RECENT DEVELOPMENTS IN SLIVER CELL TECHNOLOGY

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ABSTRACT: SLIVER cells, which were invented and developed at the ANU, allow the production of thin silicon cells and modules from standard silicon wafers, without the requirement for silicon deposition or any other expensive steps. Reductions in silicon consumption by a factor of 7-12 and reductions in the number of wafers that need to be processed per MW of a factor of 12-40 are possible. SLIVER cells are fabricated with sophisticated processing on high quality single crystal silicon substrates. SLIVER cell efficiencies above 19% are the highest reported for any commercially-viable thin-film cell. In this paper we report that a new SLIVER process has been devised that has the potential to double the throughput of a factory compared with the older SLIVER process.
Keywords: c-Si, Thin Film, Cost reduction

1 INTRODUCTION

Crystalline silicon wafers account for 90% of the photovoltaic (PV) market. However, the cost and availability of the silicon remains a major barrier to reducing the cost of crystalline silicon photovoltaics.

Improvements in silicon usage in conventional ingot based technology have arisen through improved wafer sawing to reduce kerf losses and decrease wafer thickness. These changes are incremental and are limited by processing yield.

Substantial decreases in silicon usage requires a different approach. A variety of techniques producing thin layers of crystalline silicon have been developed [1-3]. Each has limitations in material quality or yield due to the silicon manufacturing technique.

A new technique for producing thin monocrystalline silicon solar cells was invented [4] and developed [5-9] at the Centre for Sustainable Energy Systems at the Australian National University (ANU) with substantial financial support from the Australian company Origin Energy. The new technology allows for large decreases in silicon usage by up to a factor of 10 (including kerf losses). In addition, it allows for a large reduction in the numbers of wafers processed per module by up to a factor of 40 compared to standard crystalline silicon technology, These factors allow the use of moderate to high quality silicon and more complicated wafer processing that can realise high cell efficiencies while still obtaining significant $\$/W_p$ cost savings. In this paper we describe the major features of this technology and present some of the performance results that we have obtained so far.

2 THE SLIVER CELL CONCEPT

SLIVER solar cells are fabricated using 1-2mm thick silicon wafers. The wafers preferably have a high minority carrier lifetime (such as FZ or MCz or Cz:Ga) to take advantage of the high efficiency potential of SLIVER solar cells.

A key step in SLIVER cell processing is to form deep narrow grooves all the way through the wafer (Figure 1). A variety of techniques can be used. A laser or a dicing saw can be used to cut through the wafer using a narrow or guided laser beam or narrow dicing saw blades. Anisotropic etching using KOH is widely used in the micromachining industry in applications such as this. Another option is Bosch Etch, a high-speed plasma process developed specifically for the creation of deep and narrow grooves. Other methods are also possible. Several methods have been used to reliably create multiple narrow (<50µm) grooves through 1mm thick wafers on a pitch of 100µm.

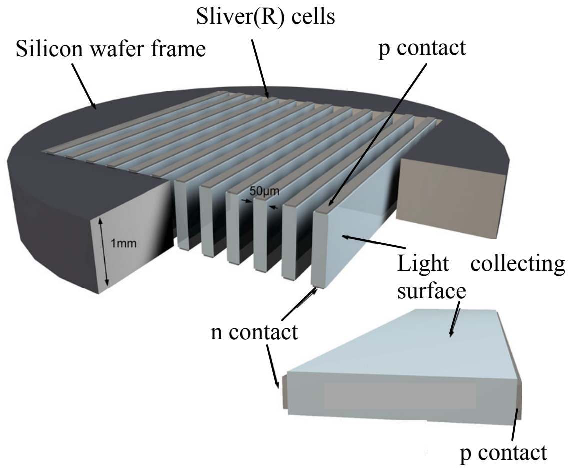

Figure 1: SLIVER wafer. Long thin silicon slices are supported by the wafer frame.

