Technological and Financial Aspects of Laser Grooved Buried Contact Silicon Solar Cell Based Concentrator Systems

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1 INTRODUCTION

Concentrator photovoltaic CPV systems have the potential of meeting the growing demand for low-cost power generation and are particularly suited to large PV power plants. Concentrating systems can play a role provided cost effectiveness against flat plate arrays can be demonstrated. The availability of low cost concentrator cells has been one of the factors limiting the achievement of lower cost as low volume manufacture of specialised cells creates higher costs than can be achieved for flat plate systems for which a typical manufacturing plant now has a capacity of >100 MWp p.a. One solution is to use a high volume one-sun solar cell line to manufacture modified solar cells for use in concentrator applications. The Laser Grooved Buried Contact (LGBC) process has proven to be reliable, producing one-sun solar cells with high efficiency in the 30 MWp p.a. high volume manufacturing plant in Tres Cantos, Spain [1]. The LGBC process has proved particularly suitable for the production of concentrator cells. LGBC concentrator cells produced for the Entech linear Fresnel system had efficiencies of 20% at 20X when used with prismatic covers [2]. Cells were also produced for the EUCLIDES™ parabolic trough concentrator system and gave cell efficiencies of 18% up to 30X concentration without prismatic covering [3].

The LGBC crystalline silicon solar cell is shown schematically in figure 1. The cell has the following principal attributes: a) a random pyramid textured surface to reduce reflection, b) a silicon nitride antireflection coating also to reduce reflection, c) a selective emitter for optimum spectral response and minimum contact resistance d) an aluminium doped back surface field (Al-BSF), e) narrow laser –machined grid lines and f) high conductivity copper metallization.

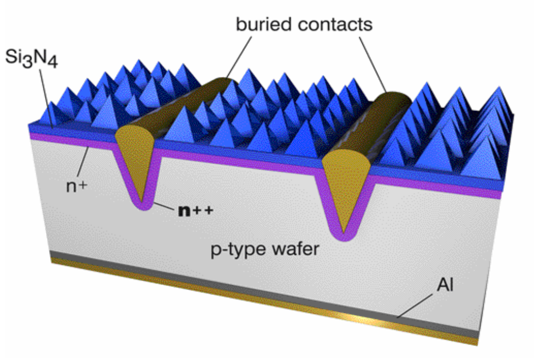

Fig.1. Schematic of LGBC solar cell.

LGBC is an attractive technology for the production of low-cost concentrator cells due to the high-conductivity buried front contact which is able 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 metallistion pattern to be changed easily, either for optimisation of the design or the production of cells for different concentration factors or illumination profiles as shown in figure 2.

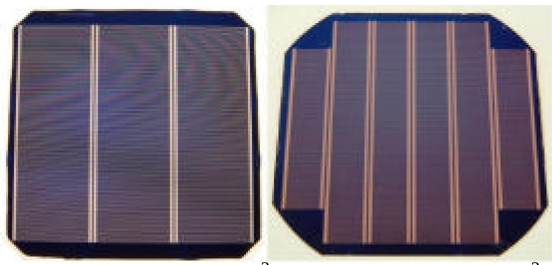

Figure 2: Left: 3 x 40cm^2 cells. Right: 38 x 2.6cm^2 active area concentrator cells on a 127mm pseudo-square wafer, optimised for 20X and 50X respectively.

2 THE LASER GROOVED BURIED CONTACT SOLAR CELL (LGBC) PROCESS

The most important parts of the process, which result in the cells being more efficient than a standard screen printing process are the anisotropic chemical etching (texturing) which result in reduced reflection from the cell surface, and the laser grooving and groove diffusion to form a local emitter to reduce contact resistance and cell shading.

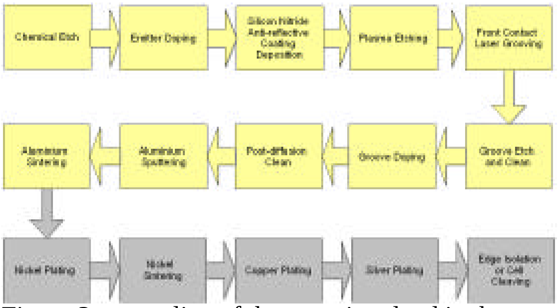

Figure 3**:** an outline of the steps involved in the process to manufacture LGBC solar cells.

