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Research Article

Sliver Solar Cells: High-Efficiency, Low-Cost PV Technology

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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 PV technology, mature Sliver technology will need 10% of the pure silicon and fewer than 5% of the wafer starts per MW of factory output. This paper deals with two distinct challenges related to Sliver cell and Sliver module production: providing a mature and robust Sliver cell fabrication method which produces a high yield of highly efficient Sliver cells, and which is suitable for transfer to industry; and, handling, electrically interconnecting, and encapsulating billions of sliver cells at low cost. Sliver cells with efficiencies of 20% have been fabricated at ANU using a reliable, optimised processing sequence, while low-cost encapsulation methods have been demonstrated using a submodule technique.

1. INTRODUCTION

Sliver technology was invented [1] and developed [2–4] at the Centre for Sustainable Energy Systems at the Australian National University (ANU), supported by the Australian company Origin Energy. Sliver cells are long, narrow, thin monocrystalline silicon solar cells capable of efficiencies exceeding 20%. 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 of individual Sliver solar cells are fabricated within a single wafer. Cell dimensions depend upon wafer size, wafer thickness, and sliver formation or patterning method; they typically have a length of 5–12 cm, a width of 0.5–2 mm, and a thickness of 20–100 μm. The very thin Sliver cells are symmetrical, perfectly bifacial, and quite fragile.

The technology allows for a 10- to 20-fold decrease in silicon usage, and a 20- to 40-fold reduction in the numbers of wafers processed per MW, compared to standard crystalline silicon technology. Sliver technology aims to simultaneously address three out of four issues in cost reduction of solar modules: material costs, manufacturing costs, and 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. Consequently, far fewer Sliver wafers need to be processed in order to obtain the same solar cell area as that produced by conventional processing, resulting in a significant reduction in processing cost per unit area of cell produced using the Sliver process. For this cost reduction to be fully realised, an efficient and robust sliver handling and module fabrication method are also required. 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 [5], ISFH [6], and UNSW [7]. However, Sliver technology also has the major advantage of yielding high-efficiency solar cells. Further reductions in material and manufacturing costs can be achieved by clever module designs, made possible by the unique size, shape, and operating characteristics of Sliver cells: a module with rear Lambertian reflector and evenly spaced-out Sliver cells can, for example, capture over 80% of incident light with only 50% of the area being covered by cells. Compared with standard wafer technology, Sliver technology allows for decreases in silicon usage by a factor of 10–20, and a reduction in the number of wafers processed per unit area by a factor of 20–40. Such a large reduction in silicon usage and wafers processed per MW_p capacity justifies the use of moderate- to high-quality silicon, and wafer processing 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 Sliver technology in respect of the large reduction in silicon usage per MW is that a single 15-cm diameter host wafer can contain enough cells to populate a module with a rating of up to 100 W. This means that a longer wafer process and good process control can be afforded. However, the original Sliver cell fabrication process still contained many more processing steps than the industry standard for high-efficiency silicon solar cells. To be successful in an industrial context, a Sliver cell manufacturing process must be able to achieve both high cell efficiencies and high process yields; preferably using standard semiconductor processes and equipment in order to capitalise on existing knowledge and experience, achieving reliable results at low cost.

Recent Sliver cell research at the ANU has been directed towards delivering a greatly simplified processing sequence, capable of producing cells with better performance and at higher manufacturing yield than the originally developed process. This has resulted in a reliable and robust fabrication process that contains around half the number of separate processing steps compared to the original Sliver cell fabrication process. This process, with fewer steps, has the advantage of providing faster turnaround, and uses fewer pieces of equipment and fewer consumables. A shorter, simpler processing sequence has the inherent advantage of introducing fewer processing errors and defects, and hence 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 optimising 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 uniform yield in turn avoids the necessity of measuring and binning every cell. Details of handling and assembly technology are too complex and extensive to include in this paper; full details will be provided in a subsequent paper. However, a brief overview is included in this paper, describing one solution to the problem using a simplified modular approach.

