# RELIABILITY TESTING OF SLIVER MODULES AND EFFECTS OF PARTIAL SHADING ON POWER OUTPUT

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ABSTRACT: SLIVER cells are a novel silicon solar cell technology that has been commercialised by Origin Energy from research at the Australian National University. SLIVER technology allows for large decreases in silicon usage compared to conventional crystalline silicon wafer technologies as well as other potential benefits. While being a novel technology, SLIVER cells are fabricated using conventional crystalline silicon wafers and therefore should offer the same high reliability found in conventional silicon technology. This paper demonstrates the excellent performance of SLIVER modules under accelerated aging and real world conditions. Furthermore, the performance benefits of SLIVER modules compared to conventional modules under conditions of partial shading are demonstrated.
Keywords: PV module, Reliability, Shading

## 1 INTRODUCTION

SLIVER technology is highly innovative [1,2]. Advantages of SLIVER cells include the potential of greatly reduced silicon usage, improved Watt per wafer productivity, perfectly bifacial cells with no grid shadow loss and high cell efficiencies. The benefits of SLIVER modules include the potential of lower operating temperatures, improved response to partial shadowing, semi-transparent bifacial modules, coloured background modules, light-weight flexible modules and high-voltage modules. SLIVER technology was invented at the Australian National University, and is being developed and commercialised by Origin Energy at their US$15million facility in Adelaide, Australia [3].

While being a novel technology, SLIVER cells are fabricated using conventional crystalline silicon wafers and well known and understood semiconductor processes. Fundamentally therefore, SLIVER cells and SLIVER modules should offer the same excellent reliability found in conventional silicon wafer photovoltaic (PV) modules. In this paper, we demonstrate the excellent reliability performance of the first commercial modules produced in the Adelaide plant. Emphasis is placed on the accelerated aging tests that are well defined in the relevant international standards (thermal cycling, damp heat etc), while some early phase real world test data will be supplied. Finally, the performance of sliver modules under partial shading is demonstrated.

## 2 SLIVER MODULE CONSTRUCTION

The unique size of SLIVER cells (long and thin) combined with their perfectly bifacial response allows novel designs to be used for SLIVER modules. In particular, incorporating a reflector at the rear of the SLIVER modules allows the SLIVER cells to be spaced apart as shown in Figure 1. Light that is incident on the gap between the cells can be reflected on to the rear side of the SLIVER cells or trapped via total internal reflection. This allows further reductions in the silicon required to construct SLIVER modules while still maintaining the module efficiency. For example, SLIVER modules constructed with 1mm wide cells and having 1mm wide gaps, generate ~80% of the short circuit current of a module with no gaps, but only use 50% of the silicon.

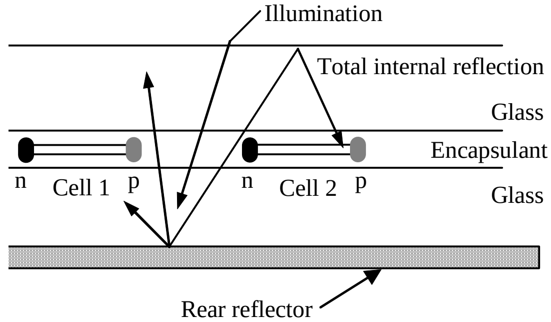


**Figure 1:** Bi-glass module design incorporating a rear reflector with the SLIVER cells spaced out to reduce silicon usage.

The first generation of commercial SLIVER modules produced from the Adelaide facility are based on the bi-glass design shown in Figure 1. The modules have nominal power outputs of 15W and 40W and have purposefully been design to produce ~17V at maximum power point so they are well suited to battery charging applications. The cell interconnects within the module are designed such that "banks" of SLIVER cells are made by series connecting 35 SLIVER cells. Banks of SLIVER cells are then interconnected in parallel. This series/parallel interconnect design found in SLIVER modules is very different compared to conventional crystalline silicon modules, which are just series connected. Bypass diodes are not required in the module construction as the SLIVER cells have a controlled low voltage breakdown [3]. The process is monolithic in nature.

