

HIGH PERFORMANCE CHARACTERISTICS OF SLIVER[®] SILICON SOLAR CELLS

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ABSTRACT: SLIVER cells are an innovative silicon solar cell technology that has been commercialized by Origin Energy Solar from research at the Australian National University. SLIVER technology allows for large reductions in silicon consumption compared to conventional crystalline silicon technology as well as other benefits. Cells are manufactured on thin (~50 micron) 1-2mm wide silicon strips produced by a micromachining process. SLIVER cells have many high performance characteristics including excellent efficiencies, high open circuit voltages, bifacial illumination response and good tolerance of reverse breakdown. These and other features allow the development of novel SLIVER module structures that can further decrease silicon usage. SLIVER technology should decrease silicon feedstock requirements to around 1 tonne per MW of peak module power in the foreseeable future.

Keywords: Silicon, High-Efficiency, Feedstock

1 SLIVER CELL CONCEPT

An innovative processing technique for the manufacture of thin monocrystalline silicon solar cells has been invented at the Centre for Sustainable Energy Systems at the Australian National University (ANU), and is being developed and commercialised by at Origin Energy Solar's pilot facility in Adelaide, Australia [1-4]. The new technology allows for decreases in silicon usage to as little as 1¹/₂ tonne per MW so that dramatic amounts of silicon feedstock can be saved. In addition, it allows for a significant reduction in the numbers of wafers processed to as few as 13 000 per MW through increases in the useable wafer surface area and module design. These factors allow the use of standard moderate quality to high quality silicon and sophisticated wafer processing that enable high cell efficiencies while still obtaining significant \$/Wp cost savings.

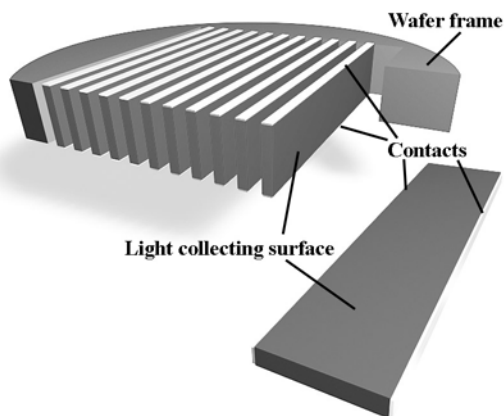


Figure 1. Micromachined wafer containing SLIVER cells. SLIVER cells are supported by the wafer frame.

The new SLIVER cell process uses a micromachining technique to form deep narrow grooves perpendicular to the wafer surface. The grooves are typically less than 40 micron in width after micromachining through the thickness of a 1mm thick silicon wafer. The result of this micromachining is a large number of thin (~50 microns) silicon strips in the centre of the wafer, held together by the unetched surrounds of the wafer. On 1mm thick, 150mm diameter wafers, there are approximately one thousand strips 80-

120mm long, 1mm wide (wafer thickness) and 50 micron thick. The SLIVER cells are constructed on the narrow strips of silicon formed during the micromachining. Cell processing is completed while the silicon strips are still supported by the silicon substrate at the edge of the wafer. The area of the cells when laid out flat vastly exceeds the area of the original wafer with proportional increases in output power per wafer processed. The cells are also very thin, dramatically decreasing the silicon required per watt of power produced.

2 SLIVER CELLS

SLIVER cells have demonstrated many high performance characteristics

- High cell efficiency exceeding 19%
- High open circuit voltage (685mV) leading to reduced power loss at elevated temperatures (0.3%/°C)
- Excellent spectral response due to the two collecting junctions and low device thickness (modelled IQE near unity even for lifetimes down to several microseconds)
- Low grid shading due to edge metallisation
- Bifacial cell with identical front and rear performance
- Low reverse breakdown voltages enabling series connection without bypass diodes
- Excellent near lambertian light trapping (effective path length enhancement of four) allowing good currents even in 50µm thick devices
- Very high power to weight ratios (>1.375 kW/kg)

