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Screen printing in laser grooved buried contact solar cells: the Lab2Line hybrid processes

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ABSTRACT

Laser grooved buried contact (LGBC) solar cell technology is proving to be an attractive method of producing solar cells that are designed to operate at one sun and at concentration. Such technology is commercially available at Narec for applications up to 100 suns. Although LGBC cells can have a higher efficiency at one sun when compared with standard non-selective emitter screen-printed solar cells, a more complex manufacturing process is required for these cells. This paper outlines the approach taken under the FP6 EU funded project "Lab2Line", in which screen-printing and LGBC solar cell processing techniques are hybridized in order to produce lower cost, high efficiency solar cells.

Introduction

Despite the ongoing economic crisis, the global PV market could reach between 10GW and 16GW of new installations in 2010, compared to between 8GW and 12GW in the previous forecast year. While the announced worldwide PV production capacity would be sufficient to cover the expected evolution of the market in the coming five years, we could nevertheless see some temporary shortages due to possible fluctuation of demand patterns. In this scenario, Europe is leading the way with almost 16GW of cumulative installed capacity in 2009, representing about 70% of the world's cumulative PV power installed at the end of 2009 [1].

> "Efficiency increases for concentrator systems can have a drastic impact on the reduction of levelized cost of energy."

It is generally accepted that the best way to continuously grow in the face of the market demand and competition from outside the EU is for a European PV manufacturer to provide high efficiency modules at low cost, in order to have the best power/price ratio. Currently, due also to the shortage of inverters, it is preferable to extract the highest power density at the lowest possible cost. At the moment, all the highest efficiency cells (and modules) are coming from producers outside of the EU (for example SunPower, Sanyo, Suntech [2–4]).

In order to obtain high efficiency, low cost cells, LGBC solar cell technology offers a route to obtain efficiencies higher than 18% on monocrystalline CZ wafers, by employing low throughput steps like sputtering and electroless chemical plating. It is also a suitable cell design for low to medium concentration due to its low front-contact shading, and its selective emitter structure.

As part of the Lab2Line project, screen-printing and LGBC solar cell processing techniques were hybridized with the aim of producing lower cost, high throughput, high efficiency solar cells processed on large-area (125 × 125mm) monocrystalline wafers using techniques scalable to industry. Two hybrid approaches have been considered: a fully screen-printed cell in which Screen-Print (SP) is applied to both the cell rear and into front-contact grooves and is subsequently cofired; and a process in which SP is applied only to the rear and then electroless plating is used to form the front contacts.

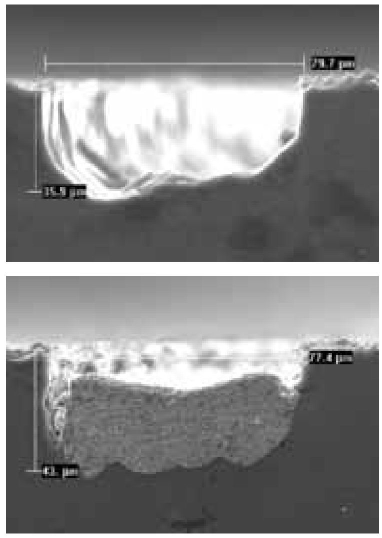


Figure 2. Scanning electron microscope (SEM) images of a front-contact groove modified to allow the application of screen print within the groove. The images show the groove prior to filling with SP paste (top) and after filling, drying and firing of the SP paste (bottom).

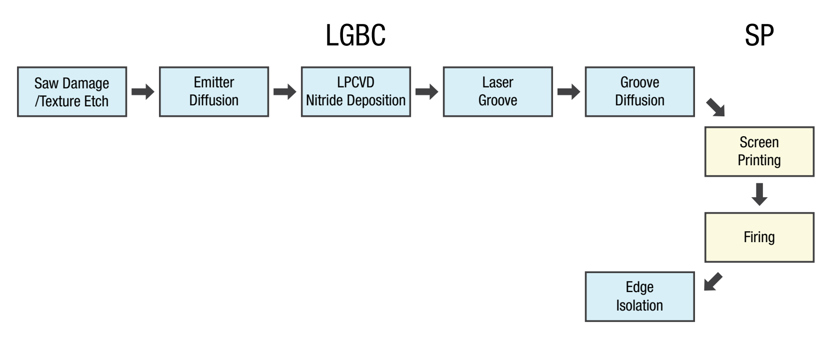


Figure 1. Outline of hybrid process 1, indicating the steps that are normally carried out in the LGBC or SP processes.

