TOWARDS 20% EFFICIENT SILICON SOLAR CELLS MANUFACTURED AT 60 MWp PER ANNUM

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ABSTRACT

The LGBG technology for high efficiency cells has grown in ten years from pilot line to 60 MWp per annum manufacturing capacity. Many improvements to the manufacturing process have been achieved in labour productivity through automation, increased laser grooving speeds and the introduction of in-line processes. Progress has been made in increasing the solar cell efficiency on monocrystalline silicon solar cells from a base line of 16.2% in present production to 17% in the new facility. Pilot line cells have demonstrated 18.3% efficiency and modelling has shown 20% cells are achievable in production. A small area cell with LGBG contacts has been made with an efficiency of 20%.

1. INTRODUCTION

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The most widely used technology for the manufacture of silicon solar cells is based upon the screen-printing and firing of silver-based thick film paste contacts to the silicon surface. This technology has a number of inherent disadvantages which include high metal contact shading of the front surface due to line-width limitations, the necessity for heavily doped emitter junctions to enable Ohmic contact formation with the printed contacts, the high cost of silver as the principle conductor and the requirement for relatively thick silicon wafers to avoid warpage when thick film aluminium back surface fields are incorporated into the cell. These all limit the potential of screen printed solar cells to achieve high efficiencies and low costs.

In 1984 Martin Green and Stuart Wenham [1] invented an alternative process in which the metal contact is *buried* into grooves machined into the silicon surface. A laser was used to machine the grooves in which the base-metal copper was subsequently plated. The laboratory results for these cells showed much promise [2] but a low-cost fabrication process was required to exploit the technology. BP Solar are one of six companies to have taken options to licence the technology but are the only group to have carried the process through to commercial exploitation. The history of the development of the industrial laser grooved buried grid has been reviewed by Mason [3]. After a period of laboratory development in Australia (1986-1989), a pilot facility was established in Alcobendas (Spain) [4] and the first commercial cells were shipped in 1992. This facility has increased its production output on an almost annual basis (Figure 1) to its current capacity of 20 MWp.

In the year 2000 a decision was taken within BP Solar to plan for to further expand this technology. The former Agere Technology microelectronics plant in Tres Cantos Spain was acquired in December 2001 and construction of the first 30 MWp phase of an initial 60 MWp facility has been completed. The ultimate capacity of the site is greater than 120 MWp. This paper describes the improvements in the manufacturing technology for LGBG cells, the efficiency improvements that have been achieved in initial production and the route to achieving efficiencies of 20% in high volume manufacture using CZ wafers.

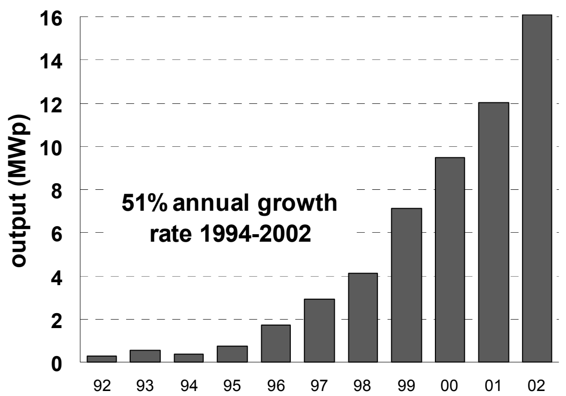

Fig. 1. Annual production output growth of the LGBG *Saturn* product.

2. THE TECHNOLOGY

BP Solar's implementation of the LGBG cell technology is marketed under the name *SATURN* and has been a highly successful product line for the company with over 50 MWp of total product sales to date. The base technology has been described in detail elsewhere [4, 5,6] but features the following principle attributes:

- random textured surface to reduce reflectance
- selective emitter for optimum spectral response and minimum contact resistance
- silicon nitride antireflection coating
- narrow (laser-machined) line width to minimise shading
- high conductivity copper metallisation

These features are illustrated in the cross-section schematic in figure 2. The base technology manufactured in the Alcobendas factory is referred within BP Solar as

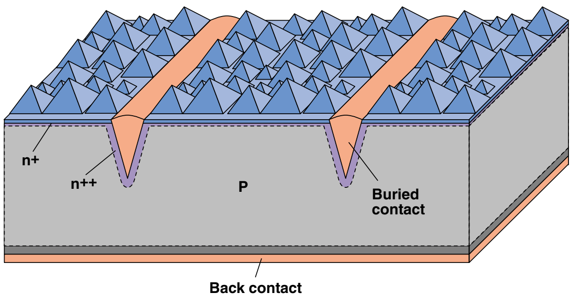

Fig.2. Cross-section schematic of LGBG Saturn solar cell

the *S0 process* and produces product with an *average* module efficiency of 13.6% (encapsulated cell efficiency 16%)

The new factory in Tres Cantos features improved processing as described in 3 below and is capable of manufacturing cells with improved efficiencies as described in 4 below.

