

DEVELOPMENT OF LASER GROOVED BURIED CONTACT SOLAR CELLS FOR USE AT CONCENTRATION FACTORS UP TO 100X

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ABSTRACT

The efficiency limitations for low cost Laser Grooved Buried Contact (LGBC) silicon solar cells for concentration factors up to 100X have been modelled using a combination of a front contact model developed in-house and PC1D [1]. Cells have been designed to suit customer requirements with different concentrator system geometries and a range of concentration factors. Cell efficiencies of 18.9% and 18.5% at 20X and 30X respectively were achieved on Cz silicon cells of 40cm² active area, while for cells of 2.6cm² active area, efficiencies of 19.3% at 50X and 18.7% at 100X were obtained. Good uniformity of cell efficiency from across a large area wafer has been achieved. The limiting factors on concentrator cell efficiency is presented and ways to achieve 20% efficiency at 100Sun is discussed.

INTRODUCTION

Concentrator systems have the potential of meeting the growing demand for low-cost power generation and are particularly suited to large PV power plants. The availability of low cost concentrator cells has been one of the factors limiting the achievement of lower cost. The LGBC crystalline silicon solar cell, which is in high volume production for 1 sun modules in the BP Solar plant at Tres Cantos, is an attractive technology for the production of low-cost concentrator cells. Due to the high-conductivity buried front contact, the metallization pattern may be readily adapted to handle the larger current densities produced at higher concentrations while maintaining an acceptable shading loss. The laser writing of the front contact grooves enables the metallization pattern to be changed easily, either for optimisation of the design or the production of cells for different concentration factors as shown in figure 1.

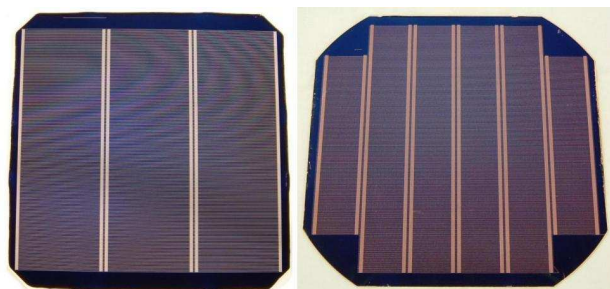


Fig. 1. Left: 3 cells, Right: 38 cells on 127mm pseudo-

square wafers, optimised for 20X and 50X respectively.

Efficiencies of 18% at 30X concentration without prismatic covers were already demonstrated in the EUCLIDES TM parabolic trough concentrator system in the 1990s [2]. Cell efficiencies of over 17% at 100X concentration have been measured by FhG.ISE on small area 1.2cm² cells laser-cut from the 30X EUCLIDES cells without further optimisation of the cell design. This paper briefly describes the in-house model used to optimise the front contact design, and presents recent experimental results of LGBC concentrator cells fabricated at NaREC designed for operation at concentration factors from 20X to 100X.

DEVICE DESIGN

In order to optimize the front contact of the concentrator cell a computer model was developed to calculate the power loss for various solar cell parameters and designs. The details of this model are described by Cole et al at this conference [3]. Several cell designs were considered, including single and double bus bar designs and two designs for a cell with bus bars along all four edges. The incident illumination for the modelling was assumed to be homogeneous. The modelling takes into account front contact losses only and compares the cell power output as a function of the resistive and shading losses. The components of the total resistive losses include those from current flow in the emitter, fingers and bus bar as well as the finger-emitter contact resistance. The shading losses considered were from the fingers only as the bus bars were designed to be outside of the illuminated region and therefore not considered as a shading loss. Experimentally determined values of emitter sheet resistance, finger resistivity, contact resistance and finger widths were used in the simulations. The model predicts the optimum number of grid fingers for the cell design. The major loss is the finger shading followed by the emitter losses and the contact resistance. The 50X concentrator cells were modelled with an active area of 16x16mm with an illuminated zone of size 12x12mm in the centre of the cell. A 2mm 'guard band' surrounding the illuminated zone was included in the cell designs to account for any drift of the illuminated zone due to mis-tracking of a concentrator array of which these cells would form part of the receiver. A conclusion from the modelling] is that the cell design of choice for low power loss, ease of production and concentrator cell density per silicon wafer

is the two bus bar design cell like the one shown in figure 2.



Fig. 2. Left: A two bus bar LGBC silicon concentrator cell designed for 50X, Right: 1 Euro coin for size comparison.