2. SLIVER CELLS AND THEIR APPLICATIONS

The key to understanding the significance of Sliver technology from the cell processing perspective is to recognise

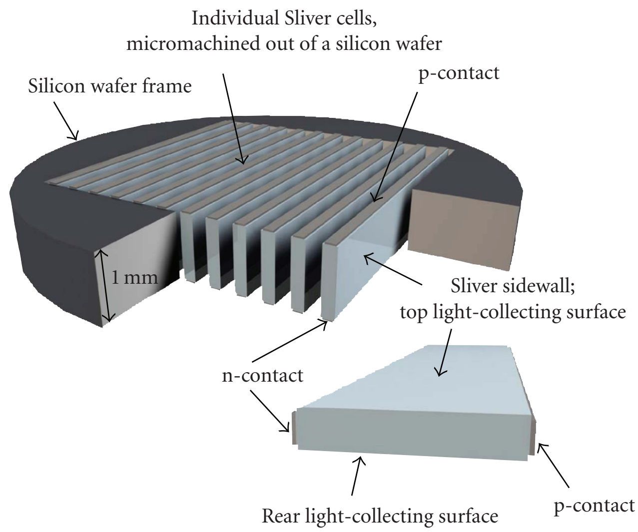

FIGURE 1: A wafer containing Sliver cells. The pn-junction is located below each of the large, light-collecting surfaces.

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.

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 slivers is to form deep narrow grooves all the way through the wafer. 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, and combinations thereof, have been used at ANU to reliably create multiple narrow ($<50\,\mu$m) grooves through 1 mm thick wafers on a pitch of $100\,\mu$m, leaving sliver substrates approximately $50\,\mu$m thick and 1 mm wide, secured at their ends by the remaining wafer frame.

Individual Sliver solar cells are constructed on the narrow strips of silicon formed during the grooving process. All 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

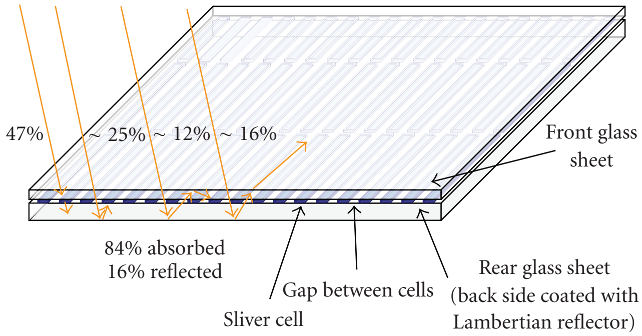

Figure 2: Depiction of a Sliver cell module with 50% cell coverage, showing absorption and reflection fractions for possible light paths.

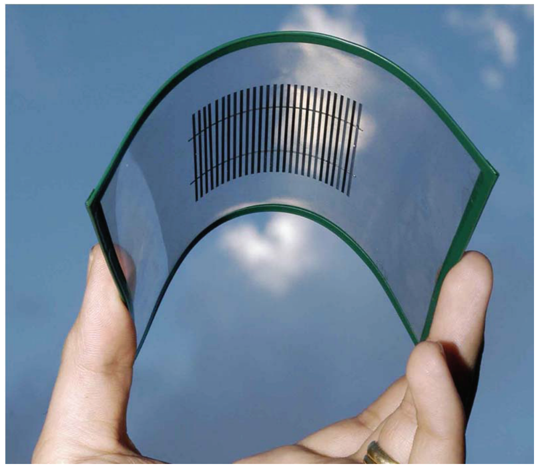

Figure 3: A flexible Sliver cell module.

of both sidewalls on a Sliver 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 below the metal contacts can be made to be very heavy. 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 [8], as depicted in the diagram of Figure 2. This allows for a further reduction in silicon usage: the number of required slivers 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 semitransparent 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. The structure and fabrication of such a submodule will be the subject of a subsequent paper.

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 [9]. 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. The current range of concentrator PV systems, both commercially available and presently under development, generally relies on high concentration ratios (>100), high-precision optics, and expensive, very high efficiency multijunction solar cells [10–13]. 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.

An additional, very important feature of Sliver technology is that some of the oft-cited, and serious performance-compromising difficulties associated with nonuniform illumination in concentrator systems using conventional concentrator cells [14, 15] can be shown to be ameliorated 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 much lower current and much higher voltage outputs. 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

One of the major challenges for any newly developed product is to ensure that the manufacturing process is easily transferable from research labs to a commercial environment without introducing significant product performance or quality degradation. This can be argued to be particularly important in the case of a product such as Sliver technology. Sliver cells already differ markedly from the dominant type of commercially available solar cell. Hence, in terms of manufacturability, the Sliver cell manufacturing process needs to be robust and reliable, with maximum width process windows, and should be optimised as far as practically possible in the laboratory. Also, the reliance on nonstandard solar

Table 1: An optimised processing sequence overview.