A second generation of SLIVER module technology is currently under development. This new module technology has the benefits that it is mono-glass in structure and does not introduce any new materials. Figure 2 shows the IV curve of a 70W sliver panel based on this new SLIVER module technology. Increasing the module size to produce higher power or different current-voltage properties is straight forward.

## 3. RELIABILITY TESTING

Suitable accelerated aging tests for investigating module reliability have been developed by the

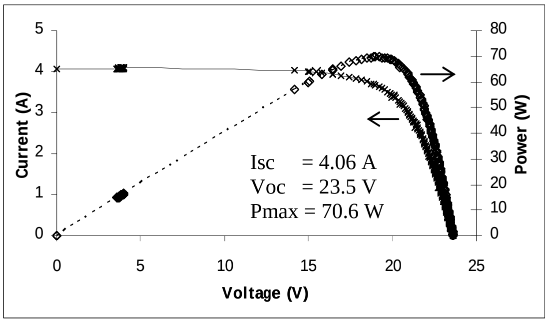


**Figure 2:** Typical I-V characteristic of recently developed 70W SLIVER modules with un-textured cells.

photovoltaic community over many decades. These tests are well documented in the relevant international standards, in particular IEC 61215, IEEE 1262 and UL1703. The most demanding tests include: 1) Thermal cycling; 2) Damp heat; 3) Humidity freeze; 4) UV exposure test; and 5) Electrical insulation tests (wet and dry hi-pot). Significant facilities have been developed at Origin Energy's Adelaide facility to perform in-house testing including three temperature and humidity chambers, a dedicated UV and temperature chamber, hail testing equipment, insulation resistance testing equipment and an outdoor test facility.

3.1 Thermal Cycling Tests

Figure 3 shows the performance of commercial 15W SLIVER modules under extended thermal cycling from -40°C to 85°C as per IEC61215 (with biasing for T>25°C). Module measurements were made with a flash tester with a typical error in $P_{max}$ of ±1% (relative). It can be seen that the SLIVER modules show very little degradation in power. The maximum power loss after 550 thermal cycles is 4%, confirming that SLIVER modules are very stable under thermal cycling. Indeed, the measurements show in Figure 3 extend out to 500 thermal cycles while the requirements of IEC61215 are less than 5% loss for only 200 thermal cycles. Furthermore, the trend for the data shown in Figure 3 indicates that SLIVER modules will remain stable under many more thermal cycles.

Thermal cycling tests are typical useful for identifying module failure modes due to the cell interconnects. The excellent results shown in Figure 3 clearly support that the interconnects developed for SLIVER modules are very robust and reliable. The following elements contribute to the robust nature of the interconnects:

- The interconnects within a SLIVER module have triple redundancy. That is, only one interconnect from cell to cell is required from a conductivity perspective but three or more interconnects are provided.
- Each interconnect carries a very small current, typically ~0.014A, compared to currents of ~1A per interconnect in a conventional panel. The power dissipated in a faulty interconnect is proportional to the current squared ($P=I^2R$), so the destructive power dissipated in a faulty interconnect in a conventional panel is approximately four orders of magnitude greater than in a SLIVER interconnect.
- Conventional panels are series interconnected. The failure of the interconnects associated with a single cell can be catastrophic as the entire series string is then unable to generate power, or at least all cells in series between a single bypass diode. SLIVER modules have a series/parallel interconnect design. Problems associated with the interconnects of a SLIVER cell will at worse effect the power output of that bank of cells only. In the 40W panel there are 54 banks, so a fault in 1 bank will result in less than 2% power loss.

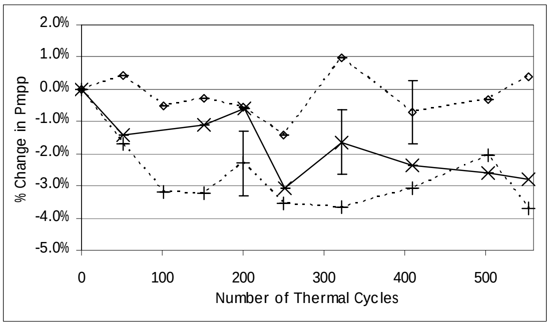


**Figure 3:** Performance of commercial 15W SLIVER modules under extended thermal cycling. The interconnects are very robust and reliable.

