UPDATE ON THE MANUFACTURING OF SLIVER CELLS AND MODULES

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ABSTRACT: The SLIVER cell and module technology is an innovative concept for silicon solar cell and PV module manufacturing, recently invented by researchers at the Australian National University (ANU) under funding from Origin Energy. This new PV technology has been transferred from a university laboratory (ANU) to a new pilot manufacturing facility. The first SLIVER cells and modules from pre-production have demonstrated excellent results in terms of performance and reliability, as well as great tolerance to partial shadowing and lower operating temperature.
Keywords: c-Si, Si-Films, Cost reduction

1 SLIVER CELL AND MODULE TECHNOLOGY

The new SLIVER technology was recently invented by researchers at the Australian National University (ANU) [1,2] as an answer to one the most urgent challenges that the PV industry is facing at the present time, namely the rising cost of polysilicon feedstock [3]. Despite a large increase in the volume of manufacturing of PV modules and the great economy of scale that it generated during the last few years, we have to recognize that the cost of solar PV module manufacturing has not decreased as much as expected [5]. The cost of the crystalline silicon PV modules, which represents more than 90% of the global PV production, is still largely dominated by material cost, particularly the cost of the mono- or multicrystalline silicon wafers. The major challenge for the crystalline silicon PV technologies is that the increase in the price of the silicon feedstock, due to a larger use of virgin polysilicon instead of recycled rejects from the electronic industry, is compensating the small reduction in silicon usage and the small increase in efficiency and manufacturing productivity.

The innovative SLIVER technology is based on an “out-of-the-box” idea to fabricate 50-micron thin mono-crystalline silicon solar cells without significant kerf loss penalty [1-4]. Using a proprietary micro-machining technology, the SLIVER solar cells are fabricated by creating narrow grooves (about 40 microns in width and 90 microns in pitch) that extend all the way through the thickness of 1 to 2 mm thick monocrystalline silicon wafers (Fig. 1). The doping of the P-N junctions, the surface passivation, the texturization, the deposition of the AR coating and the formation of metal contact are accomplished while the 50-micron thick SLIVER cells are still in a wafer form. On a 2-mm thick 6” wafer with 176 cm^2 of original surface area, more than 2,700 cm^2 of SLIVER cell area can be created. That is a gain factor of more than 15 in silicon area. Using the fact that the cells are narrow and bifacial and using the innovative SLIVER module design presented earlier [1-4], the same 6” wafer can cover up to 5,400 cm^2 of PV module area (Fig. 2). That is a gain factor of more than 30 in module area compared to conventional crystalline silicon PV modules. In other words, the wafer productivity could be up to 75 Watt/wafer with the SLIVER technology compared to 2.5 or 3 Watt/wafer with conventional PV technologies. The bottom line is that, even considering all the silicon material loss in the micro-machining process, the wafering kerf loss, head and tail loss in the ingot formation, the SLIVER technology is still capable of about 1.6 metric ton/MW in silicon usage, compared to 13 to 15 ton/MW for conventional crystalline silicon PV technologies, a 90% savings in material usage.

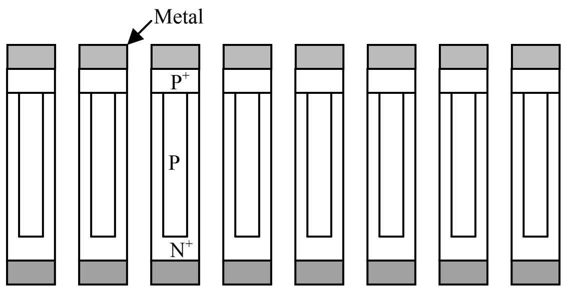

Figure 1: Cross section of a 1 to 2 mm thick silicon wafer that holds thousands of 50-micron SLIVER cells separated by 40-micron wide micro-machined grooves.