2.1 The SLIVER cell design

SLIVER cells are manufactured while the narrow silicon strips are supported by the frame of ungrooved wafer. The cells are processed with many of the high performance characteristics of record efficiency device structures, such as heavy doping under the contacts, lightly doped emitter with good surface passivation and surface texturing. A schematic of the cell structure can be seen in figure 2. Heavy phosphorous and boron diffusions are applied to top and bottom surfaces of the

wafer. These wafer surfaces become the long narrow edges of the silicon strips and therefore the cells. The sides of the grooves are textured using a novel texturing technique that has been developed at ANU and which offers near lambertian light trapping properties. The grooves are then diffused to form the emitter and passivated. The edges are subsequently metallised to form the base and emitter contacts.

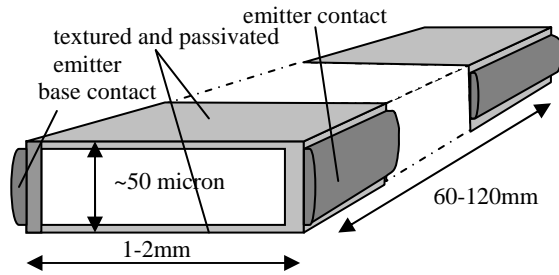


Figure 2. SLIVER cell schematic

After processing, the cells are removed from the wafer frame. The resulting cells are long, narrow and thin. The cells may be illuminated towards either side of the silicon strip (i.e. the largest surface area). Since the cell processing is symmetric, the cells are perfectly bifacial – that is, the cell characteristics are identical from either side. Cells also have low reflection losses since the metal contacts are on the sides rather than the front and rear surfaces.

2.2 Texturing

Texturing is important for all silicon cells to improve light trapping in the silicon since silicon, as an indirect band semiconductor, is a poor absorber of light near its bandgap. SLIVER cells are not well suited to conventional texturing techniques. The surfaces that need to be textured are within the grooves on the wafers, are smooth and the crystal surface orientation tends not to be suited to conventional isotropic and anisotropic textures.

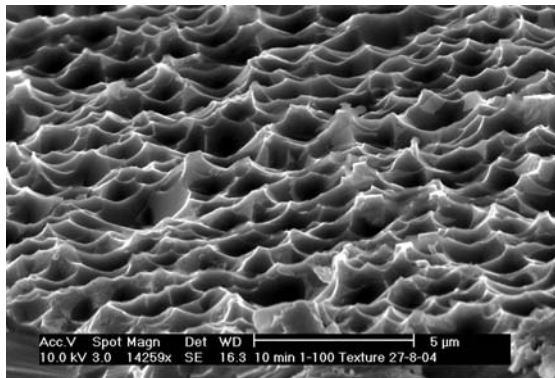


Figure 3. Silicon surface covered with etch pits from texturing process

A texture suitable for SLIVER cells (and other technologies) was developed and patented [5]. A thin layer of material with some thickness variation is deposited onto the silicon. An isotropic etchant with high selectivity over that layer then is introduced. The

etchant will reach bare silicon at the thinnest points in the layer first, opening up round etch pits. Etching continues until the silicon surface is covered with etch pits (figure 3).

This texture produces near lambertian reflection within the silicon. The average pathlength enhancement in the silicon is better than a factor of four. Therefore a textured 50 micron thick sliver cell absorbs more light than an untextured 200 micron thick cell. Reflection is also reduced by the texturing either by direct reflection of light onto another cell surface in areas of high slope or, in areas of moderate slope, by total internal reflection of light from the front cover glass after encapsulation (light trapping with the module). The texture is therefore more effective at controlling reflection in the module than it is in air. The texturing process boosts peak module performance by more than 13% when compared to modules made from planar SLIVER cells.

