showing possible absorption and reflection fractions.

In addition to module designs for normal terrestrial applications, Sliver® cells can also be used in concentrator PV systems. Modelling has shown that, with appropriate wafers and cell fabrication conditions customised for concentrator applications, Sliver® cells are very well suited for concentration ratios in the range of 5 to 50 Suns [10]. This opens up the possibility of a wide variety of system applications, with the potential for considerable further reduction in cost and silicon usage compared with conventional concentrator cells and applications.

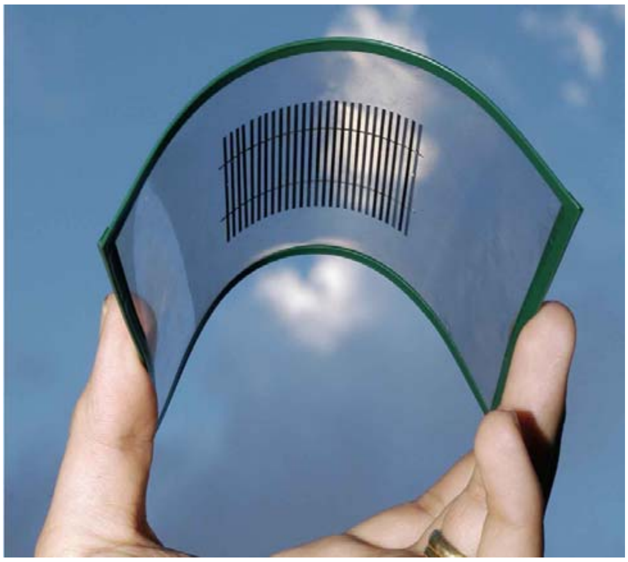

Figure 3. A flexible Sliver® cell module

The current range of concentrator PV systems, both commercially available and presently under development, generally rely on high concentration ratios

(>100), high-precision optics and expensive, very high efficiency multi-junction solar cells [11 – 14]. A source of inexpensive, high-efficiency cells tailored for low- to mid-concentration ratios has the potential to unlock a whole new range of cheaply produced, low-cost, low-precision tracking and optics for concentrator systems.

Further, Sliver® Technology provides a means of significantly reducing serious performance-compromising difficulties associated with non-uniform illumination in concentrator systems when using conventional concentrator cells [15, 16] by using a smart configuration of Sliver® cells. A typical series-connected string of Sliver® cells occupies an area comparable to that of a conventional concentrator cell yet has a much lower current and much higher voltage output. With each string of Sliver® cells connected in parallel, rather than in series as is generally required for conventional cells, the entire system output is no longer limited by the least illuminated region.

3. OPTIMISED SLIVER® CELL FABRICATION

A major challenge for any newly developed product is to ensure the manufacturing process is easily transferable from research labs to a commercial environment without suffering product performance or quality degradation. This is particularly important in the case of a product such as Sliver Technology which already differs markedly from commercially available solar cells. In terms of manufacturability, the Sliver® cell manufacturing process must be robust and reliable, with maximum width process windows, and should be optimised as far as practically possible in the laboratory. The reliance on non-standard solar cell manufacturing techniques and non-standard equipment should be minimised. Successful transfer of the Sliver® technology to an industrial manufacturing environment hinges on meeting these requirements.

3.1 Optimised Sliver® cell processing sequence

The 1st Generation processing sequence developed to produce Sliver® cells was considerably longer, by a factor of about 3, than that required to produce conventional one-sun solar cells [17]. However, the additional costs were more than compensated by the large gains in efficiency and module area that Sliver® technology establishes. But manufacturing costs can still be reduced further, with reliability correspondingly increased, by judicious design of the manufacturing process.

A complex wafer process is more expensive because it entails a larger fabrication facility, more processing equipment, higher maintenance costs, and larger consumables and waste disposal costs. Also, it is generally true that longer processing sequences have a lower expected yield. A further disadvantage of a long process is that development and refinement is more difficult: feedback takes longer, and the level of interaction between process stages increases, exacerbating the problem of lower yields commonly encountered in R&D.

The original Sliver® cell processing sequence consisted of 59 separate processing steps, where a single processing step is defined as a set of operations that take place with the assistance of a particular piece of process equipment (such as a phosphorus diffusion), or which are similar and occur sequentially (such as a wafer-washing step consisting of an RCA1 clean, DI water rinse, RCA2 clean, DI water rinse, HF dip, DI water rinse) [17].