Both of these Lab2Line hybrid approaches offer high average efficiencies at one sun with a small performance distribution, with the second process showing at least a 6% relative improvement of efficiency at concentration. Efficiency increases for concentrator systems are especially important as they can have a drastic impact on the reduction of

	V_{oc} (V)	J_{sc} (mA/cm^2)	FF %	Eff %
Best cell	0.625	35.08	79.2	17.34
Average cell	0.620	34.56	78.1	16.72
Standard deviation	0.002	0.38	2.0	0.51

Table 1. One sun IV parameters for cells processed with hybrid process 1.

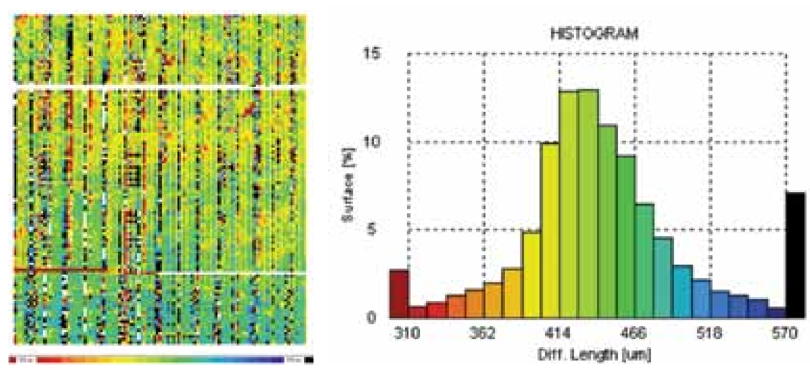


Figure 3. LBIC measurements of a wafer processed through hybrid process 1. Note that there are no centre to edge effects observed over the range of the scan (116mm), which is equivalent to the full size of the wafer measured. This would indicate that it is unlikely that there will be any issues with scaling up this process to larger wafers.

levelized cost of energy (LCOE) in areas with high direct normal incidence.

Hybrid processes

Hybrid process 1:
Fully screen-printed process

In the process summarized in Fig. 1, the SP metallization technique is used for both front and back contacts, with SP applied over the entire cell rear and only into laser grooves on the front. On the rear, aluminium compensates the back phosphorous diffusion and forms the back surface field (BSF), while silver forms the front contact fingers and busbars [6]. The major issue in this case is the laser groove filling by SP, which involves a modification of groove shape, paste rheology and front grid design to obtain low shading and a well-aligned SP/groove cell (see Fig. 2).

Hybrid process 1 results

The main issue encountered during this process is the optimization of SP inside grooves. In order to obtain complete alignment between the groove pattern and the screen-print mask, a specific front-contact grid was designed. Computer modelling with PC1D [7] was used along with in-house developed software taking into account the minimum printable finger width and the maximum number of fingers which could be effectively aligned with the SP. We obtained a grid with 66 fingers on a 125 × 125mm wafer, with each finger nominally 80µm in width, allowing effective alignment [8] with good filling and adhesion, as shown in Fig. 2.

In order to make good ohmic contact of the SP silver paste to the heavily diffused silicon in the groove, optimization of the paste dilution and the use of silver SP paste specifically designed to make ohmic contact directly onto silicon were necessary. After optimization of both printing and co-firing, a 16.70% average efficiency with best cell 17.34% was reached. The results garnered are shown in Table 1, showing an average V_{oc} of 620mV and a maximum of 632mV.

Laser beam-induced current (LBIC) measurements carried out using a Semilab WT2000 tool are shown in Fig. 3. Diffusion lengths averaging 430µm can be observed, with good uniformity over the whole area of the cell (116 × 116mm). Any observed non-uniformity appears to be random in nature and no centre-to-edge effects are observed, a result of the improved back-surface field, bulk gettering and rear-surface recombination velocity provided by Al screen-printing and firing compared to sputtered aluminium. This is an improvement over the standard LGBC process where diffusion lengths are of the order of 240–280µm.

