LATEST PRODUCTION DEVELOPMENTS IN SLIVER TECHNOLOGY

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ABSTRACT: SLIVER technology is a revolutionary crystalline silicon photovoltaic technology that provides the benefits of c-Si module performance but with low silicon consumption. In this paper we discuss the latest developments in SLIVER cell technology which clearly demonstrate that SLIVER technology is capable of obtaining a silicon consumption of ~2g/W. With further development, silicon consumption of less than 1g/W will be possible. Further, we present independent measurements of SLIVER modules which demonstrate the excellent performance of these modules through low operating temperature, low temperature coefficients and good response to low light levels.
Keywords: c-Si, Sliver, Performance

1 SLIVER TECHNOLOGY

SLIVER technology allows for a large decrease in silicon usage compared to conventional crystalline silicon wafer processes [1]. The SLIVER cell process is shown in Fig 1. Through the use of low cost micromachining technology, large numbers of thin (~50micron) silicon strips are cut from single crystal silicon. These silicon strips are processed into solar cells while still held within the silicon wafer frame. The cells are relatively long (~100mm) and narrow (1-2mm). A key aspect to SLIVER technology is that the thin solar cells are formed within the volume of the wafer, rather than on the wafer surface. By removing the cells from the wafer and rotating their orientation, a very large increase in surface area is achieved. The thinness of sliver cells combined with this large increase in surface area results in a silicon consumption (tonnes per MW) which is about an order of magnitude lower than conventional c-Si cells [2].

The performance of SLIVER cells is excellent due to the small, well diffused contact areas, the presence of moderately doped, well passivated emitters on both sides of the cells and the thinness of the cells reducing bulk recombination. The cells are capable of better than 19% efficiency with texturing [2], with voltages in excess of 675mV. The cells are also bifacial.

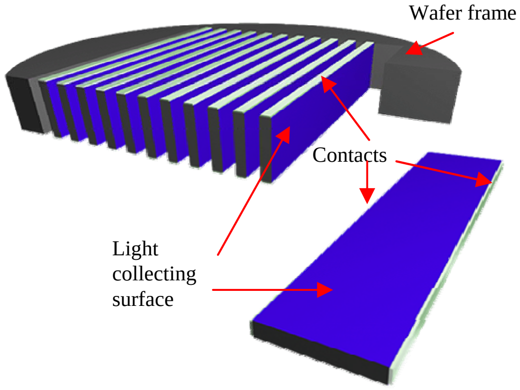

Figure 1: Micromachined wafer containing SLIVER cells. SLIVER cells are supported by the wafer frame.

2 SLIVER MODULES

SLIVER modules have been developed to further minimize the usage of silicon by taking advantage of the unique properties of SLIVER cells. The relative width of SLIVER cells (1-2mm) compared to the thickness of the module allows SLIVER cells to be spaced while maintaining high collection efficiencies for light that enters the module [3]. Light that passes between the cells strikes the rear reflector as shown in Fig 2. The reflector is used to scatter the light upwards where most of the light strikes the rear of the nearby cells or is totally internally reflected at the front of the module and has additional opportunities to strike the cells. The capture of light within the module in this situation is surprisingly efficient. Removal of every second cell only reduces the module power by ~18%, for a net saving of 50% of the cells required.

In addition to the SLIVER cells being spaced, the cells are interconnected differently to traditional c-Si modules. SLIVER modules are built from many series strings or *banks* of cells that are then connected in parallel (see Fig 3). The low reverse breakdown voltage of the cell eliminates the need for bypass diodes to protect the cells within the banks. The module voltage is determined by the number of cells in each bank. The module current is determined by the number of banks connected in parallel within the module.