2.3 SLIVER cells at Origin Energy Solar

The measured IV curve from a typical textured sliver manufactured at the Origin Energy Solar facility can be seen in figure 4. The cell was measured in-house in air under nominally AM1.5g conditions. The tested cells were 77mm long, 1mm wide and about 65um thick. The key cell characteristics are an open circuit voltage of 675mV, fill factor of 78.0% and short circuit current of 28.0mA. Cell currents are small compared to conventional cells due to the small area of the cell, in this case 0.77cm². Fill factor losses are due in part to series resistance losses in the bulk and emitter and non-ideal recombination ($n>1$).

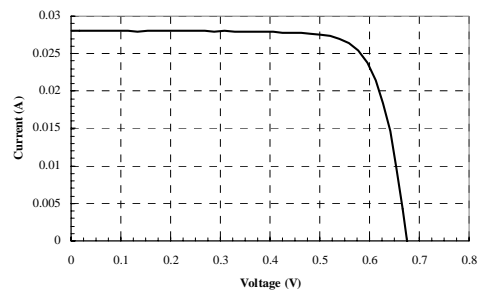


Figure 4. IV curve from a textured SLIVER cell.

Flash Voc measurements of fill factor were around 81%. This fill factor change matches the expected 4% resistive losses due to the 1mm movement of majority carriers through the emitter and the bulk while there is very little loss in the metal contacts. An ideal cell of this quality would expect to have a fill factor from flash Voc measurements greater than 84%. Non-ideal recombination ($n>1$) appears to be occurring at the ends of the cells where the cells are removed from the wafer frame. Snapping cells into shorter lengths leads to decreases in fill factor with little effect on Voc. The intersection of the junction region with the unpassivated end surface appears to explain the ideality at maximum power.

The power temperature coefficient of SLIVER cells is lower than that of conventional cells (0.3%/°C). This lower decrease in power with temperature is due to the higher voltage of the cells [6].

Cell current is very difficult to accurately

measure for individual SLIVER cells. Cells are long and thin so small (~1mm) spacial non-uniformities in the illumination have more impact than with conventional cells. Some of the SLIVER cells benefits such as edge contacting and bifacial response make cells incompatible with conventional measurement systems. Baseline current measurements have been conducted outdoors using calibrated reference cells to determine the incident light intensity. In addition, the texture for SLIVER cells that has been developed is designed to work effectively after encapsulation, through total internal reflection of light. This is not an issue in the module where the adjacent cells can absorb this reflected light but can lead to overestimates of reflection losses from individual encapsulated cells. Therefore cell current and efficiency results reported here have significant uncertainty, but are supported by module performance results.

However, internal quantum efficiency measurements of SLIVER cells do provide some insight into the current potential of the SLIVER structure. Figure 5 shows the spectral response measurements of an early 75micron thick SLIVER solar cell with 155nm oxide surface passivation (This is not a textured cell. Spectral response measurements of textured cells will be presented in future publications.) Carrier collection in the area measured (long thin aperture in centre of cell away from contacts) is effectively one dimensional so the cell was modelled with PC-1d with a collecting junction on each side of the 75 micron cell. Emitter saturation currents were set at $5 \times 10^{-14} \text{ Acm}^{-2}$ and the bulk lifetime adjusted to fit the cell voltage. The PC-1d model provided a good fit of the external quantum efficiency measurements and demonstrates the excellent internal quantum efficiency of the SLIVER cell design. The dip in spectral response beyond 900nm is due to the poor absorption in a thin silicon cell. Texturing would be expected to shift this dip to 1000 nm.

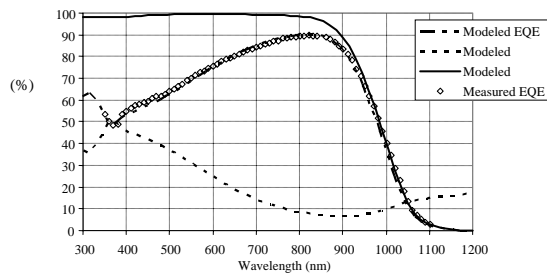


Figure 5. Spectral response of a planar SLIVER solar cell (not textured).