Recent research at ANU has focused on developing a simplified processing sequence capable of delivering higher efficiency cells, with a tight and uniform performance range, and a higher yield. The simplified processing sequence contains fewer processing steps (32 steps) and utilises fewer pieces of equipment.

Although standard texturing techniques cannot be applied to anisotropic-etched sliver sidewalls, excellent texturing [18] and light-trapping can instead be achieved via an acid etch technique through a very thin deposited silicon nitride layer [19].

Alternative simplified methods are presently under development at ANU.

3.2 Reduced Sliver® cell loss mechanisms

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

For the purpose of understanding the loss mechanism for Sliver® cells associated with the resistance of the emitter region, a 1mm wide Sliver® cell fabricated from a 1mm thick wafer may be regarded as equivalent to a conventional cell having a gap of 2mm between adjacent fingers. For high efficiency cells, emitter doping should be light enough to ensure good surface passivation and high transparency for photo-generated minority carriers.

However, for such contact spacing, a lightly-doped emitter can result in significant series resistance losses, which manifest as distributed series resistance [10], reducing fill-factor and cell efficiency accordingly. This is a particular loss mechanism for Sliver® cells greater than 1mm wide, or for Sliver® cells operating under concentrated illumination where the current is proportionally higher. Even at 1-Sun intensity with 1mm wide cells, the series resistance of the emitter regions alone can account for some 3 or 4 fill-factor points or even higher for poorly controlled, or very light, emitter diffusions.

Owing to the unique topology of sliver-patterned wafers, sliver processing can lead to higher than expected emitter losses. Measurements have shown that the level of doping of sliver sidewalls, which are diffused while the Sliver substrates are still held in the wafer frame, is considerably lower than that for normal wafer surfaces. Typically, the sheet resistance on a sliver sidewall is observed to be two to three times higher than on a planar wafer produced with the same diffusion parameters.

The other significant loss mechanism in Sliver® cells fabricated with simplified processes is caused by a region of heavily-compensated silicon, which arises due to the overlap of the phosphorus diffusion on the groove sidewalls with the boron diffusion at the Sliver® cell edge. Without careful control and optimisation, this overlap region can result in cells with reduced fill-factor, characterised by a distinct high n-factor recombination component on a measured J_{SC}-V_{OC} curve.

On the other hand, a low reverse breakdown voltage arises due to tunnelling in this overlap region. This feature provides robust tolerance of partial shading without the need for bypass diodes. Careful selection of the diffusion conditions is required to minimize the recombination problem, while at the same time retaining the beneficial effects of tunnelling, producing efficiency gains with simplified module design and construction.

3.3 Cell performance

Cells with high open-circuit voltage and high fill-factor have been consistently produced in the laboratory using the Sliver® cell fabrication sequence outlined in the previous section. Not only have high efficiency cells been produced but, equally importantly, the processing sequence has been shown to deliver a very high yield, with excellent consistency in the measured performance between Sliver® Cells, as shown in Figure 4.

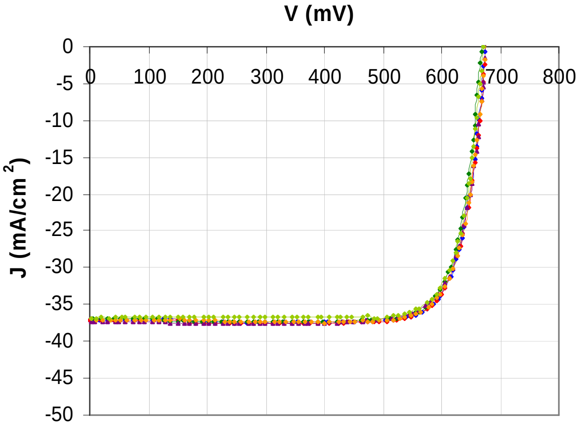

Figure 4. Measured IV curves for six Sliver® cells fabricated using the simplified processing sequence.

While no complete statistical analysis has been conducted, testing between 10 and 20 slivers per wafer reveals cell performance variance within a few percent. The high yield and uniform performance consistency is crucial in realising a cheap, high through-put module construction method that is suited to an industrial environment

We have fabricated Sliver® cells with efficiencies exceeding 20% using the optimised processing sequence. Production cell efficiencies of 21% are clearly possible, given the care that can be afforded even in a production environment because of the large effective cell surface area contained in each wafer.