RESULTS

Figure 1 shows the front contact pattern for three 40cm^2 active area concentrator cells for 20X concentration. The cell length and width were optimised to obtain the highest power output from a 127mm pseudo square wafer. The concentrator cells were measured under standard 1Sun AM1.5 radiation from an Oriel Solar Simulator and as a function of concentration up to an incident light intensity of over 30X using a flash lamp system which was designed and built by the Australian National University [4]. The Oriel Solar simulator 1Sun light level was set using a LGBC 1Sun cell calibrated at the Fraunhofer calibration laboratory in Freiberg at a temperature of 25°C. The current measurement from the flash system was scaled to the value measured on the Oriel solar simulator. Figure 3 shows the concentration dependence of a typical good cell produced on low cost Cz silicon. The peak efficiency occurs just below 20X due to a higher than modelled grid line resistance.

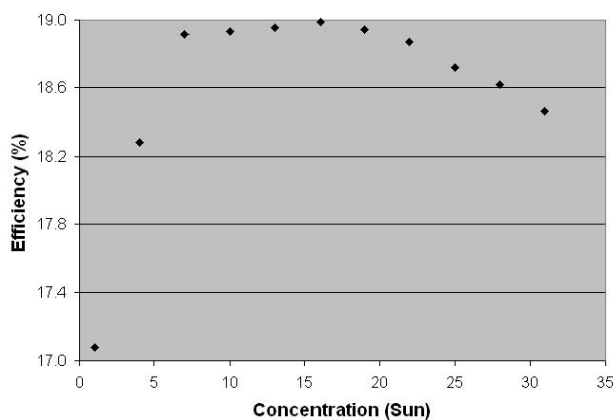


Fig. 3. Efficiency versus concentration for a 40cm^2 active area LGBC concentrator cell designed for 20X concentration.

For the 50X concentrator cells shown in figure 2 the laser scribing of the groove, groove etching and copper plating were all optimised to ensure that the final grid line width was optimal. Groove widths and depths prior to

etching were typically 13 and $22\mu\text{m}$ respectively. After etching, the groove width and depth increased to 26 and $32\mu\text{m}$ respectively. Mean groove widths after nickel and copper plating ranged between 33 and $35\mu\text{m}$ resulting in a grid line shading loss of about 9%. Best cell efficiencies at 1, 50, and 100X of 17.0%, 19.0% and 18.2% respectively were achieved using standard low cost Cz silicon wafers.

Better small cell efficiency uniformity was achieved by further optimizing the uniformity of the phosphorus diffusion both in the emitter and in the groove, to improve the emitter contact and grid line resistance uniformity. As part of these uniformity trials, cells with both one and two bus bars were produced on the same FZ wafer to compare directly with the optimized two bus bar design. From the one 125mm pseudo square wafer, 19 two bus bar and 19 one bus bar concentrator cells were produced. The cells were evenly spread across the wafer, alternating rows of two and one bus bar cells.

Table I shows the mean and standard deviation values of the cell efficiency at 1, 50 and 100Suns for all the 1 and 2 bus bar cells. 1 and 2 bus bar cells had very similar performance up to 50X but the 2 bus bar cells perform better at 100Sun due to the lower resistance losses in the fingers and bus bars. All cells have good performance at high concentration with very little difference in performance between cells from the centre and edge of the wafer.

Bus Bars	Statistical Parameter	Eff. % 1Sun	Eff. % 50Sun	Eff. % 100Sun
2	Mean	16.87	18.80	18.32
2	Std. Dev.	0.18	0.20	0.20
1	Mean	17.22	18.74	17.85
1	Std. Dev.	0.16	0.18	0.20

Table I: Uniformity of concentrator cell efficiency from across a 125mm pseudo square wafer.

Figure 4 shows the peak in the cell efficiency versus concentration is close to the designed concentration of 50Suns. The best cell from trial 3 had efficiencies at 1Sun, 50Sun and 100Sun of 17.2%, 19.3% and 18.7% respectively.

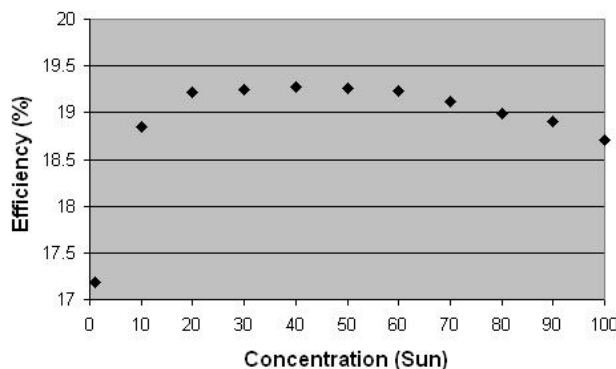


Fig.4. Best 50X concentrator cell efficiency versus concentration.

Figure 5 shows the measured spectral response curves from all the 19 two bus bar concentrator cells from

across the 125mm pseudo square wafer. The standard deviation of the integrated spectral response is 0.5%. Cells from the edge of the wafer have a slightly better red response compared to those from the centre of the wafer due to a higher diffusion length.