2.3 Bulk lifetime impact on SLIVER cell performance

The SLIVER cell structure offers the opportunity for high cell voltages. The emitter and base contact each cover less than 3% of the cell surface and can be independently doped for optimal passivation of the metal contacts. The cell voltage will be capped more by material quality than surface recombination for most grades of silicon.

SLIVER cells have demonstrated extremely good open circuit voltages on float zone material (~685mV). This indicates the high quality of the surfaces of the device through the passivation of the emitters and the

heavy diffusions under the limited area contacts in the cell design. Bulk recombination starts to become significant when the thickness divided by the product of the bulk doping and the bulk lifetime ($W/N_A \cdot \tau$) is greater than around $10^{-15} \text{ cm}^4 \text{ s}^{-1}$.

SLIVER cells are capable of near unity carrier collection efficiencies even for moderate material quality. Cells benefit from collecting junctions on both sides of the device, effectively halving the distance any carrier must diffuse to be collected. Surfaces are controllably diffused and well passivated (as confirmed by the high cell voltages and good short wavelength IQE). Provided that the diffusion length of carriers is more than about double the device thickness, then more than 99% of carriers generated will be collected. Bulk lifetimes need to drop to less than $5\mu\text{s}$ for cell lifetime to significantly impact cell current.

The relative impact on current and voltage on changes in cell efficiency due to lifetime changes can be seen in figure 6. This graphic summarises the results from an analytical model of the impact of lifetime on a $50\mu\text{m}$ thick 0.5 ohmcm solar cell. The cells are assumed to have a 10% total reflection loss and a voltage cap due to surface recombination of 685mV. SLIVER cells have been modeled from a bulk lifetime of $1\mu\text{s}$ up to 1ms and then the cell characteristics normalised relative to the best (1ms lifetime) cell. The best cell has a voltage of 683mV, 78.7% fill factor, 36.4 mA/cm^2 short circuit current density and efficiency of 19.6%. For comparison, the modeled cell with $1\mu\text{s}$ lifetime has 598.2mV, 78.6%, 34.24 mA/cm^2 and 16.1% for V_{oc} , FF, J_{sc} and efficiency respectively. As discussed above, efficiency is independent of lifetime for lifetimes greater than $100\mu\text{s}$, decreases because of voltage loss between $5\mu\text{s}$ and $100\mu\text{s}$ and then drops due to both current and voltage decreases at lower lifetimes. The loss in voltage and current at low lifetimes could be offset by decreasing the device thickness.

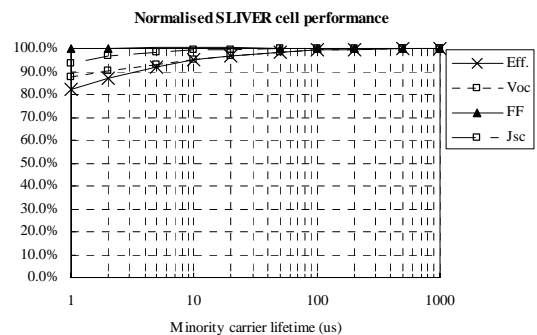


Figure 6. Modeled impact of bulk lifetime on SLIVER cell characteristics. Cell current is almost independent of lifetime for lifetimes greater than $5\mu\text{s}$ while bulk recombination impacts cell voltage for lifetimes less than $100\mu\text{s}$.

