

CHARACTERISATION OF THE THERMAL RESPONSE OF SLIVER® CELLS AND MODULES

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ABSTRACT: Sliver® cells, invented and developed at The Australian National University, are long, thin, narrow, and bifacial. They are constructed from high-grade mono-crystalline silicon. Solar modules that incorporate Sliver® cells are significantly different in their construction and performance characteristics to conventional crystalline silicon modules. In Sliver® modules, the cells are usually spaced apart to make use of the bifacial nature of the Sliver® cells. A scattering reflector on the rear of the module is used to trap most of the incident light within the module structure. However, a fraction of the incident sunlight will not be absorbed by the cells and will instead be coupled out of the module. While this loss of incident radiation results in a reduction in module efficiency, it also results in a proportional reduction in heat generation within the module. This leads to lower module operating temperatures compared with conventional modules of similar efficiencies.

Keywords: Bifacial, Performance, Thermal Performance.

1 INTRODUCTION

In this paper, the temperature response of Sliver® cells and modules is analysed and compared to conventional cells and modules. It is shown that Sliver® cells have a slightly lower temperature coefficient of V_{oc} , and therefore a lower temperature coefficient of efficiency, than most conventional cells. This is primarily due to a higher V_{oc} for Sliver® cells than conventional cells, which is generally in the range 660-690mV. The measured values of power temperature coefficients and cell temperature-dependence coefficients are in good agreement with theoretical predictions.

Measurements on Sliver® modules with 50% cell coverage and reference modules constructed from conventional multicrystalline Si cells under calm, sunny conditions have confirmed that the operating temperature of Sliver® modules is significantly lower, with measured cell operating temperatures of 51°C for the Sliver® module and 56°C for the reference modules. The efficiency decrease of the Sliver® module under these conditions was 7.0% compared to its performance at 25°C, while the corresponding decrease in performance of the multi-crystalline conventional reference modules was in the range 13% to 16.5%.

Under windy conditions, the balance of dominant cooling mechanisms for the two module types shifts and the conventional reference module and the Sliver® module temperature converges to the same value, around 50°C. However, even when the conventional module and the Sliver® module were operating at the same temperature, the reduction in efficiency of the Sliver® module was still less than that of the conventional modules.

The measured reduction in the operating performance of the modules at 50 °C, compared with the performance at STC was 6.7% for the Sliver® module. This compares favourably with a reduction of 11.7% for a reference module operating under identical conditions.

The results presented here highlight the fact that module performance under real operating conditions cannot be simply inferred from the rated module performance.

2 DESCRIPTION OF SLIVER® TECHNOLOGY

The Sliver® forming process uses micro-machining techniques, such as laser ablation, dicing saw cutting or selective chemical etching, to create narrow grooves which extend all the way through a thick silicon wafer. As shown in Figure 1, these wafers are typically 1 to 2 mm thick. The pitch of the grooves is typically 100µm. The thickness of the Slivers® is typically 50 to 60 µm, while the grooves are 30 to 40 µm wide.

The end result of the Sliver® forming process is a large number of thin silicon strips in a window near the centre of the wafer. The array of silicon strips is held together by the un-etched surrounds of the wafer. On a 1mm thick 150mm diameter wafer, these strips would typically be 100mm long, 1 mm wide, which corresponds to the wafer thickness, and from 50 to 65µm thick.

2.1 Cell Processing

Cells are constructed on the narrow strips of silicon formed during the micromachining process. Cell processing is completed while the silicon strips are still supported by the silicon substrate at the edge of the wafer.

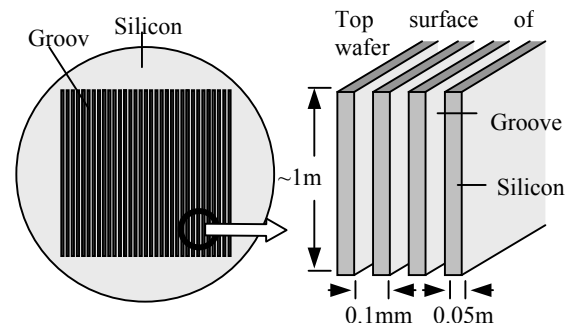


Figure 1. Schematic of a micro-machined wafer. Long, thin silicon slices are supported by the wafer frame.