A Nd:YAG Q-switched laser operated at a high frequency and x-y table speed is used to form the laser grooved front contacts. The laser vapourises silicon through a thin layer of silicon nitride. The depth of the laser groove after lasing is typically 30 microns deep and approximately 15 microns wide. In order to remove thermally damaged silicon, which acts as a recombination site, and to expose crystal facets in the groove, the wafers are subsequently etched in NaOH solution. A typical groove after etching has a groove depth of around 45 microns and widths around 35 microns. In order to reduce the contact resistance of the front contact, the cells then pass through a groove diffusion step where the remaining silicon nitride acts as a mask allowing heavy diffusion of phosphorous only in the grooves. The emitter formed earlier is therefore left as a lightly diffused layer to reduce recombination in the emitter.

The silicon nitride also acts as a mask during electroless plating in which nickel, copper and silver are used to form the high conductivity contacts. Figure 4 shows an optical microcopy image of a groove after plating. In a typical concentrator cells the resistance per unit length of finger is around 0.3O/cm and the contact resistance is approximately 0.25 O/cm of finger length.

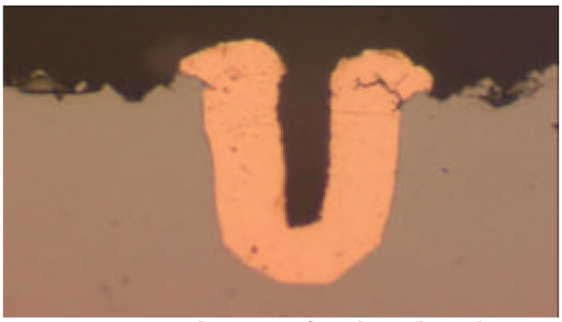

Figure 4: A typical groove after electroless plating.

After plating, another Nd:YAG laser operated at a lower frequency and table speed is used to edge isolate the large area one sun cells or to dice the large area cell into a number of smaller concentrator cells.

3 CONCENTRATOR CELLS AND OPTIMISATION

A concentrating photovoltaic (CPV)systems converts light into electricity in the same manner as a standard flat plate module, however, in a CPV system an optical element such as a lens, refracting element or reflecting element is used to focus light onto the solar cell. Although CPV technology has been known since the 1970s an optimum system design is far from being defined. There are three defined regimes of concentration:

1. Low concentration (LCPV) – upto 10X.
2. Medium concentration (MCPV) – 10X-100X.
3. High concentration (HCPV) – 100X-1000X.

The LGBC solar cell technology has been proven to work in systems ranging from 1-100X and there is scope to increase the operational range upto 150X with improvements to the front contact plating process.

One of the reasons for the high efficiency of the LGBC cell at one sun is the high volume of metal in contact with silicon without shading the cell compared to screen printed contacts. This gives the cell a low series resistance and good current carrying capacity. It has been shown that normal one suns cells can be used at up to 5X concentration before series resistance effects cause the efficiency to fall below that at one sun [4]. The grid line spacing in the one sun cell is 1.5 mm. At higher concentrations, the grid line spacing is reduced. Other than changing the grid line spacing, which is a simple reprogramming of the production laser, the only other process change is to increase the thickness of copper plating in the cell. These changes would still allow automated mass production of the cells on a one-sun solar cell production line.

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 in [5]. The modeling takes into account front contact losses only and compares the cell power output as a function of the resistive and shading losses.

Figure 5: A two bus bar LGBC 50X silicon concentrator cell, next to a 1 Euro coin for size comparison.

Figure 5 shows a cell which was designed using the modeling to maximise power output for an illumination area of 1.2 x 1.2 cm with 50X illumination. These concentrator cells were made from standard low cost Cz wafers with bulk resistivity of around 1.0 ? -cm and have yielded efficiencies of approximately 17%, 19% and 18% at 1, 50 and 100X respectively. Best cell efficiencies achieved on similar bulk resistivity FZ wafers are shown in figure 6. Efficiencies of 19.3% at 50X and 18.7% at 100X were obtained. In order to maximize the use of the silicon wafer, 38 of these small area 50X concentrator cells were tessellated onto a 127 x 127 cm pseudosquare wafer (shown in figure 1). Efficiencies of each of the small area cells were measured from across the large area pseudosquare wafer. The mean cell efficiency of these cells at 1, 50 and 100X was 16.9%, 18.8% and 18.3% respectively. Very good uniformity in cell efficiency was observed up to 100X. The efficiency standard deviation was approximately 1% relative over the whole concentration range up to 100X.

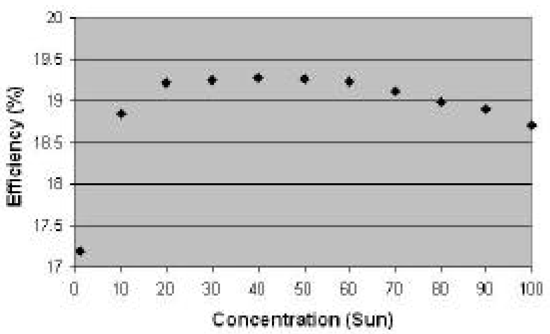

Figure 6: Best cell efficiency versus concentration.