2.4 Low reverse breakdown characteristics

The SLIVER cell architecture has allowed simple design modifications to enable safe reverse breakdown of the cell even under extreme operating conditions. While an ideal diode theoretically blocks current in the reverse direction, in reality current begins to flow when the voltage becomes large enough for carriers to tunnel

across the junction or avalanche due to the large electric field. The voltage is typically large compared to the normal operating voltages of the cell

Reverse breakdown can occur in solar cells when a significant reverse voltage is applied to the cell. This can happen during routine operation when the module is partially shaded. Cells that are shaded have reduced current proportional to the fraction of the light available compared to the other cells in the string. If the shaded cells cannot produce enough current to maintain the string at string voltage then the voltage on the shaded cell decreases while the voltage increases on the other cells. In extreme cases, reverse voltages between maximum power voltage and open circuit voltage of the module may be applied to a single cell. Fault conditions in the external power circuit can also lead to reverse breakdown of cells.

In conventional cells large amounts of power can be dissipated in the cell leading to excessive heating of the cells causing cell or module material failure. Typically, modules incorporate by-pass diodes to prevent build up of voltages.

Reverse breakdown protection (RBP) of SLIVER cells can be engineered into the cell design by controlling the locations and weight of the diffusions on the cell. Initial SLIVER cell designs broke down at the unpassivated ends of the cells where the cells were removed from the wafer frame at the end of the process. Cell temperatures were recorded in excess of 160°C (figure 7a) at the cell ends at moderate currents (0.1A or 3x Isc). The cells heated significantly at the ends due to the localised nature of the breakdown and the resistive losses associated with current crowding.



Figure 7a: SLIVER cells without reverse breakdown protection (RBP) breakdown at one end and heat beyond 160°C at currents around 3x Isc (100mA)

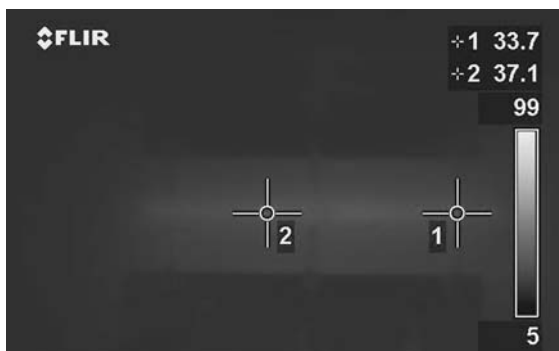


Figure 7b: SLIVER cells with RBP show little heating (<40°C) at 3x Isc (100mA).

By modifying the SLIVER cell design to allow the emitter to contact the heavy base contact doping along the entire length of the sliver cell, reverse breakdown voltages are reduced and the cell now breaks down along the entire length of the cell in preference to the ends. This reduces heating from the breakdown process because the current is distributed along the entire cell length. Resistive heating is also minimised since the entire cell width is conducting the current. Cell heating was reduced to below 40°C at 3x Isc (0.1A) and cell temperatures were only 80°C at 15x Isc (0.5A), as shown in figures 7b and 7c.

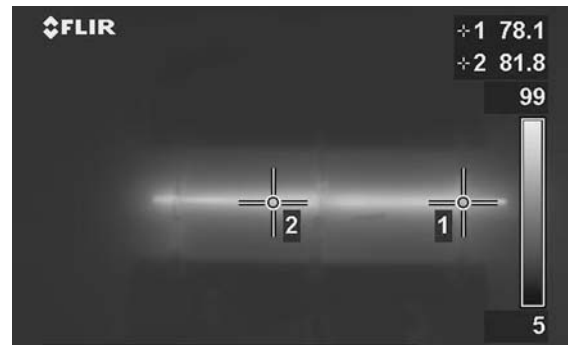


Figure 7c: Heat is dissipated along the entire length of the SLIVER cell when RBP is incorporated. At 15x short circuit current (0.5A), peak temperatures are around 80°C.

3 SLIVER MODULES

The unique shape and size of the SLIVER cells and the bifacial response to illumination allows for the development of novel designs for SLIVER modules.