Origin Energy Solar is currently developing its larger second generation module. The architecture is now monoglass, rather than bi-glass, with a more conventional glass/ pottant/ cell/ pottant/ backsheet structure. This is achieved by the manufacture of SLIVER *sub-assemblies*. SLIVER sub-assemblies are essentially the building blocks of SLIVER modules. SLIVER sub-assemblies typically consist of 10-20 banks of sliver cells depending on the module voltage required. The power produced by a sub-assembly is in the range 12-15W depending on the cell technology used. SLIVER sub-assemblies are manufactured to incorporate a busbar tab. For all intensive purposes, SLIVER sub-assemblies can be

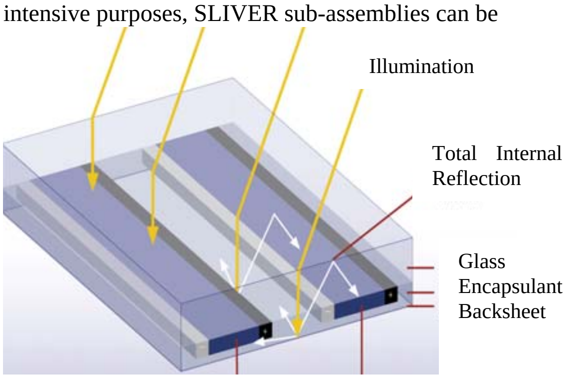

Figure 2: Schematic of a SLIVER module incorporating a rear reflector.

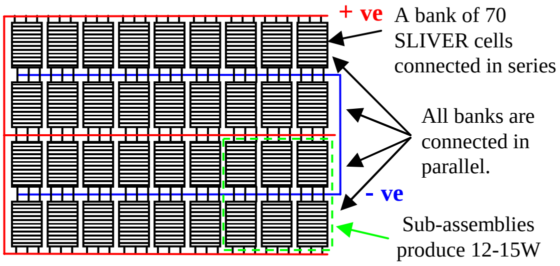

Figure 3: Simplified schematic of series-parallel interconnects within a SLIVER module.

assembled into SLIVER modules using identical module equipment and automation to conventional cells (stringers, laminators, IV testers etc). Significantly, SLIVER sub-assemblies provide some potential reductions in module capital equipment because tabbing is not required, and the power per SLIVER sub assembly is ~5 times greater than that of a conventional c-Si cell.

The IV curve of a typical monoglass SLIVER module can be seen in Fig 4. This module has power of 80.4W with an open circuit voltage of 46.3V (~660mV/cell), short circuit current of 2.21A and a very high fill factor of 78.6%. The newer monoglass SLIVER modules have reduced weight compared to previous bi-glass versions and reduced material costs. In addition, there has been a boost in current of 6.5% due to the superior reflection properties of the backsheet. Improvements in cell design have also led to an improvement in fill factor around 8.5%. Combined improvements in power compared to the earlier module design are greater than 15%.

3 VERY LOW SILICON CONSUMPTION

The SLIVER cell process enables tremendous savings in the quantity of silicon required for a given power output (g/W). We have previously reported greater than 15W of module power for each processed wafer (1mm thick, 150mm diameter) [6]. Allowing for 300µm kerf loss, this corresponds to ~3.4g of Si per Watt of module power. This compares very favourably with conventional c-Si, which has silicon consumption in the range 10-14g/W. The high Watts per wafer of SLIVER technology also dramatically reduces the number of wafers required to be processed for a given factory output. For the above baseline case of 15W/Wf, a SLIVER module factory only needs to process ~65000 wafers per MW. In comparison, conventional cell

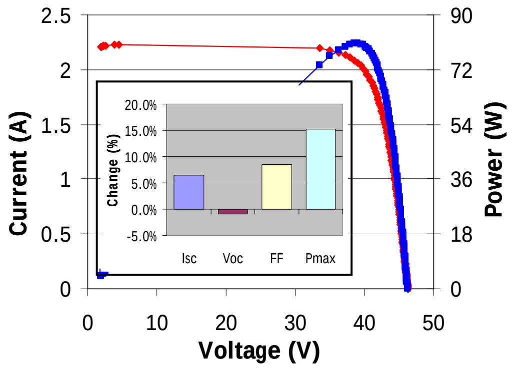

Figure 4: IV curve of a monoglass SLIVER module.

technology (2.5W to 3W per wafer) requires of the order of 350 000 wafers to produce the equivalent power.

A key focus of development work has been demonstrating further reductions in silicon consumption for SLIVER technology and increases in Watts per wafer. This work has focused on three main areas:

i) Improved cell efficiency – Via the introduction of texturing [6] and other process improvements.
ii) Reduced wafer frame – As shown in Fig 1, the wafer frame is the annulus of Si that holds the SLIVER cells during processing. Reducing the wafer frame allows more cells per wafer.
iii) Reduced cell pitch – This is the centre to centre spacing of the cells in the wafer. Reducing the cell pitch allows for more cells per wafer.