Step number	Step description
1	Wafer etch and clean
2	Heavy phosphorus diffusion and in-situ oxide growth
3	Selective removal of diffusion from one wafer surface
4	Heavy boron diffusion
5	Groove mask formation
6	Initiate grooves
7	Groove formation
8	Sidewall texture
9	Sidewall emitter phosphorus diffusion
10	ARC growth/deposition
11	Remove dielectric from both wafer surfaces
12	Metallise wafer surfaces (which become the Sliver cell edges)

cell manufacturing techniques and nonstandard 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 processing sequence originally developed to produce Sliver cells was considerably longer (by a factor of about 3) than that required to produce conventional one-sun cells [16]. As discussed previously, the additional associated costs are more than compensated for by the large gains in efficiency and module area that Sliver technology establishes. However, manufacturing costs can still be appreciably reduced, with reliability correspondingly increased, by judicious 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. Also, it is generally true that the longer the processing sequence, the lower the expected yield will be. A further disadvantage of a long process compared with a short process is that development and refinement of the process are more difficult: feedback takes longer and the level of interaction between process stages increases, with the result that the problem of lower yields commonly encountered in R&D is exacerbated.

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) [16].

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: in particular, the expensive pieces of equipment. A summary of an optimised, robust processing sequence is given in Table 1. In this instance, in the interests of saving space, only the key processing steps are shown. The steps that are omitted from the table include several wafer-washings steps (conducted at least prior to any high-temperature furnace step) and several HF deglaze and HF dip steps. Although standard texturing techniques cannot be applied to anisotropically etched sliver sidewalls, excellent texturing and light-trapping can instead be achieved via an acid etch technique through a very thin deposited silicon nitride layer [17].

3.2. Reduced Sliver cell loss mechanisms

During the development of the optimised processing sequence outlined above, 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 heavily cross-doped compensated region of silicon at the sliver corners, located directly adjacent to the metallised contact terminals.

A significant loss mechanism for Sliver cells is associated with the resistance of the emitter region. In this respect, for the purpose of understanding the origin of the loss mechanism, a 1 mm wide Sliver cell which has been fabricated from a 1 mm thick wafer may be regarded to be equivalent to a conventional cell having a gap of 2 mm between adjacent fingers. For high-efficiency cells, the emitter should be light enough to ensure good surface passivation and high transparency for photo-generated minority carriers. However, for such a spacing between contacts, a lightly doped emitter can result in significant series resistance losses. These series resistance losses manifest as a distributed series resistance [9],

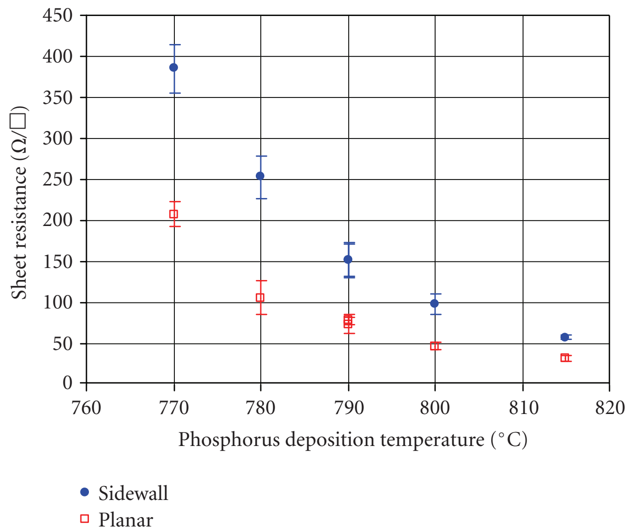

FIGURE 4: Sliver sidewall and planar sheet resistance measurements for a range of deposition temperatures.

reducing fill-factor and cell efficiency accordingly. This is a particular loss mechanism for wide Sliver cells (>1 mm), or for Sliver cells operating under concentrated illumination where the current is proportionally higher. Even at 1-sun intensity and for 1 mm wide cells, the series resistance of the emitter regions alone can account for some 3 or 4 fill-factor points, or higher for poorly controlled or very light emitter diffusions.