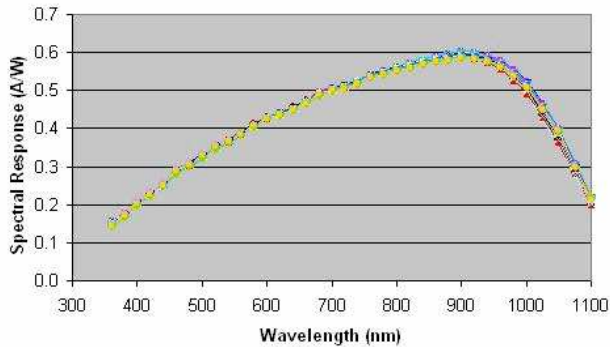


Fig. 5. Spectral response curves for all 19 double bus bar cells from across the 125mm pseudo square wafer.

The uniformity in the copper plating across the wafer was measured using an Oxford Instruments CMI900 XRF machine. The copper thickness was measured at three locations on the rear of each of the 38 solar cells from the one wafer. Good uniformity was observed. The accuracy of each individual measurement was determined as 0.2µm. The mean copper thickness was 6.7µm, with a percentage standard deviation of less than 6%.

DISCUSSION

Analysis of quantum efficiency data on our better concentrator cells indicates that our aluminium BSF can be characterised best by a rear surface recombination velocity (S_r) of 1400cm/s and a diffusion length of 300microns. 1000cm/s was chosen to represent a best possible surface recombination velocity that might be achievable from an improved aluminium back surface field process. Figure 6 shows that it is important to maintain a high diffusion length in the silicon wafer in order to obtain high cell efficiencies. Modest efficiency gains are expected by improvement in our Aluminium BSF process.

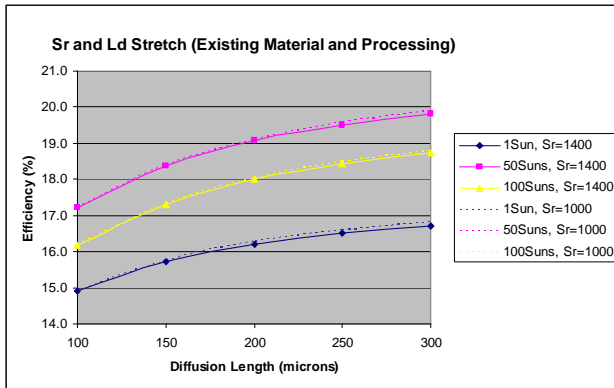


Fig. 6. PC1D modelled cell efficiency versus rear surface recombination (S_r) and wafer diffusion length for a cell made from a 280µm thick, 1.1Ω-cm wafer, with a 100Ω/□ emitter, optimised for 50Suns.

Figure 7 shows the improvement in cell efficiency that could be obtained if the material quality (diffusion length) could be improved by an order of magnitude from 200microns to 2mm (equivalent to an extremely high bulk lifetime of 1500µs), a value that is obtainable only on very high purity high cost silicon wafers. Figure 7 shows that low diffusion lengths typical in processed low cost boron doped Cholralski wafers (B:Cz) is limiting our solar cell efficiency. For our present back surface with a recombination velocity of 1400cm/s the efficiency at 50X can be expected to increase from 19.8% for good quality B:Cz ($L_d=300$ microns) to 20.7% for very high quality silicon.

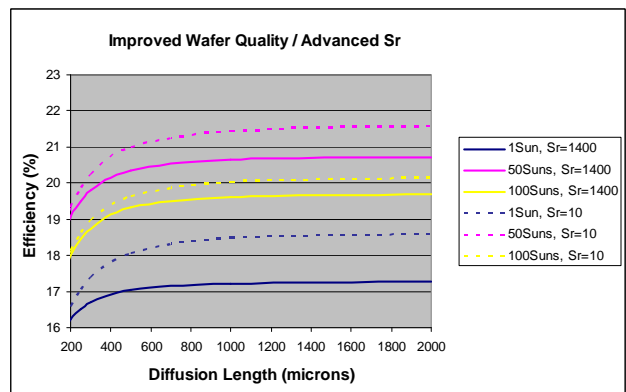


Fig.7. PC1D modelled cell efficiency for improved wafer quality and rear surface recombination for a 280µm thick, 1.1Ω-cm wafer, and a 100Ω/□ emitter, optimised for 50X.

A fraction of a per cent improvement in cell efficiency is expected by optimising the emitter sheet resistance from the 100Ω/□ diffusion used for terrestrial 1Sun solar cells. By increasing the phosphorus doping in the emitter to approximately 70Ω/□, a small increase in the 100Sun cell efficiency can be obtained if the front metal grid structure is optimised appropriately.