Figure 7 illustrates the good uniformity across the large area wafer with maps of the internal quantum efficiency obtained using a 405nm laser (left) and a map of the bulk diffusion length [Ld] (right). Both maps were made using a Semilab WT2000 system with both LBIC and Reflectance heads.

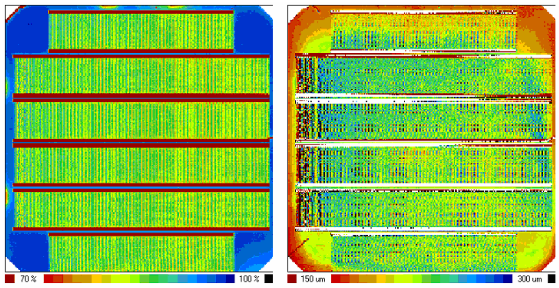

Figure 7: Left: Semilab QEint, Right Ld uniformity

5 MULTIJUNCTION TECHNOLOGIES AND MJ BASED SYSTEMS

Another cell technology currently being used in concentrator systems a multijunction solar cell manufacturered in quantity by such companies as EMCORE and Boeing-Spectrolab. Multijunction cells consist of multiple thin films deposited by molecular beam epitaxy (MBE) or metal organic chemical vapour deposition (MOCVD). Each semiconductor has a different band gap energy which therefore allows better harvesting of the solar spectrum. Due to this, the cell technology yields higher cell efficiencies but due to the complex manufacturing required, much higher cost than silicon LGBC technology, this has limited the use of MJ cells mainly to space applications where efficiency and mass are more important than cost/Wp. However, at high concentration (HCPV) the cost/Wp of a two axis tracked concentrator system becomes comparable, if not lower than standard flat-panel modules.

Taking EMCORE as an example, the current cell technology in production is the BTJ cell which yields an average efficiency of 28.5% and costs circa $300 (€236) for a 125mm wafer. The company has an aggressive research and development roadmap which suggests up to 45% second generation inverted metamorphic cells are possible. However, they have commented that although efficiencies will increase over time, cell costs will not decrease[6]. However, even with this high cell cost, some HCPV companies such as SolFocus, CONCENTRIX and Greenvolts are producing demonstrator or commercial systems. To date, the majority of HCPV systems based on this technology use concentrations in the range 300X-750X.

6 CELL COSTING

NaREC is in the process of spinning out a 5MW (1 sun equivalent) process line to produce LGBC cells for concentrator applications. At this volume the cost of small area LGBC cells will be comparatively very low. However, in order to produce high efficiency concentrator cells by the

LGBC process, high specification monocrystalline CZ or FZ wafer are required. However, due to the wafer shortage in 2006-2007, more wafering capacity has come on line, this means that these wafers are now available in low costs at large quantities from a number of wafer manufacturers ensuring that the rapid growth in LGBC concentrator cells is now no longer limited by wafer supply.

The factory gate price to customers for a processed LGBC wafer is envisaged to be from \$10.68 (€8.48) for a 10X wafer to \$12.82 (€10.17) for a 100X wafer, independent of the cell design. Note that the wafer size used will be 125x125 mm with 165mm diameter pseudosquares with useable area 150.1cm^2. Figure 8 shows the cost/Wp for this technology as a function of concentration on the cell.

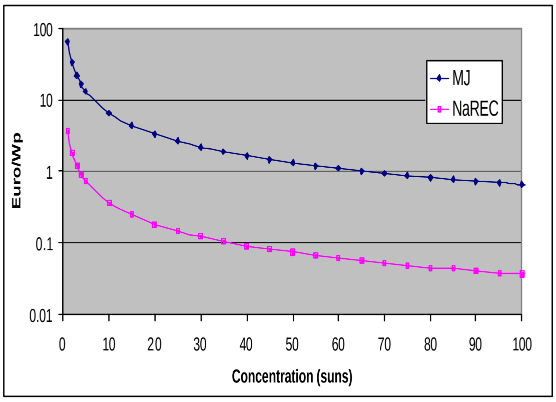

Figure 8 – Cost comparison in Euro/Wp of MJ cell with efficiency 28.5% and a cost of €236 per wafer compared with a NaREC LGBC 18% cell with a cost of €10.17 per wafer.