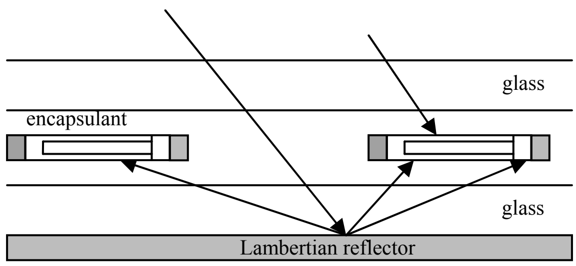

Figure 2: One of the innovative PV module designs using bifacial and narrow SLIVER cells. Here with a 50% solar cell coverage fraction, the SLIVER module optical efficiency is still better than 79%.

2 NEW PILOT MANUFACTURING FACILITY

Despite the fact that the SLIVER technology is very new, Origin Energy, the second largest energy retailer in Australia, recognized the high potential of this revolutionary technology and undertook the design and construction of a new US$15M pilot facility for the manufacturing of SLIVER cells and modules. The new facility has an initial capacity of about 7 MW/year, which can easily be increased to 25 MW/year by addition of tools. The construction began in August

2003 and the facility commissioning was finished in July 2004.

This is the first time that the SLIVER technology has been transferred from a university laboratory to an industrial manufacturing environment. The philosophy behind the design of the facility was to mitigate the risk of the investment by keeping the cost of construction and tools as low as possible, while keeping higher facility specifications than required. Many of the requirements to ensure a high manufacturing yield and low cost were unknown. A clean room design was selected for the wafer fab with class varying from ISO5 to ISO9 (Fig. 3). The SLIVER® fabrication process was improved in many ways to adapt to standard semiconductor manufacturing equipment. The wafer size was increased from 100 mm to 150 mm, and the length of the SLIVER cells was increased from 56 mm to 80 mm. The pre-production of 80 x 1 mm SLIVER cells started in December 2004. At this stage, it seems that there are no major obstacles to increasing the wafer size to 200 mm and the SLIVER cell length to 120 mm in the future.

The assembly of the SLIVER cell into modules required a custom design robot machine to pick-up SLIVER cells from finished wafers, to test them and to lay them in series connected banks of cells. The rest of the assembly process is similar to a standard PV lamination process (Fig. 4). Over the last 6 months, SLIVER modules of different sizes from 15W to 70W have been fabricated for performance and reliability testing. The beginning of commercial production of SLIVER modules is scheduled for the second half of 2005.

Figure 3: Clean room of the new pilot manufacturing of SLIVER cells.

Figure 4: Module assembly room

3 CELL AND MODULE PERFORMANCES

Despite the fact that the SLIVER® was transferred from university labs to the new pilot manufacturing facility just a few months ago and, that many process steps were modified and adapted for the new equipment, including the incorporation of Reverse Bias Protection (RBP) [8,10], the performance of the SLIVER cells and modules is very satisfactory and exceeds expectations.

3.1 Cell performances

The SLIVER cells are very thin (50 microns) and bifacial, with a collecting p-n junction on both sides of the cell and with metal contacts on the edges of the cell (Fig. 5). Because of the edge metallisation, the shading loss due to metal coverage is negligible. The light trapping in just 50 microns of thickness is excellent due to the cell texturization, which increases the effective optical thickness to more than 200 microns. The wraparound PN junction allows for very high collection efficiency of the photogenerated carriers, even with very low bulk lifetime [10]. SLIVER cells made at ANU from 4” wafers had efficiencies in excess of 19% and SLIVER modules with 13% (with 50% solar cell coverage ratio) and 17.7% (with 100% cell coverage ratio) efficiencies were measured at Sandia National Labs [3,4,8]. The 0.77 cm^2 SLIVER cells fabricated in the new pilot manufacturing facility from 6” wafer have similar results: Voc=675 mV, Isc=28 mA, FF=78%, η=19.1% (not independently confirmed) [11].