Figure 8 shows the modelled potential benefit of using heavier doped silicon wafers for 100Sun concentrator cells assuming that the material quality (bulk diffusion length) remains constant at 300µm and 200µm respectively as the bulk resistivity is reduced. If the material quality could be doped heavier without a reduction in diffusion length then cell efficiencies over 20% and 20.5% would be possible if the diffusion length remained similar to that of our present low cost 1 to 2Ω-cm B:Cz silicon wafers. Unfortunately because of a particular meta-stable defect associated with B:Cz silicon, which will be described latter, this is not currently possible. Whilst higher efficiency cells can be produced, within seconds of them being exposed to sunlight the efficiency / diffusion length degrades significantly.

Figure 8 shows that a slight improvement in 100Sun cell efficiency can be expected if the final cell thickness is reduced from the current value to 280 µm down to a

currently achievable thickness of 250 μm assuming our present aluminium BSF technology and B:Cz wafer quality. If our aluminium BSF technology can be optimized further to achieve a $S_r=1000\text{cm/s}$, then a slight improvement in 100Sun cell efficiency is possible if the cell thickness can be reduced further to 200 μm thick.

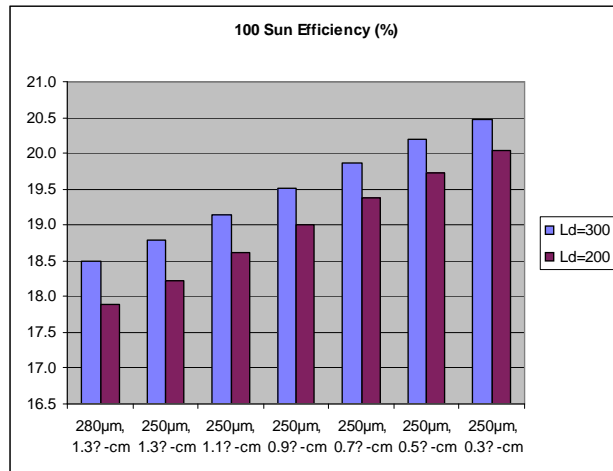


Fig. 8 PC1D modelled cell efficiency versus bulk resistivity for a grid optimized for 100X, with a $70 \Omega/\square$ emitter, aluminium BSF ($S_r=1400\text{cm/s}$) and diffusion lengths constant at either 300 μm or 200 μm .

B:Cz wafers have limitations that restrict their use in LGBC cells to resistivities above approximately 1 $\Omega\text{-cm}$. As previously mentioned, solar cells manufactured on heavily doped B:Cz silicon degrade initially in performance when exposed to light or when minority carriers are injected in the dark until a stable efficiency is reached. This effect, which is known as Light Induced Degradation (LID), is due to the activation of a specific meta-stable defect in B:Cz silicon material. Investigations [5,6] have clearly shown that Cz specific defect is correlated to the boron and oxygen concentration in the material. So the improvement in initial efficiency shown in figure 8 will not be realized as the higher boron doped wafers will degrade further.

Herguth et al [7] however recently reported an investigation into the reaction dynamics of the boron-oxygen defect. They found that the harmful boron-oxygen complex responsible for the degradation can be converted into a "regenerated" state with significantly lower recombination activity by illumination or applied forward voltages at an elevated temperature. This regenerated state, once reached, was shown to be stable under the typical working conditions of the solar cell. Since the harmful boron-oxygen complexes are neutralised within the regeneration process, the use of highly boron doped Cz-Si material without LID may be possible. The possibility of stabilising the silicon wafer quality and hence cell efficiency of highly doped boron CZ wafers at a higher level is exciting especially for concentrator cell development.

CONCLUSIONS

An in-house developed computer program and PC1D were used to design a small area LGBC concentrator cell to accommodate a 12mm x 12mm illuminated area for operation at a concentration of between 50X and 100X. The cell design for lowest power loss and ease of production has two bus bars, 42 grid lines with a total grid line shading loss of about 9%. By improving the uniformity and reducing the sheet resistance in the emitter and groove doping, concentrator cells were produced to the above design resulting in very good uniformity from cell to cell across a wafer. Cell efficiencies in excess of 19% at 50X and 18% at 100X have been achieved on low cost Cz and on FZ wafers. Best cell efficiencies of 19.3% at 50X and 18.7% at 100X have been achieved on FZ wafers and 19.0% at 50X and 18.2% at 100X on Cz wafers. Larger area LGBC cells for operation at 20X concentration have demonstrated efficiencies of 18.9% at 20X and 18.5% at 30X.

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