The grooves typically have a pitch of 100µm and a width of 40µm, which allows the SLIVER cells to have a thickness of 60µm. A 1.5mm thick 150mm diameter wafer would have about 1000 SLIVER solar cells with a combined surface area of about 1,500 cm^2, compared with the area of a conventional solar cell fabricated using the wafer of $177cm^2$.

Cells are constructed on the narrow strips of silicon formed during the grooving process. Cell processing (diffusion, oxidation, deposition) is completed while the silicon strips are still supported by the silicon substrate at the edge of the wafer.

The wafer surfaces become the long narrow edges of the silicon strips and therefore of the cells. The edges are subsequently metallised to form the p-type and n-type contacts. After processing, the cells are removed from the wafer frame and laid on their sides (the groove sidewalls). The resulting cells are long, narrow and thin. Typical SLIVER cell dimensions are 50-100mm long, 1-2mm wide and 40-60µm thick. Since the cell processing is symmetric, the cells are perfectly bifacial.

The cell structure has the potential for excellent cell efficiencies. The cell is thin and there are collecting junctions on both sides of the cell. The emitter is lightly doped and the surfaces are well passivated. Therefore the cell has unity collection efficiency, even with low quality silicon.

The cell structure offers the opportunity for high cell voltages. The n and p contacts each cover only ~3% of the cell surface (at the two edges) and can be heavily doped for optimal passivation and contact resistance of the metal contacts.

On cells processed on FZ wafers, open circuit voltages are in the range 670-690mV showing that the cells are very well passivated. Efficiencies above 19% have been achieved.

3 STATIC CONCENTRATION

SLIVER cells differ radically from conventional cells in size and shape, being long, narrow, thin and perfectly bifacial. This allows further silicon reductions through the use of novel module designs incorporating rear reflectors. A simple design approach is to introduce a Lambertian reflector at the rear of a bi-glass module. The cells are positioned between the two layers of glass or other suitable material, spaced by a multiple of their width (typically from 1.5 to 3) (Figure 2).

Some of the light scattered from the rear reflector is directed onto the rear surface of the bifacial SLIVER cell while another fraction of the light is reflected onto the glass where it is totally internally reflected back into the module. The remainder of the light is lost through the front glass. Conventional cells cannot use this technique because it relies upon the cell width being similar to the thickness of the rear glass layer.

For cells spaced at double their width, the performance ratio of the structure is about 79%, that is, 79% of the light entering the module is captured relative to a module with 100% cell coverage, in return for using only 50% coverage of silicon. With 3-times spacing 62% of the light in the module is captured in return for using only 33% coverage of silicon. Modeling indicates that, for a cell width of 1mm, the performance ratio is independent (to within 1%) of front sheet thickness and direction of incidence of sunlight for a rear sheet thickness of 3mm.

The ability to easily trade module efficiency for module cost by adjusting the coverage fraction of the SLIVER cells has important commercial implications.

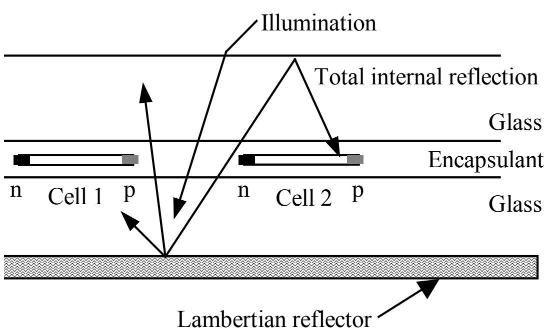

Figure 2: Lambertian reflector module design. The small width and bifacial nature of the SLIVER cell enables the cells to be spaced out (in this case double cell width, halving silicon use).

4. SIMPLIFIED WAFER PROCESSING

Complex wafer processing is expensive. For a given wafer throughput a more complex process will entail a larger fabrication facility, more process equipment, higher maintenance costs and larger consumables and waste disposal costs.

A long fabrication process will generally have a lower yield than a similar but shorter process. For example, if the yield of a fabrication process is 90% then the yield of a process that is twice as long would be expected to be around 80%.