In order to calculate the cost per Wp of cell shown in figure 8, several assumptions were made. The LGBC cell active area was assumed to be 150.1cm2 (which excludes one millimeter around all edges of the wafer needed for edge isolation) with a modest efficiency across the concentration range of 18%. The price per wafer was maintained at the €10.17 range across the whole concentration range. For the MJ cell, a useable area of 126.7cm2 (the total area of the wafer), an efficiency of 28.5% and a wafer price of €236 was assumed[6]. For both wafers there is no account taken for front contact busbars or kerf width (from cell dicing) that would reduce the available active area, this would depend on the actual cell designs in question for both technologies.

According to the data in figure 8, at 100X the price per Wp of LGBC cell is 3.8 Euro cents. Extrapolation of the data in figure in this figure for the MJ cell yields the same cell cost for a MJ cell when the concentration is around 1800X. Even increasing the MJ cell efficiency to 45% and leaving the LGBC cell efficiency at 18% moves the cost per Wp for MJ cells to the same as the cost for LGBC cells at 1100X assuming that there is no increase in MJ wafer cost when the cell efficiency is increased by a relative factor of 59%!. Modest improvements of the LGBC technology to 20% and pushing the active concentration range up to 150X moves this cost equality point to 1900X. This calculation indicates that there is a market for LGBC cells and for MJ cells but the costs at the cell level restrict the use of MJ cells to the very high concentration range. Very few MJ systems are operating above the 1000X range currently so improvements in optical systems will be needed to push the systems up to 1800X.

7. SYSTEMS

When designing HCPV system, the manufacturing tolerances and operating tolerances are very exact this is due to the optical system acceptance angle reducing with increased concentration. This increases the cost of concentrator support structure, tracking electronics and lenses relative to a lower concentration PV system. Although there is progress in non-imaging optics to maintain high acceptance angles at higher concentrations, these elements should prove more expensive than a simple 100X fresnel lens. For example, Whitfield Solar operate a 100X single fresnel lens system and have an acceptance angle of 1.75^o, the Boeing-LPI system capable of operating at 1000X has an acceptance angle of 1.80^o but is a two part optical system consisting of a free form lens and a mirror[6].

NaREC currently supplies LGBC concentrator cells, manufactured on its pilot line in Blyth, UK, to 33 different CPV systems manufacturers. Of these 5 are in pilot system production and 5 have a commercial product, the remaining 23 are in product development. The goal of the majority of NaREC's CPV customers is grid parity, with price per kWh being quoted as low as 10 USD cents/kWh for electricity production.

An example of a CPV system manufacturer using LGBC cells is Absolicon Solar Concentrator AB, based in Sweden. This single axis tracked system shown in figure 9 concentrates sunlight at approximately 10X using a parabolic reflector in order to produce electricity and hot water. Absolicon's long term selling price goal is 3€/Wp for PV and solar thermal or 1.5Wp for PV alone. For more information see [7].

Figure 9 – Absolicon Solar Concentrator AB – X10 PV/T system[7]

Another company using LGBC cells is the UK based Whitfield Solar. The Whitfield Solar WS-Ti24 system uses LGBC cells designed to operate effectively between 50-100X using a fresnel lens as the optical element. The system is a double axis purely PV system which is shown in figure 10. Whitfield Solar's MW scale unit selling price is planned to be 2.4€/Wp[6]. For more information please see [8].

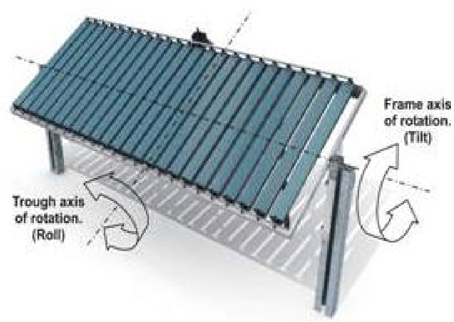

Figure 10 – Whitfield Solar – WS-Ti24 system[8]

It must be noted that both the system designs shown here have their own unique selling point advantages and are subject to ongoing research and development and should not be considered purely on the cost per Wp value alone.

The values quoted offer a significant saving over flat plate cell costs and opens up the potential for low-cost concentrator systems where neither cell cost nor availability is a limiting issue. Comparing this to MJ systems, the values per Wp for current MJ systems lies around the 4€/Wp level[6], but the HCPV MJ system production companies also have long term production targets as aggressive as the MCPV system production companies. However, low to medium concentration systems are much closer to a lower cost solution partially due to the lower cost of cells and partially due to the acceptance of less accurate manufacturing tolerances.

6 CONCLUSIONS

Using the LGBC process, 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. LGBC solar cell technology is an attractive technology for MCPV. System manufacturers are targeting cost per kWh of as low as 10 USD cents per kWh which would achieve grid parity. MCPV using LGBC cells offers an attractive, rapid, route to market with MCPV systems using LGBC cells currently coming to the market place.

8 REFERENCES

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