3. IMPROVED PROCESSING

3.1 Manufacturing equipment

The existing Alcobendas facility increased capacity in a piecemeal fashion with individual work stations being added to replicate existing equipment with little automation or streamlining of the production process. In the Tres Cantos plant all process tools are automated with cassette-to-cassette wafer processing (though cassettes are manually handled between tools). A two-fold improvement in productivity (cells/operator) is anticipated but it should also lead to improved yield through reduced manual handling. Each 50-wafer plastic cassette contains an embedded microchip that automatically identifies the "batch number" to process tools and quality control instrumentation. This allows a comprehensive database to be maintained of the batch fabrication history and QC data. The manufacturing software will enable continuous statistical process control (SPC) of the production process and provide a early warning of process variance on a tool-by-tool basis.

Significant improvements have been made to the design and throughput of the laser grooving tools. The laser equipment manufacturers were challenged to double the productivity of the existing design. This was comfortably achieved with each new laser tool capable of an annual output in excess of 5 MWp. The new tools incorporate multiple beam splitting of a high power laser and fast robotic wafer transfer. The 14 metres of laser machined grooves on a 125 mm cell are completed in 18 seconds with multiple wafers processed simultaneously. This long length of grid line, compared to 2.5m in a screen printed cell gives very low contact and series resistance and is a key element in the higher efficiency of the Saturn cell.

The new Tres Cantos production facility also incorporates fully automated cassette-to-cassette wet chemical process stations for etching and cleaning wafers and electroless plating of the metal contacts. These systems have been designed to handle thin wafers in anticipation of future developments with this technology (see section 5). In-line cassette-to-cassette sputtering units are used to deposit the aluminium layer on the rear contact that replace the manually-loaded filament evaporation batch process used in the Alcobendas S0 process.

3.2 Environmental aspects

From its concept, the Tres Cantos manufacturing plant was designed to operate the CLEAN™ process. The factory is located adjacent to a nature reserve and the site is not connected to a city drain. A number of features are worthy of note.

The plant is designed to minimise water consumption through recycling. As with all semiconductor-manufacturing processes, the fabrication of silicon solar cells requires large volumes of high purity water for silicon wafer cleaning. The water treatment plant in Tres Cantos is designed to be operated with a high degree of water recycling. All exhaust emissions from the factory will pass through a series of effluent scrubbers. All liquid effluent including hydrofluoric acid and soluble metal salts will be treated on site. An on-site metal reclamation plant will treat all waste streams from the electroless plating processes.

Further longer-term improvements have been identified in minimising environmental impact by the replacement of electroless copper plating with an electrolytic process [7]

4. Improvements in Cell Efficiency

4.1 Initial Production at Tres Cantos

The efficiency of cells produced by the *S0* process at Alcobendas is limited by high rear surface recombination. The greater degree of control over aluminium thickness and uniformity afforded by the sputtering process at Tres Cantos allows improved formation of a back surface field (BSF) [8] increasing the cell efficiency. The ramp up of cell production at Tres Cantos has begun and figure 3 shows the evolution of cell efficiency with time with the improved *S1.1* process.

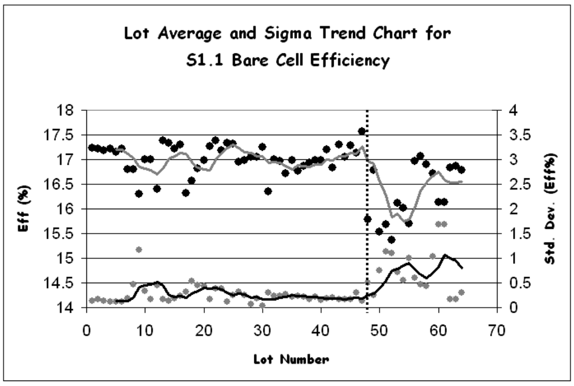

Fig.3. Lot average efficiency in start up trials at Tres Cantos

Figure 3 shows that at average cell efficiency of 17% has been achieved in the production trials and further optimisation of the process is possible.

Test modules, containing both 36 and 72, 125 x 125mm, p-square cells have been made with the results summarised in Table I.

Table I. Measured module powers in early production trials

Modules	36 cell	72 cell
#of modules	5	7
Mean power (Wp)	89	177
Highest Power (Wp)	90	179
Mean Cell Eff (%)	16.8	16.7

These early trials have confirmed the improved manufacturing capability of the new production line and the ability to manufacture 180Wp modules has been demonstrated.

4.2 Pilot line Trials

The pilot line in the UK at Sunbury on Thames is used to demonstrate new processes prior to their introduction into the manufacturing plant. Further optimisation of the improved aluminium process is possible using thicker aluminium and improved conditions for sintering of the aluminium.