Owing to the unique topology of sliver-patterned wafers, sliver processing can lead to higher emitter losses than expected. Measurements have shown that the level of doping of sliver sidewalls, which are diffused while 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 from the same diffusion parameters. An example of sliver sidewall and planar sheet resistance measurements for five consecutive phosphorus diffusions, covering a range of deposition temperatures, is given in Figure 4. The phosphorus diffusions were carried out in a tube furnace under the following conditions

(i) A liquid dopant source ($POCl_3$) was employed, having N_2 bubbled through it at a rate of 133 cc/minue; oxygen reactant was added to the furnace at a rate of 45 cc/min.

(ii) Main carrier gas flow of 250 L/h N_2 was present throughout.

(iii) Reactant gases were introduced to the furnace for 20 minutes only at a fixed and stable deposition temperature, after which they were turned off and wafers remained at the deposition temperature for further 10 minutes before being cooled down for 10 minutes to the unload temperature.

(iv) Wafers were removed from the furnace and deglazed prior to a 30- to 90-minute 1100°C drive-in in an atmosphere of N_2.

(v) Planar wafer sheet resistances were measured using a four-point probe.

(vi) Sliver sidewall sheet resistances were also measured using a four-point probe, albeit with new, accurately calibrated geometry factors. It can be seen that to achieve an ideal lossless emitter, with final sheet resistance of around 100 Ω/□, heavier doping (as low as 40–50 Ω/□) is required. More detailed measurements of sidewall doping profile, achieved by creating laser-isolated channels, revealed that the doping is reasonably consistent across the sliver sidewall, but marginally heavier at sliver edges (corresponding to being closer to the normal wafer surface). This is due to the fact that the final dopant density is partially limited by the ability of the diffusion reaction product to travel through the narrow gaps between slivers and deposit uniformly on sidewalls.

Improved control of the emitter diffusion on the Sliver cell sidewall is a current area of research activity and is vital for ensuring that high-efficiency cells can be reliably produced.

Another significant loss mechanism observed in Sliver cells fabricated with simplified processes is attributed to a region of heavily compensated silicon which arises due to the overlap of the phosphorus diffusion on the groove sidewalls with the Sliver cell edge boron diffusion. Without careful optimisation, this overlap region can result in a cell having 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, which 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, thereby offering further efficiency gains.

3.3. Cell performance

Cells with high open-circuit voltage and high fill factor have been consistently produced 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, and excellent consistency between Sliver cells in their measured performance. While no complete statistical analysis has been conducted, testing between 10 and 20 slivers per wafer reveals that all cells behave within a few percent of each other. The high yield and performance consistency are crucial in realising a cheap, high throughput module construction method that is suited to an industrial environment.

The highest-efficiency Sliver solar cells that have so far been fabricated at ANU were made from 1 mm thick wafers, and incorporated an LPCVD SiN ($n \approx 2.1$) antireflection coating. The cells were fabricated without surface texturing, but included the application of a postprocess rear surface Lambertian reflection coating. A highly reflective, white Lambertian coating is easily applied to one sidewall surface of the Sliver cells once they have been removed from the

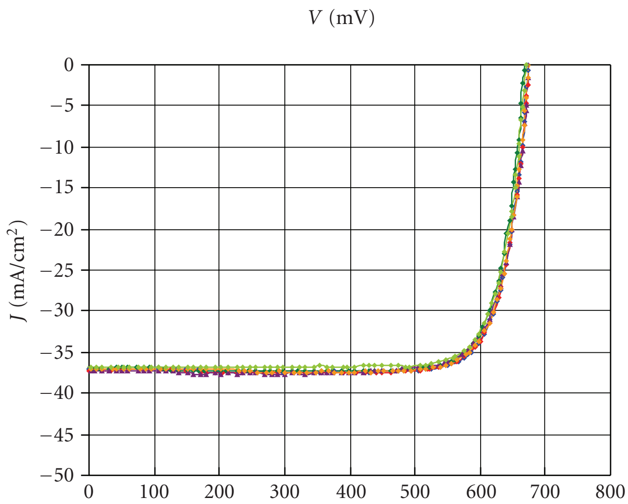

FIGURE 5: Measured IV curves for several Sliver cells fabricated using the simplified processing sequence.