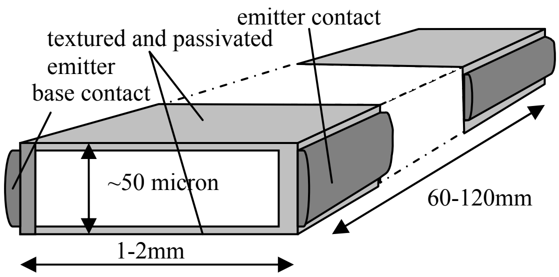

Figure 5: SLIVER cell schematic

3.2 Module performances

Only six months ago, assembly of SLIVER modules commenced using the new custom design automated pick-and-place equipment. Small size modules (15W) were built first. The module size was progressively increased as confidence in the automatic assembly process built up (fig. 6). Module performances are summarized in Table 1. All SLIVER modules were built with 50% coverage of cells. The modules were designed to supply about 23 V in open-circuit condition, which required banks of 35 series-connected cells. Higher efficiencies would be obtained if the module voltage and the number of cells per bank were increased, in order to reduce busbar losses.

Table 1
Performance of pre-production SLIVER modules

Size (m^2)	Textured cells	Isc (A)	Voc (V)	Pmp (W)	FF (%)	η (%)
0.123	Yes	0.83	23.8	14.9	75.1	12.1
0.332	No	2.13	22.3	35.3	74.2	10.6
0.701	No	4.06	23.6	70.6	73.8	10.1

Figure 6: 15W, 40W and 70W SLIVER modules

4 PARTICULARITIES OF SLIVER MODULES

4.1 Lower operating temperature

One interesting feature of SLIVER modules is their low absorptivity, resulting in a cooler normal operating temperature. A conventional PV module typically uses 14% efficient solar cells and about 10% of the light is lost by reflection, resulting in a PV conversion efficiency of 12.6%. The remain power, about 77.4%, is converted to heat. The module being cooled by convection (and to a lower degree by radiation), the cells are usually running about 25C above ambient temperature, resulting in a lower "real-life" efficiency than the SRC rated efficiency.

The SLIVER cells are typically more efficient, about 18% in average. However, because of the spacing between cells, about 30% of the light is lost by reflection. The PV conversion of a SLIVER module would be 12.6% in this case (same as a conventional crystalline Si module), but only 57.4% of the light would be converted to heat, resulting in a cooler operating temperature of the cells. Similar to space solar cells, low absorptivity results in a lower cell temperature.

In an experiment to compare conventional and SLIVER modules, both modules were built with integrated thermocouples. It was demonstrated that the SLIVER cells are running about 6C cooler than laminated conventional Si solar cell [6], with in addition a lower voltage temperature coefficient due to a larger open-circuit voltage [10]. This corresponds to about 3% more annual energy than a conventional Si PV module of equivalent rated power.

4.2 Tolerance to partial shading

Another very interesting characteristic of SLIVER modules is their tolerance for partial shadowing due to the small size of the SLIVER cells, their low reverse breakdown voltage providing a reverse bias protection (RBP) and the high number of parallel connections between series-interconnected banks of cells. This dramatic advantage over conventional wafer-based Si technologies was demonstrated in a series of experiments that are described in another paper [11]. Depending on the orientation of the shaded area with respect to the banks of SLIVER cells, the SLIVER modules still provide an electric output power more or less proportional to the non-shaded area, whereas the output power of conventional wafer-based Si modules could vanish with a shaded area as small as 10%. This characteristic of the SLIVER modules, i.e. tolerance to partial shading, which could be due to trees, buildings, leaves or bird droppings, could result in significant more produced energy over the years.

4.3 Low embodied energy

As presented in a previous paper [7], the SLIVER modules also have a lower embodied energy than conventional crystalline Si PV modules, due to their much lower consumption of Si feedstock. It has been calculated that the energy payback period is about 1.5 years for SLIVER modules, compared to about 4 years for other crystalline silicon PV modules.