4. SLIVER® MODULE CONSTRUCTION

The existence of a fast, reliable and inexpensive construction method for producing Sliver® modules is an essential ingredient in the commercial success of a Sliver® cell fabrication facility. Industrial solar module manufacturers have relied heavily upon the manual testing, binning, laying-out, tabbing and interconnecting of cells, although some large manufacturers have now incorporated automated testing and binning into their production facilities. For Sliver® cell module assembly this is simply not an option: the sheer number of Sliver® cells precludes the use of manual handling in any realistic commercial environment, so some degree of automation is required.

A solar power module constructed from Sliver® cells will contain between 5,000 and 10,000 cells per square metre of module area, compared with 70 to 80 conventional solar cells for the same module area. Furthermore, because of the physical properties of the Sliver® cells, conventional cell-handling methods and PV module designs cannot be used. As an indication of the scale of the task of handling Sliver® cells, a 100 MW capacity manufacturing plant would need to process in the order of 150 Sliver® cells per second, 24/7, 360 days per year. It is a significant engineering challenge to devise a method for separating, testing, binning, assembling, and electrically interconnecting this very large number of solar cells in a rapid, reliable, and cost-effective manner.

Early Sliver® cell handling and assembly techniques were based on a modified pick-and-place technique [20]. Individual Sliver® cells were removed from the wafer, tested, and individually assembled in a temporary array. The assembled array was then transferred and bonded to a substrate which defined the size of the finished module array. The electrical interconnections were established by printing or dispensing pads of electrically conductive material on the substrate. Depending on the process and the materials chosen, the conductive material may be placed on the substrate before or after the Sliver® cell array is bonded in place.

A simplified modular approach to Sliver® cell separation, handling, and assembly has been developed.

4.1 The Sliver® sub-module concept

Rather than separating individual Sliver® cells from the wafer using an expensive automated process as described above, modular sub-assemblies, which can be thought of as conventional solar cell analogues, are formed.

The downstream component of the 2nd Generation Sliver Technology developed at ANU relates to methods for separating, handling, assembling, and electrically interconnecting large numbers of Sliver® cells in a low-cost, efficient, robust, and reliable manner. ANU has developed a sub-module approach which offers a means of low-cost assembly of groups of Sliver® cells to form a conventional solar cell analogue that, because of its appearance, is called a Raft, as shown in Figure 5 [21]. Origin have subsequently also published a sub-module approach [22].

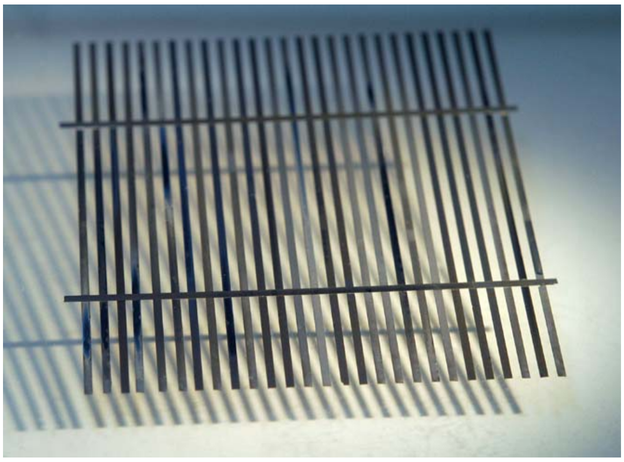

Figure 5. A Raft sub-module, consisting of a group of Sliver® cells interconnected by two thin, narrow substrate supports; it can be handled and encapsulated in the same manner as a conventional solar cell.

The modular sub-assemblies comprise essentially planar arrays of parallel Sliver® cells oriented orthogonal to, and affixed on, a supporting medium. These planar arrays are comparable in size to a conventional solar cell. The supporting medium can be a collection of long, thin material in the form of a ribbon or a track, or it may be quite wide, up to slightly larger than the size and shape of the Sliver® cell array. The supporting medium can be transparent or opaque, and can be selected from a large range of materials depending on the sub-assembly application, and it may be flexible or rigid. A simple method has been developed to extract the slivers from their host wafer and to subsequently lay them out on supporting beams in a bulk handling approach [21]. Sliver® cells can be fixed to the supporting medium using adhesive or solder.

Extraction of the cells from the host wafer can be accomplished at very low cost using a variety of techniques [21]. Rafts can be produced at high speed using low cost equipment and entirely conventional materials, and without vision systems or robots.