TABLE 2: Measured data for six Sliver cells fabricated using the simplified 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%

wafer. While not quite as effective, in terms of light-trapping characteristics, as excellent surface texturing, the Lambertian coating does produce a very good short-circuit current in Sliver cells. Median and standard deviation data for six cells produced using the optimised processing sequence are presented in Table 2, while the corresponding IV curves are plotted in Figure 5. Only calibrated in-house cell measurements are reported.

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 or otherwise of a Sliver cell fabrication facility. Most industrial solar module manufactures rely heavily upon the manual testing, binning, laying-out, tabbing, and interconnecting of cells, though some large manufacturers have now incorporated automated testing and binning into their production facilities. For Sliver cells, this is simply not an option: the sheer number and size of Sliver cells preclude the use of manual handling in any realistic commercial environment. A degree of automation is therefore required.

A solar power module constructed from such 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.

Sliver cell handling and assembly could be based on a modified pick-and-place technique. In this monolithic approach, individual Sliver cells could be removed from the wafer, tested, and individually assembled in a temporary array. The assembled array could then be transferred and bonded to a substrate which defines the size of the finished module array. The electrical interconnections could then be 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.

From a manufacturing perspective, it is well known that serial monolithic assembly of large numbers of small components introduces disadvantages such as limited speed, yield compromise due to tolerance accumulation, substrate size limited to placement range capability; limited product design and layout flexibility, inability to introduce input/output buffers to any of the process stages in the entire monolithic process, a factor that compromises throughput expectation, and frequent manual intervention. This significantly increases cost and reduces yield and throughput.

A simplified modular approach to Sliver cell separation, handling, and assembly has been developed that avoids the problems of monolithic assembly.

4.1. Sliver submodule concept

Rather than separating individual Sliver cells from the wafer using an expensive automated process such as described above, modular subassemblies, which can be thought of as conventional solar cell analogues, are formed. The modular subassemblies comprise arrays of parallel Sliver cells-oriented orthogonal to, and affixed on, a supporting medium and 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 the supporting medium may also be quite wide, even 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 subassembly application, and 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. Sliver cells can be fixed to the supporting medium using adhesive or solder.

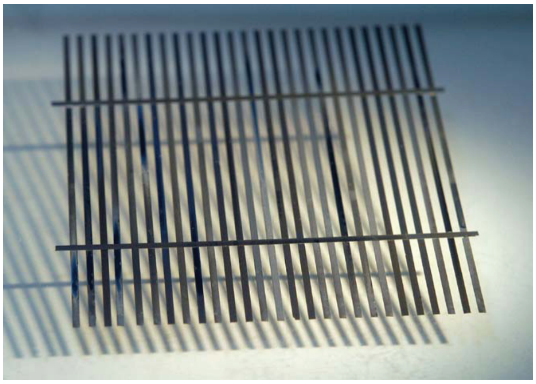

Figure 6: A submodule consisting of a group of Sliver cells interconnected by two thin, narrow substrate supports; it can be handled and encapsulated in the same manner as a conventional solar cell.

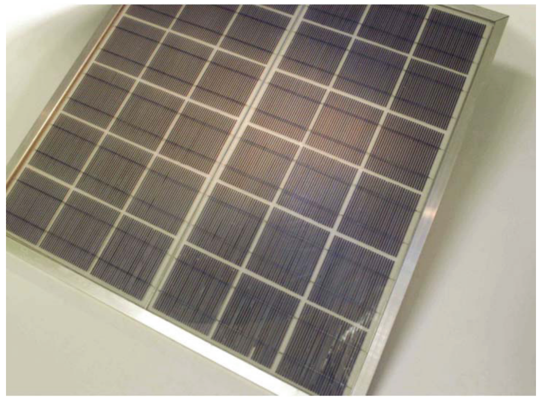

Figure 7: A Sliver module constructed from submodules.