Another disadvantage of a long process compared with a short process is that development and refinement of the process is more difficult. One reason for this is that feedback takes longer. Another reason is that the problem of lower yields commonly encountered in R&D, which makes interpretation of experimental results difficult at the best of times, is exacerbated in a long process.

A fabrication process that makes repeated use of a narrow range of equipment will generally be less expensive than a similar process that requires a wider variety of equipment. One reason for this is that maintenance is less costly because spare part inventories are smaller and maintenance staff become more familiar with the equipment. A second reason is that utilisation of each piece of equipment is higher, and so fewer pieces of equipment are required.

A suitable benchmark for evaluating the process complexity of SLIVER wafers is the buried contact solar cell (BCSC) that was invented at the University of New South Wales [10] and commercialised by BP Solar. The BCSC process is more sophisticated than conventional screen-printed solar cell technology but produces higher cell efficiencies. Tube furnaces, lasers, vacuum evaporation and metal plating are typically employed in the BCSC process. Similar equipment is used in the SLIVER wafer process at ANU.

Relatively complex processing of SLIVER wafers is affordable because far fewer wafers are required per MW compared with conventional processing. However, simplification is a desirable goal. Over the last year work at ANU has focused on reducing the complexity of SLIVER wafer processing without sacrificing cell efficiency. Progress has been made which has the potential to significantly reduce SLIVER process complexity.

A comparison can be made between the New (May 2005) and Old (December 2003) SLIVER wafer processes being run in ANU's research laboratories and the BCSC process. Similar steps can be easily compared. Dissimilar steps can be evaluated for relative complexity & cost and a weighting applied if necessary. Caution must be applied to our estimates since immature and mature technologies are being compared, and surprises (pleasant or otherwise) can occur during commercial implementation of a technology.

The analysis that we performed covers the fabrication process from the purchase of silicon wafers to the testing of the finished solar cell. A step in the process sequence is defined as a set of operations that take place with the assistance of a particular piece of process equipment (such as a phosphorus diffusion) or which are similar and occur sequentially (such as a wafer-washing step).

According to our analysis ANU's Old SLIVER process has 59 steps while ANU's New SLIVER and the BCSC processes have 32 and 22 steps respectively. The Old SLIVER process requires 18 different types of process equipment compared with 14 and 12 for the New SLIVER and BCSE processes respectively. Taking into account the lower yield of a longer process, the approximate wafer throughput for a given factory size is expected to be in the ratio 28:59:100 for the Old SLIVER, New SLIVER and BCSE processes respectively.

For a given wafer throughput, a solar cell factory will produce a far greater area of completed solar cells (and hence modules) if a SLIVER rather than conventional process (such as BCSC) is employed. The area ratio (SLIVER/conventional) for completed modules lies in the range 12-40, and depends primarily upon the thickness of the Silicon wafer, the pitch of the SLIVER grooves and the coverage of SLIVER cells in the module. An advantage for SLIVER cells of a factor of 15 is achievable using conservative parameters such as 1mm thick wafers and a static concentration ratio for the module of 50% (ie 50% of the module is covered with SLIVER cells – see section 3).

Provided that the work at ANU can be successfully transferred to commercial production the approximate area of module that can be produced per year for a given factory size is expected to be in the ratio 42:88:10 for the Old SLIVER, New SLIVER and BCSE processes respectively (Figure 3).

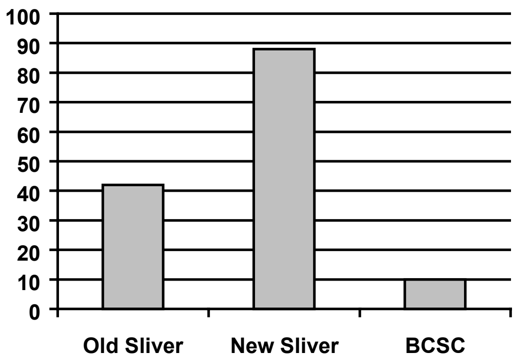

Figure 3: Modelled relative area of module produced per year for a given factory size for 3 different process sequences.