The improved BSF results in cell efficiencies of over 18% Table II details the cell parameters of the best cell made to date in these trials as measured at the FhG.ISE Calibration Laboratory. This is highest efficiency for a cell of any type of this area measured at the FhG.ISE.

Table II. Cell parameters under AM1.5 global measured at the FhG.ISE Calibration laboratory.

Parameter	
Jsc (mA/cm^2	36.28
Voc (mV)	625.1
FF	.806
Eff. (%)	18.3
Area (cm^2)	147.5

A limited number of modules have been made with these cells and a 36 cell module has given a Pmax of 95Wp.

4.3 Laboratory cells and the potential to achieve 20% efficiency.

It was reported as long ago as 1988 [2] that LGBG cells could achieve 20% efficiency. However these were small area laboratory cells made on high quality float zone silicon. The challenge to meet the market demand for higher efficiency modules at ever lower costs is to use Cz material in high volume manufacturing processes. The potential to for normal commercial CZ wafers to achieve 20% efficiency has already been demonstrated in the laboratory [9] but not with the LGBG process. Detailed modelling has been carried out at FhG.ISE with real parameters measured on present production LGBG cells and with 2D modelling of current collection around the grooves improving on the modelling reported in reference [9]. It has been shown that the existing simple procedure for emitter diffusion to around 100 Ohm per square is adequate to achieve 20% efficiency. As is well known the critical parameters are front and rear surface recombination velocities and bulk recombination as measured by the minority carrier diffusion length. Wafer thickness is also important where low diffusion length silicon is used as in solar grade Cz material. The parameter space has been examined extensively. The LPCVD silicon nitride ARC used in production cells has a relatively small surface recombination velocity on the emitter surface which may be as low as 5000 cm.s^{-1} .

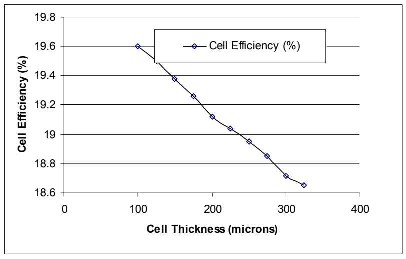

Figure 4. Modelled efficiency versus for an LGBG cell with S_{front} = 5000 cm/s; S_{rear}= 150 cm/s and minority carrier lifetime =25 µs.

Minority carrier lifetimes of 25 µs are typical for CZ wafers. High efficiency will require cells with low rear surface recombination . Figure 4 shows the results of modelling these parameters with an S_{rear} of 150 cm.s^{-1}. This shows for a relatively poor scenario efficiencies above 19% can be achieved when wafers thinner than 200 µm are used. Moderate improvement in materials quality will make 20% achievable.

To demonstrate this model, a hybrid route has been followed where cells are partly process on the industrial pilot line and other processes are carried out in a high efficiency processing clean room. The best result for a small area cell is given in Table III.

Table III. Cell measurements at FhG.ISE of an LGBG cells on 0.5 Ohm-cm FZ wafer

Parameter	Small Area	Large area
Jsc (mA.cm-^{2})	37.2	37.3
Voc (mV)	663.8	660.0
FF	.808	.792
Eff (%)	20.0	19.5
Area cm^2	4	140

The cell was fabricated on a 0.5 Ohm-cm FZ wafer. All processing was carried out at the FhG.ISE except for the laser grooving and final plating which were performed using standard industrial equipment in the BP Solar pilot line. A silicon oxide front side passivation was used together with a passivated rear surface. The Ohmic contact was defined using photolithographic techniques. Further trials will be carried out to migrate the cell processing to an entirely industrial process on CZ wafers. This result is the first step towards realising a fully industrial 20% efficient solar cell capable of large scale mass production.

5. APPLICATIONS OF LGBG CELLS.

Because of their innovative nature LGBG cells have been in demand for high profile demonstrations of photovoltaic technology. The first system was the 25 kWp power funicular railway at the Swiss Parliament in Berne, followed by 550kWp in the Toledo 1 MWp plant. Further installations include the zero energy house for the G8 summit in 1998 and the boulevard lighting for the Sydney 2000 Olympic Games Stadium. One of the most recent application is the 876 kWp segment of the 1.2 MWp plant in Navarra (Spain).

6. CONCLUSIONS

The Saturn laser buried grid solar cell process has become well established method for the mass production of high efficiency silicon solar cells. A new World class highly automated line is in the first stages of commissioning with an initial capacity of 30 MWp. The first production will be 17% efficient solar cells giving modules of 180 Wp. In the short term this cell efficiency will be increased to 18%. Modelling has predicted that near 20% efficient solar cells can be expected in the medium term with commercial grade CZ wafers and industrial processing. Proof of concept cells of 20% efficiency have been obtained.

7. ACKNOWLEDGEMENTS

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