At the end of the cell forming process, the completed cells are cut out of the wafer using a dicing saw or a laser oriented perpendicular to the strip length or wafer surface. The Slivers® are then turned on their side.

The Sliver® cell process allows the fabrication of

single crystalline, thin silicon cells. These cells have a high efficiency potential, are perfectly bifacial, and have no metal shading on the faces exposed to light. The Sliver® cells are quite thin, around 50 to 60 µm thick, and are very narrow, typically around 1 to 2 mm wide.

2.2 Sliver® Module Structure

The Sliver® cell features described above can be usefully exploited in novel module designs in which only 50%, or even less, of the module surface is covered with cells. By suitable light-trapping module-designs, up to 85% of the incident light can be captured by modules with only 50% cell-coverage. This high optical efficiency is achieved using a highly reflective lambertian, or scattering reflective, layer at the rear of the module. Most of the sunlight which passes through the space between the cells is subsequently reflected, scattered, and absorbed by the cells. Light that is scattered at a sufficiently high angle will be trapped by total internal reflection within the module if it is not absorbed by the cell following the first reflection. However, a fraction of light, which is reflected at a low angle and does not hit the cells, will not be trapped within the module, inevitably escaping the module. Further details can be found in [1].

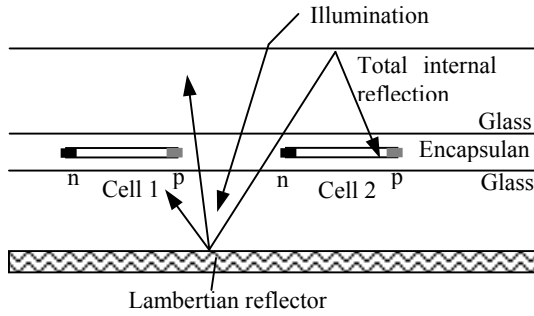


Figure 2. Lambertian reflector module design. The narrow width and the bifacial nature of the Sliver® cell enables the cells to be spaced, in this case at double the cell width, further reducing silicon use by a factor of two, with only a small decrease in module efficiency due to the fraction of light escaping from the module.

3 THERMAL RESPONSE OF SLIVER® CELLS

The efficiency of silicon solar cells falls as the temperature increases, chiefly due to a decrease in the open circuit voltage V_{oc} . An empirical expression for the temperature dependence of V_{oc} is [2]

$$\frac{dV_{oc}}{dT} = \frac{V_{go} - V_{oc} + \gamma (kT/q)}{T} \quad (1)$$

where V_{go} is the linearly extrapolated zero temperature band gap voltage dependency, and γ includes the temperature dependencies of the remaining parameters determining the saturation current density J_0 .

The value of γ generally lies between 1 and 4. With a value of V_{go} of 1.2 V, V_{oc} of 660 mV, cell temperature of 25 °C, and $\gamma = 3$, the theoretical value of dV_{oc}/dT is 2.07 mV/°C. The value of γ has only a small effect on the thermal coefficient. By far the greatest factor

influencing the thermal coefficient is the value of V_{oc} , which is a major advantage for Sliver® cells.

The net effect of cell temperature increase is a reduction in efficiency, typically around 0.3 to 0.4% per degree Celsius for conventional multi-crystalline cells, which is primarily due to the falling open-circuit cell voltage of between 2.2 and 2.4 mV/°C. For Sliver® cells, the reduction in efficiency is typically around 0.25 to 0.3% per degree Celsius, again primarily due to the falling open-circuit cell voltage of between 1.6 and 2.0 mV/°C. In general, cells with higher V_{oc} have reduced temperature sensitivity.