The cost of wafers for the SLIVER cell process is considerably higher than for the BCSC process: the wafers are 2-5 times thicker (although the wafer slicing cost is correspondingly reduced) and best performance is obtained from FZ wafers. However, the combined cost of wafer purchase and cell & module fabrication for the SLIVER process is expected to be below the cost of conventional processes.

An advantage of the SLIVER process over conventional solar cell processes is that the factory cost will be substantially lower per MW of capacity. This reduces the investment risk. If the New SLIVER process can be successfully implemented in a factory then we expect it to have double the throughput of a similar factory running the Old SLIVER process. It would be relatively inexpensive to convert a factory running an Old SLIVER or BCSE process to a New SLIVER process.

5 SLIVER MODULES

By connecting cells in series, it is easier to build voltage than in conventional modules where the economies of scale favour large cells. Module output can be tuned from standard 12V applications to several hundred volts for grid-connected applications. SLIVER strings with 200-400V output only require lengths of a few tens of centimetres. Strings can be connected in parallel to increase current. These high voltage modules could allow for direct conversion from DC to AC without the requirement for voltage up-conversion.

Since the cells are relatively small in area, so are the cell currents. This decreases the reverse current that any cell needs to tolerate during shading events. Modules containing strings of SLIVER cells have passed hot spot tests without by-pass diodes.

A method of packaging SLIVER solar cells has been devised that appears to have considerable advantages over previous techniques. As far as possible the method takes advantage of standard PV modularisation technology. The only materials used in the module are those found in the great majority of conventional PV modules. The module design is sufficiently close to conventional module designs that we have confidence that it will have similar reliability to conventional modules.

6 CELL TEXTURING AND AR COATINGS

If anisotropic etching is used to create the silicon strips, then standard texturisation techniques for random pyramid formation cannot be used, as the sidewalls of the strips will be of (111) orientation. Texturing is particularly challenging because the sidewalls are obscured while the SLIVER cells are still in the wafer.

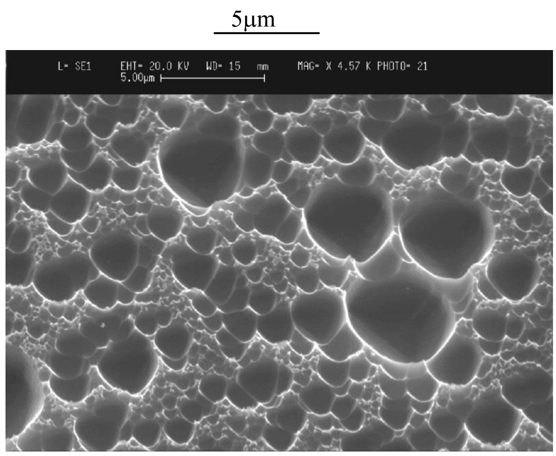

Figure 4: SEM micrograph of a textured silicon surface. The surface was polished, with (111) orientation, prior to texturing. The image was taken at a tilt angle of 45 degrees.

A novel texturing technique has been developed which is particularly suited to SLIVER cells. The technique utilises a very thin layer of silicon nitride, deposited by low-pressure chemical vapour deposition. An important feature of LPCVD silicon nitride is that it is highly conformal, coating all surfaces uniformly. The technique results in random, roughly hemispherical pits of varying sizes in the silicon surface, as shown in fig. 4.

This texture has been found to result in excellent light trapping and reflection control once encapsulated behind glass.

7. CONCLUSIONS

SLIVER PV technology offers large reductions in silicon consumption (10-fold) and wafer processing (30-fold) while maintaining all of the advantages of single crystalline silicon, including efficiency, reliability, market acceptance and the ability to borrow skills and infrastructure from the conventional IC and PV industries. SLIVER modules can be transparent, flexible, high voltage and perfectly bifacial, and can have a high power-to-weight ratio and a sharply reduced energy payback time. SLIVER concentrator cells have important advantages over conventional 10-50 sun concentrator cells.

We have been able to eliminate more than half of the process steps to fabricate a SLIVER module. The new process is capable of halving the cost of the SLIVER wafer process. The new process also halves the capital cost of a factory for a given throughput.

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