THE LAB2LINE LASER GROOVED BURIED CONTACT SCREEN PRINTED SOLAR CELLS HYBRID P-TYPE MONOCRYSTALLINE PROCESS

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ABSTRACT: Laser grooved buried contact (LGBC) solar cell technology is an attractive method for the production of solar cells designed to operate at one sun, and at low to medium concentration. This is mainly due to the low shading of the solar cell front by the grid contact and the front selective emitter, which ensures better collection for the short wavelength light. However, compared to standard screen printed solar cells, LGBC cells have a higher efficiency but require a more complex manufacturing process. As part of the EU funded project, “Lab2Line” we are marrying the screen printed and LGBC solar cell processing techniques in order to produce high efficiency 1 sun solar cells on large area (125x125 mm) wafers at the lowest cost. A fine line, screen printing technology has been used previously [1,2,3] along with LGBC processes to produce solar cells on multicrystaline Si. Using improved processing steps, this project aims to produce industrially scalable production of high efficiency, fully Screen Printed, Laser Grooved, Buried Contact Solar Cells (SPBCSCs) on large area monocrystalline wafers.
Keywords: Laser Processing, Buried Contacts, Screen Printing.

1 INTRODUCTION

The vast majority of industrially produced solar cells use p-type boron doped silicon and have a homogeneous emitter, a PECVD Silicon Nitride antireflective and passivating coating and have screen printed metal contacts on the front and rear of the cells. The conversion efficiency for this technology is approximately 15% in industry [2]. In order for PV to become a financially viable source of energy there needs to be increased cell and module efficiencies and a reduced production cost to reduce the cost per Wp [4,5]. LGBC technology is an attractive technology for the production of solar cells designed to operate at one sun, and at low to medium concentration. This is mainly due to the reduced shading loss of the front contact of the solar cell and from the selective emitter. However, although LGBC cells have a higher efficiency at one sun, (up to around 17-18% at an industrial scale) compared to standard screen printed solar cells they require a more complex manufacturing process.

The LGBC solar cell has been manufactured commercially by BP Solar in Madrid since 1992 and by NaREC since 2005. The LGBC solar cell has several advantages over the standard screen-printed cell. Local, highly doped front contact grooves and a lower doped emitter elsewhere on the cell front promotes a good blue response and, along with the large contact area between the electroless metal plated buried contacts and the silicon, a low contact resistance. High purity copper is plated into the grooves which is low resistivity and promotes good cell fill factors. Also the widths of the fingers are about a third of that achieved through screen printing, reducing shading.

The screen printed process has fewer steps and the process time is shorter. However the blue response is reduced due to the homogeneous emitter and the fill factor suffers from the higher resistivity contact fingers. In the LGBC process the rear back surface field (BSF) is formed by depositing a thin layer of aluminum by DC magnetron sputtering which is sintered into the wafer at high temperature. This yields a rear surface recombination velocity of around 1400cm/s[6]. However, when using a screen printed and fired Al rear there are reports in literature of a rear surface recombination velocity as low as 900-200 cm/s [7,8].

As part of the EU funded project, “Lab2Line” we are marrying the screen printed and LGBC solar cell processing techniques in order to produce high efficiency 1 sun solar cells on large area (125x125 mm) wafers at the lowest cost.

2 APPROACH

2.1 Hybrid process

The work of NaREC and ENEA has been focused on the integration of the two technologies. A hybrid process has therefore been designed and is shown schematically in Figure 1. Firstly the most critical issues for matching the two technologies have been identified; the laser groove morphology must be modified so that the screen printed contacts are able to be printed directly into the laser grooves on the front of the wafer. In the LGBC production process at NaREC a pulsed Nd:YAG laser with a wavelength of 1064nm is used to ablate silicon from the front of the wafer and form the grooves required in the process. To produce a good cell fill factor and low shading (around 4.5% total shading loss for a one sun cell) the groove morphologies are nominally 35µm wide and 45µm deep after alkaline etching to remove the thermal damage produced by the laser. Screen printed front contacts are usually in the range of 100-125 µm wide and are therefore incompatible with the groove morphology optimised for the LGBC process.

Work at ENEA has initially been focused on developing a technique to carry out “fine line” screen printing (SP). This has involved the optimisation of non-planar screen printing by modifications to the screen design and reducing the opening width. In order to match the screen printed contacts to the laser grooves, optical alignment of the screen printed pattern to the groove pattern has been carried out. To gain the accuracy required for this process, deep laser grooves are formed parallel to the edges of the wafer at the same time as the front contact grooves are formed. The wafers are cleaved

along these grooves forming an optically recognisable datum which is a fixed distance and orientation from the front contacts.
These last setups are crucial when dealing with large area cells which have a large number of front contact fingers.

The work at NaREC has been focussed on developing groove morphologies compatible with the screen printing process developed at ENEA.