In particular, significant additional savings in the quantity of the silicon required per watt of power output can be obtained by spacing the SLIVER cells in the module and incorporating a scattering reflector at the rear of the module. A schematic of such a structure can be seen in figure 8. Light that passes between the cells that is scattered by the rear reflector may strike the rear of a bifacial SLIVER cell or may be totally internally reflected by the front glass for another chance to be absorbed.

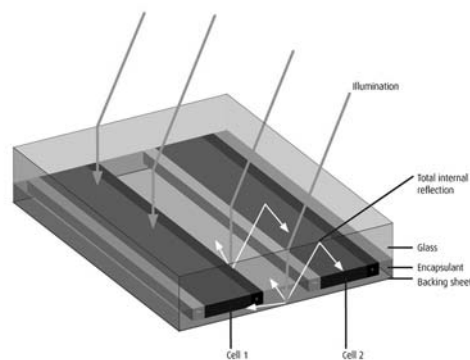


Figure 8. SLIVER module design incorporating a rear reflector with the cells spaced out to reduce silicon usage.

This structure is remarkably efficient at recovering the light incident between cells. Removing every second cells leads to a decrease of 15% in module power, but

only requires 50% of the silicon. An optimisable trade off between module efficiency and silicon usage exists. This is an additional silicon and wafer saving on top of the original savings gained through the cell manufacturing process.

First generation commercial SLIVER modules from the Adelaide plant are biglass. Modules have a nominal output of 15W and 40W and have been engineered to produce 17V at maximum power. A layout for a 15W module can be seen in figure 9. Banks of 35 cells are connected in series to produce the desired voltage output then banks are connected in parallel. Modifying the voltage output from the panel is simply a matter of increasing the number of cells in a bank and increasing current is simply a matter of increasing the number of banks connected together. This provides tremendous flexibility of the module output characteristics.

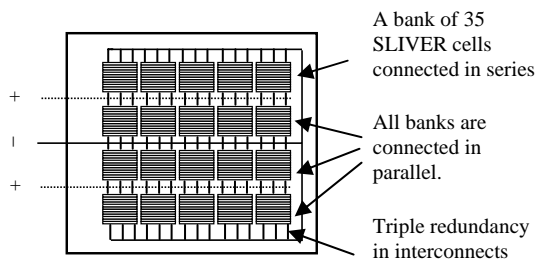


Figure 9. Schematic of the series-parallel connection scheme for a SLIVER module.

The module design is robust and has demonstrated excellent performance under accelerated aging tests. 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. Details of these test results are reported elsewhere at this conference [7].

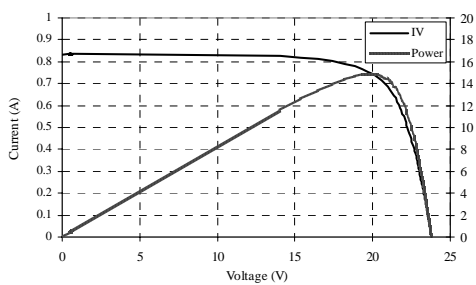


Figure 10. IV curve for a biglass 15W sliver panel.

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. Increasing the module size to produce higher power or different current-voltage properties is straight forward. 15W, 35W and 70W prototype panels have been constructed with planar cells. A similar performance boost (13%) is expected with the inclusion of textured cells.

Small scale production of modules is due to commence in the second half of 2005. A more detailed update on the pilot facility for manufacturing SLIVER

cells and modules is presented in another paper at this conference [8].

4 SILICON SAVINGS with SLIVER TECHNOLOGY

The features described in the earlier sections describe the attributes of SLIVER technology that enable tremendous reductions in the silicon feed stock consumption and the processing effort required.

Our projected technological development pathway has been modelled below to demonstrate the potential of the technology to provide dramatic cost savings. The key fixed assumptions are that the wafers used are 150mm diameter, kerf loss is 300µm and 80% of an ingot is waferable. The scenarios model our current (pilot), scale up and foreseeable expectations of SLIVER technology development.