Problems of differential expansion introduced by the use of dissimilar materials into the structure can be controlled by using materials with similar thermal expansion coefficients, and by virtue of the small dimension of the bonded area which adheres the dissimilar material substrate supports to the individual Sliver cells. If the supporting medium is very narrow, the structure also allows the bifacial 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 passing through the submodule arrays back onto the rear surface of the Sliver solar cells. A high-efficiency form of the modular subassembly structure constitutes cells abutting adjacent cells, providing 100% area cover submodules for high-efficiency solar power modules. In both these implementations, the modular subassembly produces a high voltage—up to 60 V, and a correspondingly low current—as low as 1/100th of 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 subassemblies, solder ideally forms the electrical interconnections as well as, in certain implementations, also providing the mechanical structural support for the subassembly. The solder can be deposited by a wide variety of methods, some of which have the potential to be very rapid because of the low thermal mass of the submodules. A solder approach would eliminate stencilling, dispensing, printing, component alignment requirements, and equipment cleaning, as well as totally eliminating the requirement for any adhesives. Crucially, the solder process provides a cheap, fast, well-understood, and reliable process that eliminates the use of nonconventional materials in Sliver cell solar power modules, which is a critical factor when considering product warranties of 25–30 years.

A submodule approach offers a means of low-cost assembly of groups of Sliver cells to form a conventional solar cell analogue. Figure 6 shows a submodule made from many Sliver cells, both physically and electrically connected using two long, thin, and narrow substrates. Submodules 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 submodule 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 submodule arrangements, they must be matched closely in terms of operating current, and a single flawed cell can reduce the output of the entire modular subassembly. Therefore to achieve a high yield of manufactured submodules, 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 submodule 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 $12 \times 12\,\text{cm}^2$. Each submodule can be incorporated as a cell analogue in a photovoltaic module, allowing the use of similar techniques for testing, binning, handling, assembly, electrical connection and encapsulation, and to those currently used for conventional solar cells. The appropriate number of submodules 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 based on submodules is shown in Figure 7. The highest recorded efficiency for a $103.5\,\text{cm}^2$ Sliver cell module is 17.7%.

A very important advantage of the submodule approach is that solar power modules constructed using Sliver submodules 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 submodules 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.

Submodules will have a large voltage and a correspondingly small current if the constituent Sliver cells are connected in series. For example, a $12 \times 12\ \text{cm}^2$ submodule composed of sixty 1 mm wide, series-connected Sliver cells with a gap between each cell of 1 mm will have a Voc and Jsc of about 40 V and 70 mA, respectively, after encapsulation (and including a Lambertian rear reflector for the module). This compares favourably with typical figures of 0.63 V and 5 A, 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. Hence at operating temperatures well above standard test conditions, Sliver module efficiency will degrade significantly less than an equivalent conventional solar module.

The submodules 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 submodules can be primarily connected in parallel. This parallel connection ability can greatly reduce the effect on module output of nonuniformities in illumination, arising for example from shadows cast by dirt on the module surface or from neighbouring buildings.

Advantage can be taken of the flexibility of submodules fabricated using thin and flexible Sliver solar cells and substrate supports to mount the submodules conformally onto a curved supporting structure. The submodules can optionally be made semitransparent by spacing the Sliver cells apart. It is difficult to achieve such outcomes using conventional solar cells. The submodule approach lends itself readily to the fabrication of flexible modules.

5. CONCLUSIONS

Sliver cell and Sliver module technologies have the potential to provide low-cost solar-generated electricity. The novel Sliver cell and module design offers the potential for a 10–20 times reduction in silicon consumption for the same sized solar module, while also having the added benefit, in an industrial production environment, of requiring 20–40 times fewer wafer starts per MW than for conventional wafer-based technologies. However, successful commercial implementation of the Sliver technology hinges upon there being both a robust and high-yield Sliver cell processing sequence and a low-cost, high-throughput method for constructing modules from many thousands of wafer-bound Sliver cells. These two components go hand in hand: the fundamental Sliver properties necessitate the existence of an efficient handling method, while a cost-effective submodule assembly process demands high yield and consistency in finished sliver cells. Research at ANU has proven that it is possible to optimise the Sliver cell fabrication process so that high-efficiency cells can be produced using a simplified processing sequence that promotes high consistency and a very high yield. Simultaneously, efficient module production via the submodule method can be used, using low-cost equipment and standard PV materials only, to reliably and rapidly produce Sliver submodule units which can then be easily handled in a similar manner to conventional solar cells.

An optimised Sliver cell processing sequence that is 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.

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