Sliver® cells are characterized by high open circuit voltages, generally between 660 and 690 mV, so they would therefore be expected to display a lower temperature sensitivity between 2.0 to 2.1 mV/°C. This compares quite favourably with commercial cells which generally have thermal coefficients in the range of 2.2 to 2.4 mV/°C with a V_{oc} generally around 600mV.

4 THERMAL RESPONSE OF SLIVER® MODULES

In Sliver® modules in which only some fraction of the module surface area is covered with cells, some light escapes from the module without being absorbed. This loss of light results in a reduction in module efficiency, but it also results in a proportional reduction in the quantity of heat which is generated within the module.

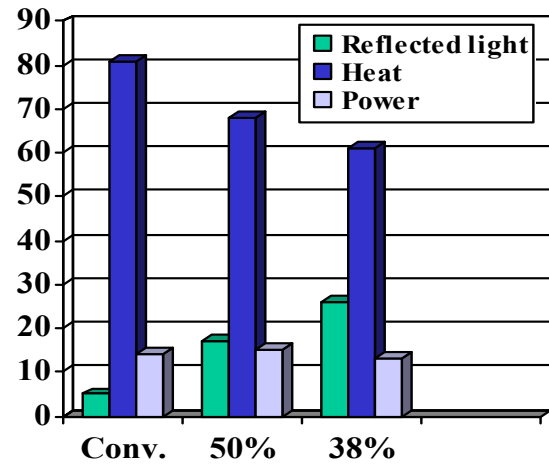


Figure 3. Comparison of module outputs; reflected light, heat and electrical output power, for a conventional module (Conv) and two Sliver® modules, (50% and 38%), with 50% and 38% respectively cell-to-module surface area ratios.

The relative proportion of lost or reflected light from the module, the quantity of heat generated within the module, and the electrical power extracted from the module for several module types is illustrated above in Figure 3. The chart compares the output of a conventional module assumed to have 95% coverage with 15% efficient cells, with that of two Sliver® modules with 50% and 38% cell coverage, with each Sliver® module assumed to contain 18% efficient cells.

The results in Figure 3 were obtained using an analytical model described in a separate paper presented at this conference [3]. The amount of heat generated by

the Sliver® modules, compared with the conventional module, is significantly reduced. However, the Sliver® module efficiency of 14.9% for the 50% coverage, and 13.3%, for the 38% coverage module, compares very favourably with that of the conventional module efficiency of 14.3%. The comparable efficiency between conventional modules with 95% cell coverage and Sliver® modules with 50% cell coverage is due to a combination of the higher Sliver® cell efficiency and the concentrator function of the lambertian reflector on the bifacial Sliver® cells.

Most of the heat which is deposited in the module during normal operation is generated within the solar cells. The heat, initially concentrated within the Sliver® cells in the spaced array of Sliver® cells, spreads out by conduction through the encapsulant and the glass to the module surfaces. A very small proportion of heat is lost from the module surface by radiation. However, any heat radiated from the cells is absorbed by the glass since glass is opaque to infrared radiation at these wavelengths. At the module surfaces the heat is carried away, predominantly by conduction and convection. A very small quantity of heat is lost by radiation from the module surface because the temperature is low and the emissivity of the clean glass surface is also quite low.

Convective heat transfer is the dominant process for removing heat from the module. Due to the fact that Sliver® cells are narrow and spaced at roughly the width of a Sliver®, the heat sources are localized within the module. However, the flow of heat, spreading laterally through the encapsulant and glass from the Sliver® cells, results in quite a uniform module surface temperature. Infrared images of a Sliver® cell module, operating under normal conditions, show that the surface temperature of the glass above the cells and above the spaces is similar, to within 1 to 2°C. This even spread of heat at the module surface results in efficient cooling of Sliver® modules.

5 EXPERIMENTAL RESULTS

In one set of experiments, the temperature coefficient of Sliver® cells with V_{oc} of about 660mV was measured to be around 2.09mV/°C. This is in good agreement with the theoretical predictions of equation (1). The temperature coefficients of recently produced Sliver® cells, which have V_{oc} values in excess of 680mV, have been measured by Sandia National Laboratories. These Sliver® cells were arranged in 12 parallel strings of 85 cells per string. The module area was 0.147 m² with a nominal 50% cell coverage. The aperture-area efficiency of this prototype production module was reported by Sandia to be just over 13%. Another prototype, with closely-packed Sliver® cells providing an effective 100% cover, was reported by Sandia to have an aperture-area efficiency of about 17.7%.