3.2 Damp Heat Tests

Figure 4 shows the performance of commercial 15W SLIVER modules under extended damp heat testing at 85°C and 85% relative humidity as per IEC61215. It can again be seen that SLIVER modules show very little degradation in power. At the IEC61215 requirement of 1000hrs, the maximum power loss is only 3%, well within the 5% power loss allowed. Even with extended damp heat testing to over 1700hrs, all the SLIVER modules still exceed the IEC requirements. SLIVER modules are clearly very stable under damp heat testing. Analysis of the small changes in SLIVER modules during damp heat testing show that it is due to small decreases in short-circuit current, most likely due to optical losses within the encapsulant.

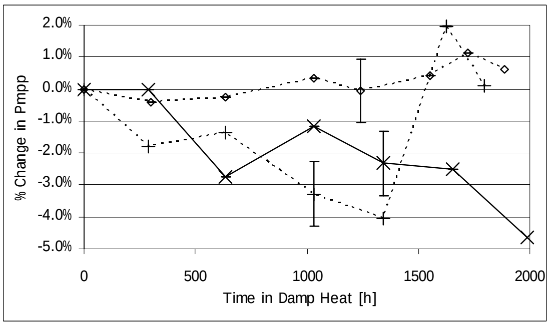


**Figure 4:** Performance of commercial 15W SLIVER modules under extended damp heat testing. The encapsulation system and modules are very robust and reliable.

3.3 UV Exposure and Humidity Freeze Tests

Figure 5 shows the performance of commercial 15W SLIVER modules under cummulative UV exposure (UV-A and UV-B), followed by thermal cycling from -40°C to 85°C and then humidity freeze tests as per IEC61215. It can been seen that there is no change in the power output of the SLIVER modules (all measurements are within the measurement accuracy of ±1%). This is further support of the excellent reliability offered by SLIVER modules. Figure 5 also shows the performance of 15W SLIVER modules under extended UV exposure testing. Even when the UV exposure is twice that required by IEC61215, the maximum power loss is <2%.

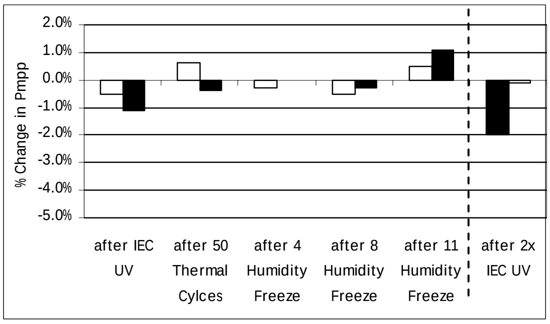


**Figure 5:** Performance of commercial 15W SLIVER modules under UV exposure, thermal cycling and humidity freeze testing (cumulative results). The modules are very robust and reliable.

### 3.4 Outdoor Exposure Tests

Commercial 15W SLIVER panels were first mounted at Origin Energy's outdoor test facility in Adelaide, Australia during February 2005. The typical summer climate in Adelaide is hot and dry with day time temperatures in excess of 30°C and peak light intensity >1100W/m$^2$. Figure 6 shows some early stage real world testing for these modules, where the modules are periodically remeasured under controlled laboratory conditions and then returned outside. The data to date is limited, but essentially shows no changes beyond the measurement accuracy. It is clear however that there are no short term light induced degradation or annealing phenomena with SLIVER modules. This is related to the use of high quality float-zone silicon wafers.

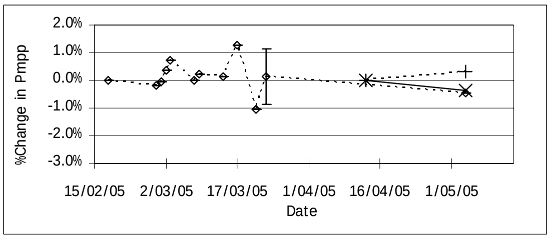


**Figure 6:** Performance of commercial 15W SLIVER modules under outdoor conditions.

### 3.5 Other Reliability Tests

Commercial 15W SLIVER modules have also passed the mechanical loading test of IEC61215. The maximum load tested to date is 13500Pa without any effects on the modules, which is greater than five times the IEC61215 requirement. SLIVER modules have also passed 6KV dry insulation tests and wet leakage current tests, with the voltage maintained for up to 15mins, without any power loss or structural damage.