The long wavelength performance, evaluated in terms of internal quantum efficiency (IQE), is shown in Fig. 4. Theoretically, if we optimize every step to move the average V_{oc}, J_{sc} and FF to the maximum measured at one sun, efficiencies close to 18% can be obtained with a relatively simple, high throughput and potentially low-cost process sequence.

Even though the IV parameters of cells produced by this process are good, the difficulties arising from the accuracy required for front screen-printing alignment and a small process window for a stable co-firing process could make the hybrid process 1 less appealing for an industrial scale-up. Some of these issues could be mitigated by using an ink-jet or stencil-printing approach, for example.

Hybrid process 2:
Back screen print of LGBC cells

During hybrid process 2, SP Al paste is applied to the rear of the cell only, which is then dried and fired. This avoids front-contact alignment issues or the larger shading produced by 80µm-wide screen-printed fingers. The remaining residual SP paste is then etched away and the metallization is carried out with the LGBC process's standard electroless chemical plating. This results in an LGBC front with

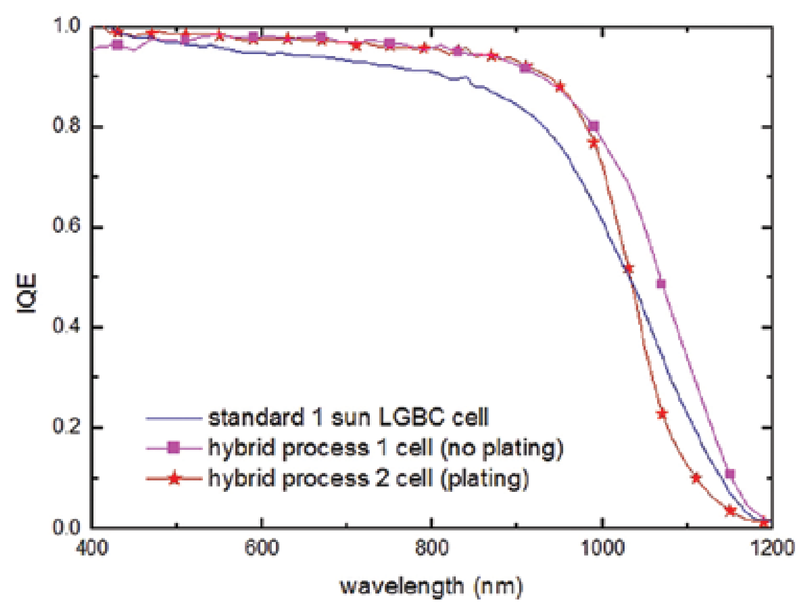


Figure 4. Internal quantum efficiency measurements for wafers processed through the standard LGBC process and hybrid processes 1 and 2.

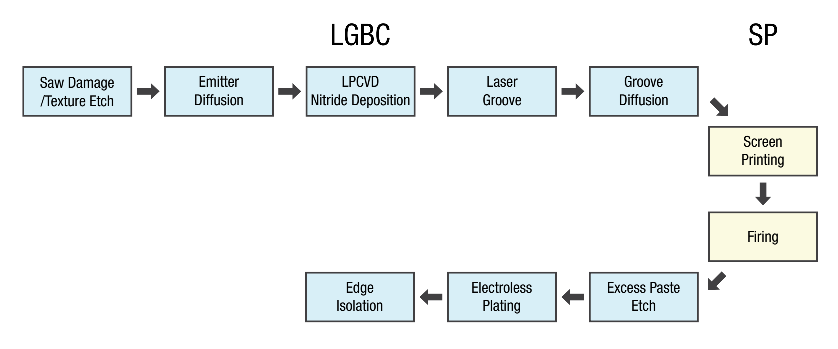


Figure 5. Outline of hybrid process 2, indicating which steps are normally carried out in the LGBC or SP processes.

low shading, low contact resistance and high conductivity and an SP rear which has a superior BSF, lower rear surface recombination velocities and improved bulk gettering properties than the traditional LGBC Al-sputtered rear.

Hybrid process 2 results

Several hundred of one sun cells have been produced using this process, the results of which are depicted in Table 2. The IQE of cells produced by both methods have been measured, and is presented in Fig. 4 with a standard LGBC cell for comparison. All cells have an excellent blue response due to the selective emitter structure produced by the LGBC process. Furthermore, the improvement in the long wavelength region is clearly appreciable for the hybrid processes. An unexpected result is the difference in behaviour between the IQEs for hybrid process 1 and 2 cells in the 950–1200nm range. However, comparing this to the cells' V_{oc} values, the comparison is surprisingly inconsistent as both processes produce very similar V_{oc} values.