Significant gains have been demonstrated at a development level in each of these areas. Table 1 summarizes the variables investigated for 1mm thick wafers. Case A is the baseline cell technology and results are shown in Fig 5. Compared to baseline, a relative decrease of ~7% in silicon consumption (g/W) has been achieved by reducing the wafer frame. Independently, texturing has demonstrated a ~11% reduction in silicon consumption (g/W), compared to baseline, by improving the cell efficiency. Finally, a reduction in the silicon consumption of ~25%, compared to baseline, has been demonstrated through incremental reductions in cell pitch down to 90µm. Combining all three improvements is expected to result in an overall silicon consumption of ~2.2g/W, a combined reduction of ~38% compared to baseline. The wafer power with all three improvements is expected to be ~24.8 W/Wf, resulting in ~40,000 wafers needing to be processed per MW of module output.

Further reductions in silicon consumption for 1mm thick wafers are believed to be feasible, including further reductions in wafer frame and pitch, and increases in cell efficiency and length. The potential silicon consumption for SLIVER technology, once mature, is <1g/W [5,6].

Table 1: Improvements in the SLIVER cell process have demonstrated reduced silicon consumption.

Case	A	B	C	D	E*
Textured	no	no	yes	no	yes
Frame	old	new	old	old	new
Pitch (µm)	120	120	120	90	90
Wf width (mm)	1.0	1.0	1.0	1.0	1.0
g/W	3.5	3.2	3.1	2.6	2.2
W/Wf	15.5	16.6	17.4	20.7	24.8
Wf/MW	64.5k	60.1k	57.6k	48.4k	40.3k

* expected performance

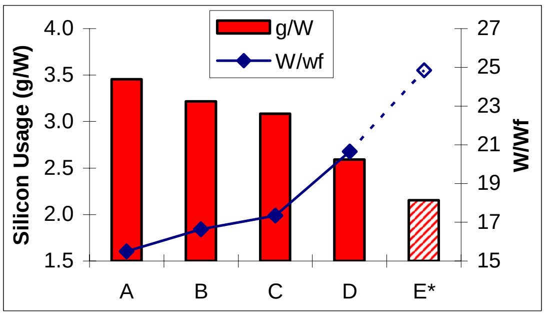

Figure 5: Demonstrated and expected (hashed pattern) improvements in silicon consumption of SLIVER cells from 1.0mm thick wafers.

Work has recently commenced on processing SLIVER cells from 1.5mm thick wafers. The use of thicker wafers greatly increases the surface area per SLIVER cell and therefore strongly impacts the W/Wf. Results to date indicate that the cell current scales linearly with the surface area as would be expected. The Voc is comparable to 1mm SLIVER cells with Voc~675mV per cell demonstrated in small 15W modules. Fill factors for small modules have reached 76% and are expected to improve with further optimization. It is expected that ~40W/Wf is achievable with 1.5mm thick wafers in the near future, with silicon consumption equal to, or less than that for 1.0mm wafers.

4 PREMIUM MODULE PERFORMANCE

4.1 Low Operating Temperature

The SLIVER module structure described in section 2 has the additional benefit that it results in a lower absorbtivity for the module structure. A 50% reduction in silicon is obtained with only a ~18% reduction in module power. This means that ~18% less heat is being absorbed and generated within the module. It follows that, for a given light intensity, SLIVER modules will operate substantially cooler than conventional c-Si modules. This is demonstrated in Fig 6, which shows measurements made by TUV of the effect of light intensity on module temperature (relative to ambient temperature: Tm-Ta). For these measurements, a monoglass SLIVER module with Pmax of 76W at STC was used. The average wind speed during the measurements was 1.1m/s and the average ambient temperature was 21.0°C. These are ideal conditions for determining the module operating temperature at NOCT. It can be seen from Fig 6 that Tm-Ta responds linearly with light intensity. Furthermore, at 800W/m^2 (NOCT conditions), the module temperature is 19°C above ambient. The module temperature for these SLIVER modules at NOCT is therefore 39°C. This compares extremely well to conventional c-Si modules which have an NOCT temperature in the range of 45-50°C.