Based on the V_{oc} measurements performed by Sandia at 1000W/m² illumination and a cell temperature of 50°C compared with the V_{oc} measurements at the same illumination intensity and 25 °C cell temperature the temperature coefficient was determined to be 1.44 mV/°C. It is important to note that there is some voltage boost because of the small increase in the effective

illumination falling on the Sliver® cells. This results in a power temperature coefficient for the prototype module of -0.24%. The Sliver® cells in this module had an average V_{oc} of 689.2 mV under SRC conditions.

A similar result was obtained for the 100% cover prototype module. Operating at 1000W/m² illumination and a cell temperature of 50°C compared with the V_{oc} measurements at the same illumination intensity and 25 °C cell temperature the temperature coefficient for the 100% cover module was 1.62 mV/°C. This results in a power temperature coefficient for the 100% cover prototype module of -0.24%. The Sliver® cells in this module had an average open circuit voltage of 684 mV under SRC conditions.

While these results highlight the favourable attributes of Sliver® cells, care needs to be taken in their interpretation. The Sandia experiments were not directly aimed at determining cell or module power thermal coefficients. There was no direct attempt to measure the actual Sliver® cell temperatures.

The ASTM measurement procedures for determining thermal coefficients specify that temperature coefficients are determined using a standard solar spectral distribution at 1,000 W/m² irradiance. No attempt was made to adjust the irradiance so that the intensity reaching a Sliver® matched the effective intensity reaching a conventional cell in a conventional module structure. The bifacial nature of the Sliver® cells and the structure of the Sliver® cell module further complicate any strictly comparative approach because the radiation intensity reaching each side of the cell is unequal.

In the case of modules and large arrays of cells, the temperature coefficients should be directly related to measurements for the component cells. Care should be taken to avoid systematic conditions such as non-uniform temperature distributions, or temperature measurements that do not indicate actual cell temperatures.

In particular, problems can arise where the outer region of the cell that is being measured operates at a lower temperature than the central region where the temperature is being monitored. This can result in temperature coefficients that are up to 20% smaller than true values obtained where the entire cell is at a uniform temperature [4]. While this problem is obviously a matter of scale it should not be assumed that the matter is more easily dealt with for sliver cells than for large-area conventional cells.

Other test modules with 50% cell coverage were measured at Sandia National Laboratories. A 580cm² Sliver® cell module, with a measured efficiency of 12.3% under standard rated conditions, 1000 W/m² illumination intensity and a cell temperature of 25°C, was used to determine cell operating temperature. Under PVUSA PTC conditions, 1000 W/m² and 20 °C ambient temperature and 1 m/s wind speed, the cell operating temperature was 42.6°C ±2.8°C. This compares to typical module operating temperatures under these conditions of around 50°C, obtained from data taken from the Sandia database on the performance of a range of commercial c-Si modules. The Sliver® cell temperatures were calculated from the module performance results.

In order to more directly determine the module temperature response, Sliver® cell modules have been fabricated with very thin thermocouple wires which were embedded in the module and bonded to the back of the

cells in order to be able to directly measure the cell temperature. A 50% cell coverage fraction and a suitable lambertian reflector with an excellent reflectivity of greater than 90% was used. The cells were electrically interconnected and encapsulated between two sheets of glass. For comparison purposes, reference c-Si modules were constructed using commercial 120 mm square multicrystalline cells. A thermocouple was attached to the middle of the back of the cells using thermally conductive adhesive. The prepared cell assemblies were laminated to the rear of a 3 mm thick glass and the assembly encapsulated with EVA and a Tedlar backing.