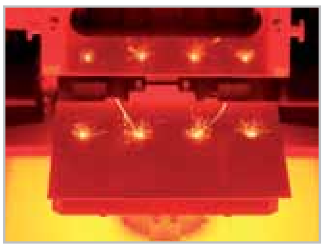
Since the only difference between hybrid processes is the chemical plating, and as we have previously noted that cells with front plating or SP show similar performance under standard AM1.5 conditions [7], we can relate this effect to the metal growth on the back side. A further small batch (circa 15) of cells was processed using the hybrid 2 process with certain process steps optimized. This yielded the results shown in Table 3.

	V_{oc} (V)	J_{sc} (mA/cm^2)	FF %	Eff %
Best cell	0.631	35.60	79.7	17.9
Average cell	0.623	35.30	79.1	17.4
Standard deviation	0.004	0.15	1.1	0.33

Table 2. One sun IV parameters for cells processed with hybrid process 2.

Introduction to concentrator photovoltaics (CPV)

One route to reductions in LCOE from PV is by using concentrator systems. In a typical crystalline silicon one-sun module, around 80% of the cost of the module comes from the silicon solar cells. CPV systems offer a route to reduce the amount of PV material by focusing sunlight onto the cells using comparatively cheap mirrors or lenses; however, sun tracking may be required, depending on the level of concentration of incident light on the cells. As calculated in-house by Narec, in areas of high direct normal incidence (DNI), the LCOE of well-designed concentrator systems can potentially be



	V_{oc} (V)	J_{sc} (mA/cm^2)	FF %	Eff %
Best cell	0.629	36.05	0.799	18.11
Average cell	0.628	35.33	0.799	17.97
Standard deviation	0.001	0.10	0.002	0.08

Table 3. IV parameters for cells processed with hybrid process 2 using optimized process steps.

much lower than for crystalline silicon or thin-film PV modules.

Narec currently offers LGBC crystalline silicon cells suitable for low- to medium-concentration (up to circa 100×) and has supplied cells designed for various concentrations and illumination profiles to over 70 companies, institutes and universities. According to the European Commission's PV Status Report 2010, market share of CPV is still relatively small as it is still in the development phase; nevertheless, an increasing number of companies are focusing on the CPV sector, around 60% of which were founded in the last five years. In 2008 about 10MW of CPV systems were produced, and market estimates for 2009 are in the 20–30MW range, with estimates for 2010 reaching the 100MW mark. Consensus industry-wide is that CPV will be in the GW scale by 2013, most likely consisting of a mix of silicon- and multijunction-based CPV systems [9].

Application of hybrid process 2 to CPV cells

Cells were manufactured using the hybrid 2 process (produced in the same batch as those displayed in Table 2) that have a size (2cm × 1.6cm) and front contact optimized for CPV applications. These cells were optimized to work best with an illumination of 50 suns, and yielded a best cell that reached 19.6% efficiency (at 50×) and 18.9% (at 100×) on 200µm CZ wafers (see Fig. 6). This is a 6% relative improvement for the same cells manufactured on comparable wafers using the standard LBGC process. Cells of over 20% efficiency have also been manufactured following optimization for 25× with a similar design. Also, as the V_{oc} value is higher than is normally obtained with standard LGBC technology, this should result in lower performance degradation with increased temperature – a factor that could be especially important for concentrator applications.