4.2 Low Temperature Coefficients

SLIVER cells have high open circuit voltages. This reduces the degradation of module output as module temperature increases [4]. Independent measurements of the temperature coefficients of monoglass SLIVER modules with nominal power of 75W have now been

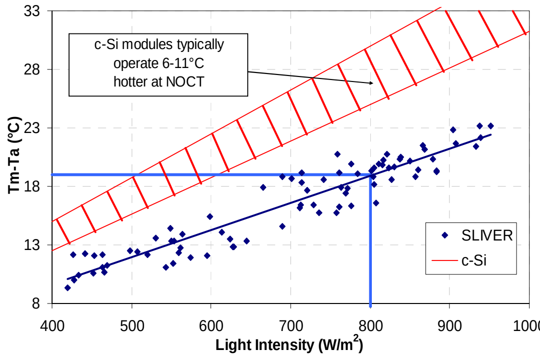

Figure 6: Effect of light intensity on module temperature. SLIVER modules have a low operating temperature of ~39°C at NOCT, resulting in higher energy output.

Table 2: Measured temperature coefficients for 75W SLIVER modules.

Coefficient	Absolute Units	Relative Units
Voc (β)	-0.137V/°C	-0.299%/°C
Isc (α)	+1.7mA/°C	+0.079%/°C
Pmax (γ)	-0.31W/°C	-0.40%/°C

made by TUV. Values for the temperature coefficients are given in Table 2 in absolute and relative units. It can be seen that the co-efficient for Voc (β) is confirmed to be very low at -0.299%/°C. This corresponds to -1.96mV/°C per cell for this module. This compares well with many conventional c-Si modules which have β~-0.36%/°C. That is, SLIVER modules have a superior temperature coefficient for Voc compared to many c-Si modules by approximately 20% in relative terms.

The superior temperature coefficient of SLIVER modules has also been confirmed for Pmax where a value of -0.40%/°C has been measured. This compares very favorably with the typical values for many c-Si modules of -0.5±0.05%/°C. It should be noted that the superior temperature coefficients for SLIVER modules are in addition to the low operating temperatures demonstrated in section 4.1.

4.3 High Energy Yield

The lower operating temperatures and superior temperature coefficients of SLIVER modules provide a higher energy yield from SLIVER modules compared to many similarly rated c-Si modules. An estimate of the higher energy yield can be made for some typical conditions. The conditions considered are:

i) NOCT - which has an ambient temperature of 20°C and an irradiance intensity of 800W/m2.
ii) High Temp, high intensity – for which we assume an ambient temperature of 40°C and an irradiance intensity of 1100W/m2.

The data from Fig 6 and Table 2 were used to model the SLIVER module performance. For a typical c-Si module, a temperature coefficient of γ=-0.5%/°C was used, and the effect of irradiance intensity of Tm-Ta was assumed to be linear and result in an NOCT operating temperature of 48°C (a typical industry value).

The estimated increase in energy yield for these two conditions is shown in Fig 7. It can be seen that for NOCT conditions, the SLIVER module is estimated to generate 2.3% more energy due to its superior temperature coefficient and a further 3.6% more energy due to its lower operating temperature. This is a total increase in energy yield of 5.9% at NOCT compared to a

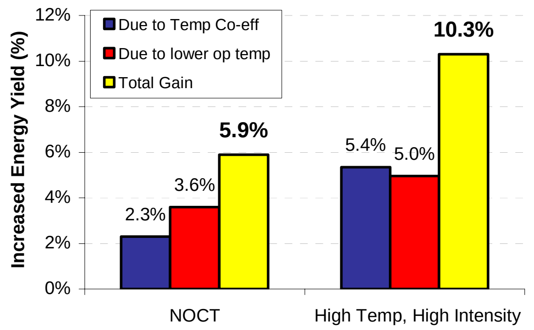

Figure 7: Estimated increases in energy yield for SLIVER modules for typical conditions.

typical c-Si module. Also shown in Fig 7 is that the improved energy yield of SLIVER modules is estimated to be even greater when the irradiance intensity or ambient temperature is higher. For the second condition modeled, the SLIVER module is estimated to generate 5.35% more energy due to its superior temperature coefficient and a further 4.95% more energy due to its lower operating temperature. This is a total increase in energy yield of 10.3%.