5 NEW MODULE CONCEPTS

5.1 Coloured background SLIVER modules

The revolutionary design of the SLIVER modules enables one to fabricate PV modules with different coloured Lambertian reflectors. The results of an early experiment with changing the background colour of a SLIVER module were very promising: the largest reduction in short-circuit current was with a red coloured reflector and was only 8.3%. The short-circuit currents with seven different colours were all ranging between 91.7% and 97.1% of the original white background SLIVER module. Even with a non-uniform colour background, a logo for example, the reduction in short-circuit current was less than 5% [8].

In a more recent experiment with new SLIVER modules fabricated at the pilot facility, the enhancement of the short-circuit current with respect to the colour of the backside reflector was measured by comparison to the same module without backside reflector. The results of these measurements are given in Table 2.

Table 2
Normalized Isc of SLIVER modules with colour backside reflector (normalized to Isc without reflector)

White	Orange	Green	Red	Dark Blue
1.62	1.57	1.32	1.20	1.03

5.2 Bifacial and Flexible SLIVER modules

The innovative SLIVER technology opens the door for dramatically new applications and new module concepts, such as modules with different cell coverage ratios (therefore different efficiencies), bifacial bi-glass modules, and flexible modules (Fig. 7).

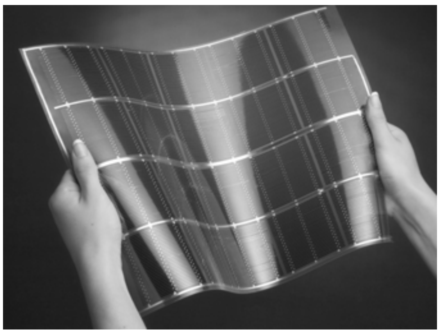

Figure 7: Picture of a flexible, bifacial and semi-transparent SLIVER module.

At this stage of the SLIVER technology

development, the fabrication of bifacial, semi-transparent or flexible modules is still in early development for evaluation purpose. The possibilities of new designs and concepts, including new BIPV modules, are many.

6 SLIVER MODULE RELIABILITY TESTING

The new SLIVER modules were submitted to an extensive program of reliability testing following the IEC 61215 standard. The SLIVER cell itself is fabricated using mono-crystalline silicon wafers and with conventional semiconductor processes. It was expected that the cell would be very stable in performance and as reliable as the other crystalline silicon cells. The assembly process of the SLIVER module, particularly the cell interconnection technique, is, however, somewhat different than the assembly of conventional modules.

The SLIVER modules have demonstrated very high reliability for all the tests required to meet IEC 61215 and have not shown degradation after extended accelerated aging [11], including so far:

- 500 thermal cycles (-40C to +85C),
- 1600 hours of damp heat (+85C, 85% RH),
- combined UV exposure, 50 thermal cycles, 11 humidity freeze cycles and a double UV exposure,
- 3 month outdoor exposure,
- 13500 Pa mechanical load,
- 6 kV dry insulation test, and
- partial shading hot spot test.

7 CONCLUSIONS

The new SLIVER cell and module technology has been transferred from the university laboratory to a new pilot manufacturing facility with increased wafer size and SLIVER cell dimensions. The performance of the SLIVER modules in pre-production and their reliability have exceeded expectations. The SLIVER modules are composed of several banks of series-connected solar cells that are specially designed to have a low reverse breakdown voltage. As expected, due to this particular design, the SLIVER modules exhibit a much greater tolerance to partial shadowing than conventional wafer-based PV modules. Additionally, the SLIVER modules have a low absorptivity and, therefore, the SLIVER cells have a lower normal operating temperature, about 6C lower than conventional silicon PV modules. As a consequence, the annual energy production of a SLIVER module is expected to be greater than the one of an equivalent conventional crystalline PV module. Exciting new designs, including flexible, bifacial and semi-transparent SLIVER module, are in development.

8 ACKNOWLEDGMENTS

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