The performance parameters of the modules, as a function of cell operating temperature, were obtained using an IV curve tracer on a sunny day. Table I summarises some of the key results. The operating temperature of the Sliver® module following 30 minutes exposure to sunlight was about 5°C lower than that of the reference modules. Together with the reduced temperature sensitivity of Sliver® cells, this resulted in significantly lower performance degradation.

Module	Initial		After 30 min		% Change
	T°C	Eff%	T°C	Eff%	
Sliver® Module	25.4	11.5	50.9	10.7	-7.0
Reference Module 1	23.2	10.7	56.0	9.3	-13.1
Reference Module 2	23.8	11.5	55.9	9.6	-16.5

Table I. Summary of the comparison of operating efficiencies of conventional and Sliver® cell modules functioning in hot and cold states. Ambient temperature was 26 °C. Measurements were performed on a calm day.

Additional measurements were performed on a windy day. Under windy conditions, the temperature of the conventional and the Sliver® module was the same at 50°C. This is probably as a result of more efficient cooling of the rear of the conventional modules under windy conditions, compared to the Sliver® module. However, the reduction in efficiency of the Sliver® module, -6.7%, was still less than that of the reference modules, -11.7%, for the reference module M1.

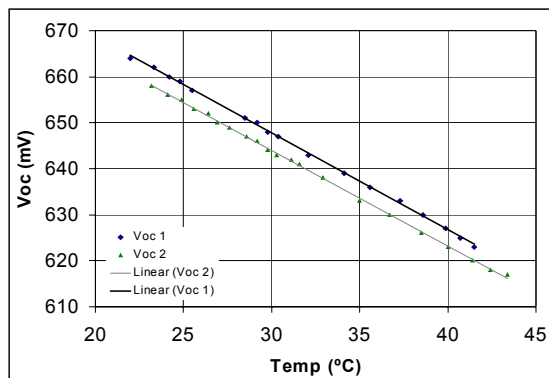


Figure 4. Open circuit voltage as a function of temperature for Sliver® cells 1 and 2 measured dynamically during module heating. The data are fitted with a linear least squares fit.

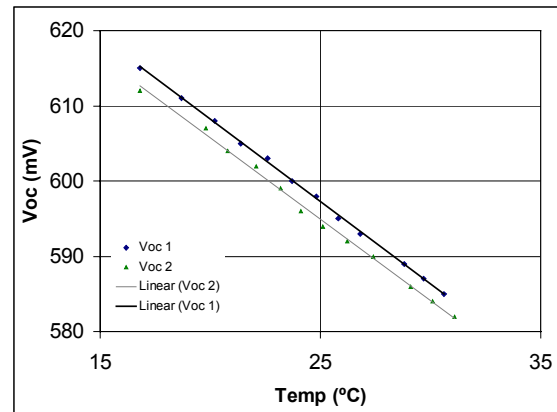


Figure 5. Open circuit voltage as a function of temperature for conventional module C3 (Voc1) and C4 (Voc2) measured dynamically during module heating. The data are fitted with a linear least squares fit.

An additional Sliver® cell module was constructed, similar to the test module reported above, but where individual Sliver® cell temperatures and open circuit voltages could be directly measured. Two conventional modules were also prepared so that a similar set of measurements could be obtained.

The individual Sliver® cell temperature coefficients from the data in Figure 4 was $-2.09 \text{ mV} \cdot ^\circ\text{C}^{-1}$, or -0.32% , and for the entire module $-1.90 \text{ mV} \cdot ^\circ\text{C}^{-1}$ per cell or $-0.29\% \cdot ^\circ\text{C}^{-1}$. For conventional modules C3 and C4, Figure 5, the value for C3 was $-2.20 \text{ mV} \cdot ^\circ\text{C}^{-1}$ and for C4 was $-2.19 \text{ mV} \cdot ^\circ\text{C}^{-1}$ or $-0.37\% \cdot ^\circ\text{C}^{-1}$ @ 25 °C. These results, obtained from measurements during module heating, avoid systematic errors and significantly reduce the problem associated with non-uniform cell temperatures.

6 ACKNOWLEDGEMENTS

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