4.4 Low Light Performance

SLIVER cells have a high efficiency cell structure incorporating well passivated contacts and emitters. Efficiencies in excess of 20% have been reported under laboratory conditions [5]. Additionally, the excellent internal quantum efficiency of SLIVER cells has been previously reported [6]. The low light performance of SLIVER modules is therefore expected to be good, with little impact from non-ideal diode behaviour or shunt resistance. Fig 8 shows independent measurements made at TUV for a ~75W module at different light intensities with STC conditions otherwise. It can be seen that the Voc of the module decreases slightly with light intensity as is expected for a silicon diode. Importantly, the module FF remains very high.

Fig 9 shows the dependency of Isc, Voc and FF with light intensity for the I-V curves in Fig 8, where all values have been normalized against the values at STC (Isc=2.14A, Voc= 45.88V, FF=77.8%, Pmax=76.4W). The dashed curves in Fig 9 are theoretical curves for the change in Isc and Voc. The curve for Isc is based on a purely linear response for Isc to light intensity. For Voc, the curve is based on the unavoidable Voc change expected from the ideal diode equation. It can be seen that Isc data does drop off linearly with light intensity, as would be expected, and is well fit with the curve. For Voc, the curve fits the data well when the ideality is n~1.1, which indicates the Voc changes as expected. Finally, the FF actually rises by ~1.7% in relative terms as light intensity decreases. The FF for SLIVER modules is already very high by industry standards at STC (~78%) and approaches ~80% at lower light intensities. Overall, this data shows that SLIVER modules have the properties of low series resistance, very high shunt resistance and near unity ideality. This demonstrates the good low light performance of SLIVER modules.

4.5 High Tolerance to Partial Shading

The excellent tolerance of SLIVER modules to partial shading has previously been demonstrated [6]. This is an outcome of the unique series-parallel

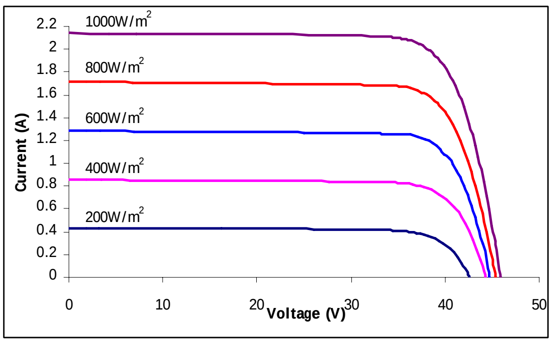

Figure 8: IV curves for a ~75W SLIVER module at different light intensities.

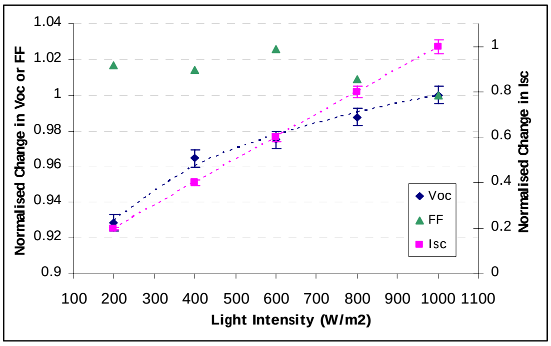

Figure 9: Normalised change in Isc, Voc and FF with light intensity for a ~75W SLIVER module. The dashed lines are theoretical curves.

interconnect design, where shading effects are restricted to only the banks that are shaded, with no significant impact on the remainder of the module.

5 SUMMARY

SLIVER technology continues to be developed by Origin Energy Solar. The latest technology developments clearly demonstrate that SLIVER technology is capable of obtaining a silicon consumption of ~2g/W using 1mm wafers. This has been demonstrated through improved cell efficiency, reduced wafer frame and reduced cell pitch. Additionally, independent measurements of ~75W SLIVER modules have demonstrated excellent module performance. High energy yields are expected due to low operating temperature, low temperature coefficients, good low light performance and excellent tolerance to partial shading. Origin is continuing its in-house technology development program. Pilot plant activities are focusing on the technical developments required for building a large scale SLIVER plant as soon as possible.

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