The variable assumptions for the silicon use are captured in table 1. The pitch or spacing of the SLIVER cells on the wafer determines how many cells will be produce for a given area of wafer. Increasing the number of sliver lengths increases the fraction of the wafer that can be utilised to make SLIVER cells and decreasing the cell coverage in the module decreases the silicon usage with a small sacrifice in module efficiency.

Timing	Pilot	Scale up	Forseeable
Pitch	120 µm	100 µm	90 µm
Sliver lengths	1	2	>2
Wafer thickness	1mm	1mm	2mm
Module coverage	50%	50%	50%
Module efficiency	13.3%	14.0%	14.0%

Table 1. Technical assumptions for SLIVER silicon use projection.

The expected silicon usage for each scenario is shown in figure 11. With the current production set up at the Origin Energy Solar facility in Adelaide, SLIVER technology can be expected to produce modules with a feedstock requirement of around 3 tonnes per MW of SLIVER module production. Through decreases in SLIVER cell pitch, slight cell efficiency improvements and improved wafer utilisation this can be expected to decrease to slightly more than 1½ tonne per MW in the foreseeable future. Feedstock consumption for conventional modules is included for comparison [9]. These savings translate into significantly lower dependence on silicon in the total module cost.

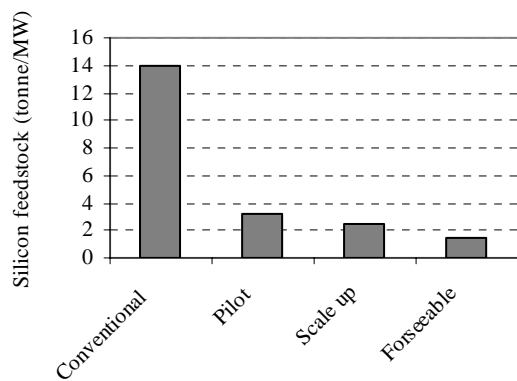


Figure 11. Silicon feedstock requirements for SLIVER modules.

The number of wafers required to be manufactured to produce each MW of SLIVER modules is expected to decrease even more dramatically. In addition to the gains discussed in the silicon usage, wafer throughput decreases further through increases in wafer thickness to 2mm. Already, each wafer produced in the current Origin Energy Solar pilot facility is capable of producing 18W of module power. Within a few years it is expected that almost 75W of module power will be produced from every wafer. A SLIVER module factory will need to process only of the order of 13 000 wafers for each MW of modules produced. In comparison, conventional cell technology (2.5W to 3W per wafer) requires of the order of 350 000 wafers to produce the equivalent power.

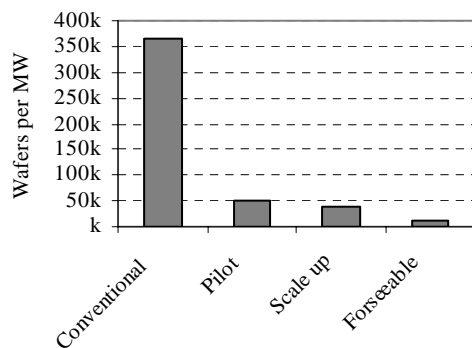


Figure 13. Factory wafer throughput requirements to produce SLIVER modules.

5 CONCLUSIONS

SLIVER technology is a monocrystalline silicon technology that has the potential for dramatically reducing the cost of manufacture of solar modules through silicon savings and reduced wafer throughput requirements. SLIVER cells have many high performance characteristics including high efficiencies, excellent tolerance of varying material quality, bifacial nature and low shading. The nature of the SLIVER cells allows novel module designs that make benefits from these features. The technology has the potential for decreasing the silicon feedstock requirements to around 1½ tonne per MW while still maintaining good performance due to the excellent cell performance.

Acknowledgments

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