## 4. EFFECTS OF PARTIAL SHADING

The majority of crystalline silicon modules have the cells connected in a simple series string as shown in Figure 7. Commonly, bypass diodes are used every 12-24 cells to protect the module against hot-spot heating. This interconnect design has relatively poor tolerance to partial shading, because the worst cell in each series string (eg a shaded cell) defines the current of the entire series string. In worse case, a single shaded cell can result in the entire module producing no power.

In SLIVER modules, the individual cells are interconnected to form "banks" of 35 cells, The banks are then interconnected in parallel to build current within the module as shown in Figure 8. Due to this series/parallel interconnect design, even when one bank of cells is shaded and not producing power, the other banks of SLIVER cells are virtually unaffected and continue to produce power at their maximum power-point.

The superior performance of SLIVER modules compared to conventional silicon modules was evaluated by performing controlled shading tests under laboratory conditions at an ambient temperature of 25°C. A flash-tester was used to determine the maximum power output of both SLIVER and competitor crystalline silicon modules, where the modules were progressively shaded using opaque black cloth in a horizontal, vertical and diagonal directions as shown in Figure 7.

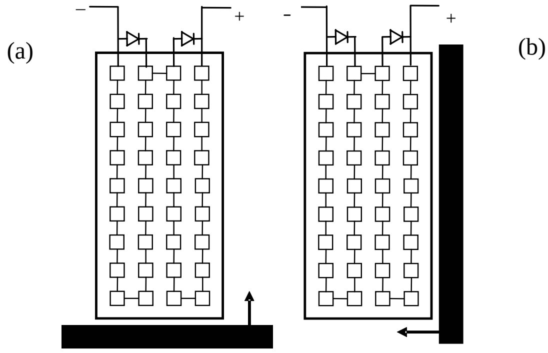


**Figure 7:** Series interconnected cells in a conventional crystalline module with by-pass diodes. Shading a single cell effects all cells within that bypass diode. Horizontal (a) & vertical (b) module shading methods are shown.

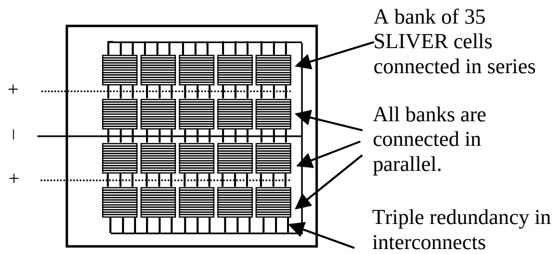


**Figure 8:** Simplified schematic of series-parallel interconnects within a SLIVER module. Shading a single banks does not effect other banks, which still produce at their maximum power point.

Figure 9 shows the typical performance, due to vertical shading, of a 15W SLIVER module ( 4 rows of 5 banks) compared to a 20W conventional crystalline silicon modules that had 36 series connected cells (4 columns of 9 cells) and no bypass diodes. It can be seen that the output power of the SLIVER module decreases very slowly and is equal to the amount of shading (ie 50% shading reduces the power output to ~50%). In comparison, the conventional crystalline module loses power very rapidly with partial shading and produces no power when ~25% of the module is shaded. This is to be expected as one column of cells in the conventional module is now shaded and no current can flow. In comparison, at ~25% vertical shading, the 15W SLIVER module is producing over 70% of it unshaded power due to the unique series/parallel interconnect design.

Figure 10 shows the typical performance of the same 15W SLIVER module and 20W conventional module under horizontal and diagonal shading. Again the drop off in power produced by the SLIVER module is quite slow with shading, as the unshaded banks continue to produce power almost independently of the shaded banks. It should also be noted that the step function response of the SLIVER module under horizontal shading is expected as this represent the different rows of SLIVER banks becoming shaded. In comparison, the conventional panel again losses power very rapidly upon shading, with virtually no power produced when ~12% of the module is shaded. This is again expected as this represents one row of the cells in the conventional module being shaded and no current can flow. It should be noted that the horizontal shading condition is the worse case for both SLIVER and conventional modules, but importantly, while the conventional panel produces almost no power at ~12% horizontal shading, the 15W SLIVER module is still producing over 80% of it's unshaded power. Results under diagonal shading are similar with the SLIVER module being very tolerant to partial shading, but the conventional module losing power rapidly.