The use of materials that are thermally compatible as a sub-module array support medium eliminates problems of differential expansion introduced by the use of dissimilar materials into the structure. A similar result, using a dissimilar material substrate, can be achieved by ensuring a suitably small bond dimension used to fix the dissimilar material substrate supports to the individual Sliver® cells. Providing the supporting medium is very narrow, the structure also allows the bi-facial properties of Sliver® cells to be utilised by placing a scattering reflector on the rear surface of the solar power module to redirect the light which passes through the sub-module arrays back onto the rear surface of the Sliver® solar cells. A high-efficiency form of the modular sub-assembly structure constitutes cells abutting adjacent cells, providing 100% area cover sub-modules for high efficiency solar power modules. In both these implementations, the modular sub-assembly produces a high voltage – up to 60V, and a correspondingly low current – as low as 1/100th that of a comparable conventional cell, with a total power output better than a conventional cell because of the higher efficiency of Sliver® cells.

With both contiguous and spaced implementations of Sliver® cell modular sub-assemblies solder may form the electrical interconnections as well as, in certain implementations, also providing the mechanical structural support for the sub-assembly [23]. The solder can be deposited by a wide variety of methods.

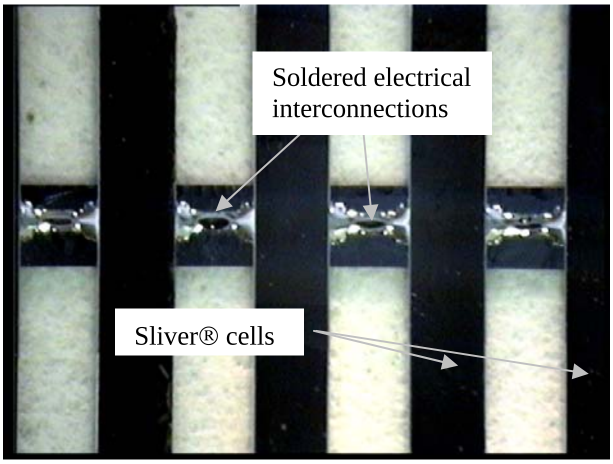

Figure 6. Detailed view of a soldered Raft formed using a multi-stack cassette.

A sub-module approach offers a means of low-cost assembly of groups of Sliver® cells to form a conventional solar cell analogue. Figure 6 shows a sub-module made from many Sliver® cells, both physically and electrically connected using two long, thin, and narrow substrates.

Sub-modules can then be used in place of conventional solar cells to produce a PV module of any desired size, shape, current and voltage, and power.

Successful implementation of the sub-module concept requires a highly reliable Sliver® cell fabrication process. Since cells are connected in series strings, via substrate supports or direct electrical interconnection for contiguous Sliver® cell sub-module arrangements, they must be matched closely in terms of operating current, as a single flawed cell can reduce the output of the entire modular subassembly. Therefore to achieve a high yield of manufactured sub-modules, the Sliver® cell fabrication process must be able to reliably deliver a very high yield of working Sliver® cells as described above.

4.2 Sliver® modules

The Raft sub-module approach avoids the placing of Sliver® cells one by one into a solar power module. Modular subassemblies can be formed in sizes similar to conventional solar cells, typically 12x12 cm^2. Each sub-module can be incorporated as a cell analogue in a photovoltaic module, allowing the use of techniques similar to those used for conventional solar cells and modules for testing, binning, handling, assembly, electrical connection and encapsulation of Sliver® solar cells. The appropriate number of sub-modules can be deployed to form a photovoltaic module with any desired shape, area, current and voltage characteristics, and associated output power. An example of a Sliver® module constructed using Raft sub-modules is shown in Figure 7. The highest recorded efficiency for a 103.5 cm^2 Sliver® cell module is 17.7%.

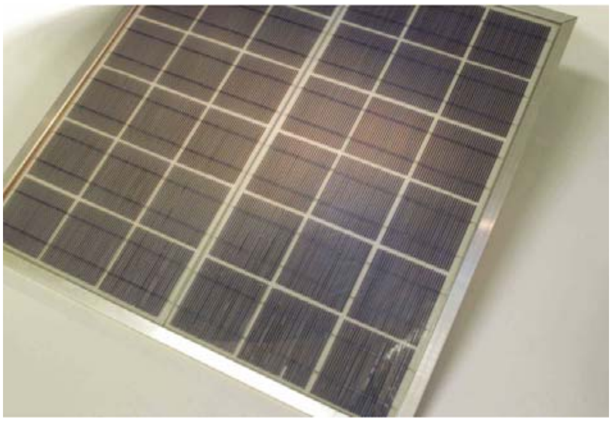

Figure 7. A Sliver® module constructed using Raft submodules.