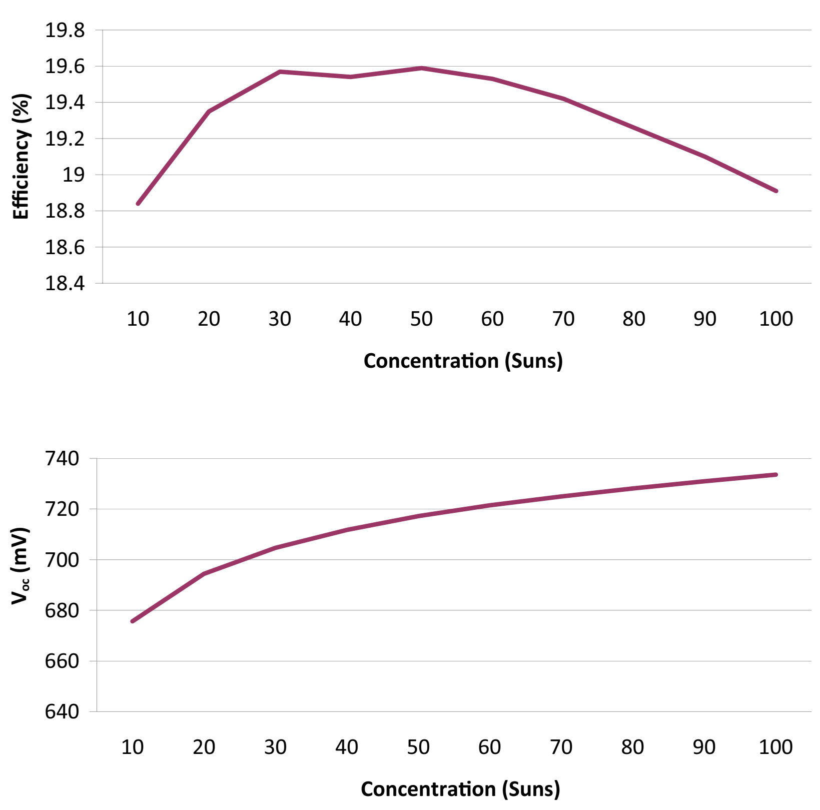


Figure 6. Efficiency and open circuit voltage (V_{oc}) as a function of illumination level. An efficiency of 19.6% is achieved at 50 suns and 18.9% at 100 suns, representing a 6% relative improvement over LGBC technology on the same wafers.

In order for CPV to be even more competitive with standard PV technology, especially as the cost of one-sun modules is falling at a rate of approximately 22% with each doubling of installed capacity, the CPV systems must show cost reductions on a similar scale. These reductions could be reached in component prices, with parts such as cells and lens tracking systems each playing a part. However, increasing efficiency effectively reduces the cost of almost every component, while land-based costs are reduced as the power density is increased.

An example of a company using silicon-based concentrator cells that is currently shipping product to high direct normal irradiance (DNI) areas is the British company, Whitfield Solar. This company can provide a point-focus Fresnel lens system that uses Narec's LGBC silicon cells at 50 suns. These lenses are manufactured from PMMA, and the system operates as an open-looped, tilt-and-roll tracking system. The efficiency of the concentrator cells is a very important factor in order to allow realization of the cost-reduction potential in any CPV system. Increases in cell efficiency lowers all cost per Wp-related costs and provides a higher power density. As the hybrid 2 cells have the same front and rear contacts as standard LGBC cells, they should act as a straight, 'drop-in' replacement for the existing cells provided by Narec.

Conclusions

This article has reported the important results of the three-year Lab2Line FP6 project. Screen-printing processes were hybridized with LGBC processes in order to enhance the efficiency of the cells at one sun and at concentration. At one sun, a cell efficiency of 17.3% was achieved with hybrid process 1 (screen printing into grooves on the front of the cell and over the entire rear of the cell) on large-area wafers (125mm). This process should prove to be immediately scalable to larger-area wafers (156mm) due to the uniformity measured by LBIC.

Using hybrid process 2, an efficiency of 18.11% was achieved at one sun on large-area (136cm^2) wafers, which could be further improved by adjusting specific process steps such as altering the plating technique or optimization of the emitter doping profile. Applying the same hybrid process 2 to concentrator cells yields a 6% relative improvement in efficiency compared to standard Narec LGBC cells when using like-for-like wafers. Other benefits include faster processing (Al sputtering is currently a bottleneck) and improved uniformity, which is also scalable to larger wafers such as 156mm pseudosquares.

We have therefore shown two processes that hybridize the screen-printing process

Figure 7. Whitfield Solar's WS:Si24 solar concentrators installed on a residential rooftop in Queensland, Australia.

and the LGBC solar cell process, which yields benefits in efficiency, process time and uniformity, especially in the application of concentrator cells. Narec hopes to offer these new hybrid cells for concentrator applications, such as for the Whitfield Solar WS:Si24 CPV system in the near future.

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