Figure 11 shows the typical performance due to shading of a larger 40W SLIVER module (6 rows of 9 banks) compared to a 40W conventional crystalline silicon modules that had 36 series connected cells (4 columns of 9 cells) both with and without 2 bypass diodes. The results are very similar to those described above for the smaller modules. Again it can be seen that the 40W SLIVER module is very tolerant to partial shading. It loses power very slowly and the power loss is approximately equal to the amount of shading (ie 50% shading reduces the power output to ~50%). The loss of power with shading is again very dramatic for the 40W conventional panel. Under horizontal shading, the conventional panel again produces virtually no power at ~12% horizontal shading (1 row of cells shaded), regardless of the presence of bypass diodes. The 40W SLIVER module is producing over 80% of its unshaded power for the same 12% horizontal shading. Under vertical shading, the response of the 40W conventional module is very different depending on the use of bypass diodes or not, as each bypass diode protects the two series strings. Without bypass diodes the power output of the conventional panel drops off very quickly (~no power with 25% vertical shading, corresponding to one column of cells), while with bypass diodes the power output drops to 50% quickly and is then stable before droping off again at 50% vertical shading. What remains clear is that the 40W SLIVER module shows significantly better response to partial shading than a conventional crystalline silicon module, regardless of the amount of shading and whether bypass diodes are used in the conventional module or not.

## 5 CONCLUSIONS

The excellent performance of 15W SLIVER modules under accelerated aging tests has been demonstrated in this paper. Tests included extended thermal cycling, damp heat, humidity freeze, UV exposure, mechanical loading and dry/wet insulation tests. SLIVER modules have far exceeded the IEC61215 requirements for all tests. Furthermore, it has been shown that SLIVER modules have excellent tolerance to partial shading compared to conventional silicon modules, due to the series/parallel interconnect design of SLIVER modules.

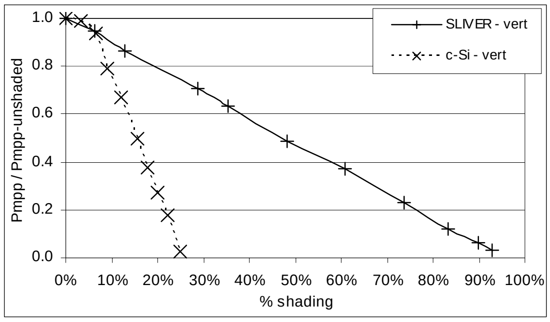


Figure 9: Partial vertical shading of 15W SLIVER modules compared to a 20W crystalline silicon module.

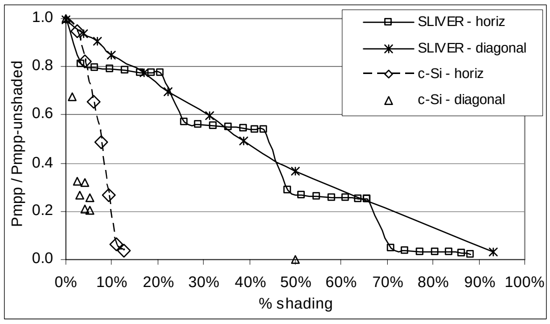


Figure 10: Partial horizontal and diagonal shading of 15W SLIVER modules compared to a 20W crystalline silicon module.

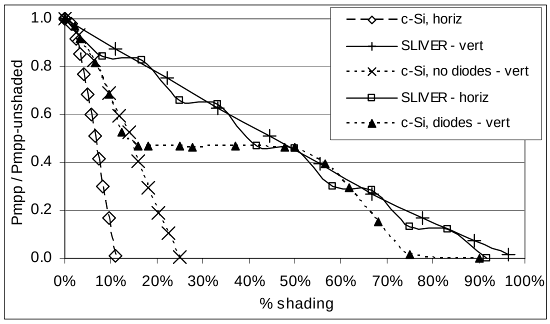


Figure 11: Partial horizontal and vertical shading of 40W SLIVER modules compared to a 40W crystalline silicon module both with and without bypass diodes.

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