A very important advantage of the Raft sub-module approach is that solar power modules constructed using Sliver® sub-modules can be manufactured using entirely conventional PV module materials - the Sliver® cells, solder and conventional bus-bars, EVA and glass. The measurement of the efficiency of a large number of individual small Sliver® solar cells is both inconvenient and expensive. However, the characteristics of sub-modules can be directly measured, thus effectively allowing dozens to hundreds of small solar cells to be measured together in a single operation and binned according to performance.

Sub-modules will have a large voltage and a correspondingly small current, if the constituent Sliver® cells are connected in series. For example, a 12x12 cm^2 sub-module composed of sixty 1mm wide, series-connected Sliver® cells with a gap between each cell of 1mm will have a Voc and Jsc of about 40 volts and 70mA respectively after encapsulation (and including a Lambertian rear reflector for the module). This compares very favourably with typical figures of 0.63V and 5A respectively for a conventional cell of the same area.

Sliver® modules have advantages over conventional modules with respect to the elevated temperatures typically experienced during real operation. Since Sliver® cells are high open circuit voltage devices they have smaller temperature coefficients. Further, a combination of module design, particularly with Lambertian rear reflector arrangements, and high efficiency Sliver® cells results in a Sliver® module operating at lower temperatures compared to a conventional module under identical conditions. Hence at operating temperatures well above standard test conditions, Sliver® module efficiency will degrade significantly less than an equivalent conventional solar module [24].

The Raft sub-modules can be connected primarily in series to further build voltage, allowing the voltage up-conversion stage of an inverter associated with the photovoltaic system to be eliminated. Alternatively, the sub-modules can be primarily connected in parallel.

Figure 8. A flexible Sliver® module constructed from flexible Raft sub-modules.

This parallel connection ability can greatly reduce the effect on module output of non-uniformities in illumination, arising for example from shadows cast by dirt on the module surface or from neighbouring buildings. For example, the Raft module shown in Figure 7 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 arrangements are also easily implemented.

Advantage can be taken of the flexibility of Raft sub-modules fabricated using thin and flexible Sliver® solar cells and substrate supports to mount the sub-modules conformally onto a curved supporting structure. The sub-modules can optionally be made semi-transparent by spacing the Sliver® cells apart. It is difficult to achieve such outcomes using conventional solar cells. The sub-module approach lends itself readily to the fabrication of flexible modules, such as the example in Figure 8.

5. CONCLUSIONS

Novel Sliver® cell and unique module design opportunities offer the potential for a 10 to 20 fold reduction in silicon consumption with from 20 to 40 times fewer wafer starts per MW than for conventional wafer-based technologies. Successful commercial implementation of Sliver Technology relies upon a robust and high-yield Sliver® cell processing sequence and a low-cost, high-throughput method for module construction. These two components go hand-in-hand: the fundamental Sliver® properties necessitate the existence of an efficient handling method, while a cost-effective sub-module assembly process demands high yield and consistency in finished Sliver® cells.

Research at ANU has provided an optimised Sliver® cell fabrication process to produce high efficiency cells using a simplified processing sequence that promotes high consistency and a very high yield.

Efficient module production via the sub-module method, using low-cost equipment and standard PV materials only, to reliably and rapidly produce Sliver® sub-module units which can then be easily handled in a similar manner to conventional solar cells completes the technology development pathway.

An optimised Sliver® cell processing sequence capable of producing 20%+ cells, when coupled with a robust, low-cost Sliver® module construction method, can be expected to significantly reduce the costs of commercial PV modules.

Much skilled engineering work is still required to translate the exceptional promise of Sliver Technology into commercial reality. However, we believe that the essential building blocks are now in place and that the technology can, if handled appropriately, be successfully transferred to industry.

Sliver® cell, Raft sub-assembly, and Sliver® module technologies combined have the potential to provide low-cost solar generated electricity for *any* application. The potential for climate change amelioration, democratisation of energy generation, centralised and distributed applications, and development of novel devices is unsurpassed by any other PV technology

6. ACKNOWLEDGMENTS

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