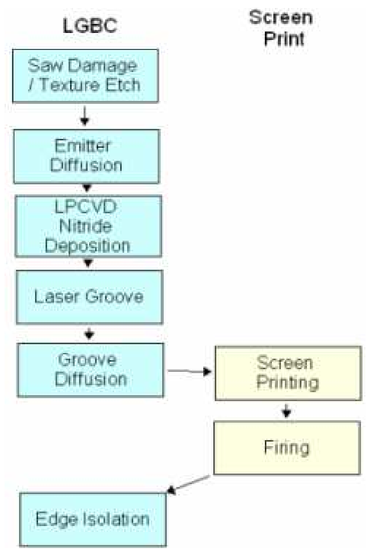

Figure 1. The hybrid process designed to produce SPBCSCs.

2.2 Early groove modifications and printing

Early work [9] showed that by modifying the laser process conditions, widths could be achieved of 45-50µm and depths of 10-15µm. Although with ENEA's fine line screen printing technology the print width can go down to 50µm, in order to obtain a good realignment between the front screen printed pattern and the laser grooved one over a full sized 125x125mm wafer the screen printing mask has to be parallel with the chuck holding the wafer and the print has to be performed with the mask in direct contact. This therefore produces a complete superposition of printed and grooved pattern, even though in this way a larger finger print width is inevitable.

The print size here is too large for the groove (upto 85µm) which gives overfilling resulting in increased shading, poor contact resistance and the possibility of some localised shunting. Wider and deeper grooves are therefore required to give complete realignment, while complete filling of the grooves is possible with screen print paste once the correct rheology is individuated.

3 PROCESS DEVELOPMENT

3.1 Laser groove modification

Through modifications to the laser groove process we are able to achieve a wide, flat bottomed grove. The morphology of this groove is controllable by changing the laser processing parameters, so grooves with no upper limits on widths are possible. These new grooves, shown in Figure 2 were used for further processing of cells through the hybrid process.

3.2 Screen printing.

With the screen print mask in direct contact to the wafer, complete superposition of printed and grooved pattern is possible, even though in this way a larger finger is inevitable. To allow the paste to go through the 400 mesh screen it was diluted to the correct rheology and the squeegee pressure and velocities adjusted to high pressure and high velocity to facilitate the correct fine line printing required. This procedure gives good printing resolution which obtains complete or almost complete groove filling, as shown in the SEM images in Figure 2 and good adhesion. After drying in a conventional IR belt dryer the rear surfaces (only) of the cells were cleaned in HF. Then Al paste was printed on the back using a low mesh count screen (165) and dried in IR belt dryer. The co-firing step was carried out in an IR belt furnace having three active zones. When completed the cells were isolated using either a dicing saw or an infra red laser.

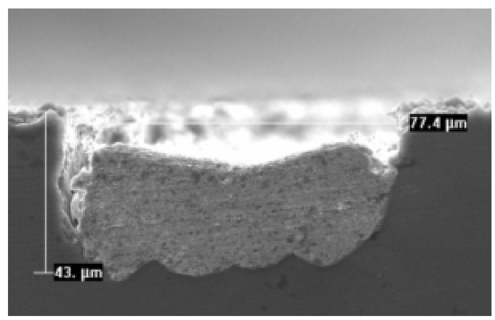

Figure 2. Wide, laser processed groove after screen printing and drying/firing.

3.3 Cell and Process Designs

Three cell/process designs were trailed, all three had fine line Ag SP on the front and Al SP on the the rear of the cells. The three processes/cell designs are summarised as follows

- Design 1 – initially the standard "one sun" LGBC pattern finger spacing was used for processing, this has 82 fingers on a full 125x125mm pseudosquare wafer and a shading of approximately 9%. The wafers used for processing cells of this design were 300µm thick Cz wafers.
- Design 2 – in house developed modelling indicates that in order to get the best power output for hybrid SPBCSC cells with 70µm wide fingers, 66 fingers per cell are needed. This reduces the front contact shading down to approximately 5%. The cells therefore processed as Design 2 have this new 66 finger front contact pattern and 200µm thick Cz wafers. During the development of the processing of the Design 2 cells, there have been process improvements which include improved low diffusion Ag front contact paste, improved Al rear contact paste and an extra thermal step during processing to reduce front surface phosphorous concentration.

- Design 2 with rear phosphorous doping – The cells for this process had 66 70µm wide fingers with Cz wafer thicknesses of 200µm. The advanced processes developed for Design 2 were also applied here. In addition, differently of what is commonly done for LGBC cells, phosphorous diffusion onto the rear side of the wafer was tried in order to promote enhanced bulk gettering.

3.4 Screen printing – grove alignment issues

We remark that large area alignment is feasible with the Design 1 cells, but the complete alignment on 125 mm side pseudo-square is also related to the finger number: the more fingers, the higher the systematic error in repositioning of both laser and screen printing from the first finger to the last. So if we have about 80 fingers, an error of 1 µm for each groove means 80 µm displacement from the first to the last, which implies an incomplete alignment at the border edge. This has resulted in smaller cells processed as design 1 as the non aligned parts have been removed with respect to Design2, in which the alignment is complete over the full cell i.e. all the 66 fingers.

The cells were then characterised in terms of light I-V (AM1.5); Internal quantum efficiency and laser beam induced current (LBIC) measurements have also been carried out

4. RESULTS AND DISCUSSION

4.1 Cell Characterisation

In Figure 3 the IQE for all three cell/processes is shown compared to a standard LGBC cell with a sputtered Al BSF and electroless chemical plating for the front and rear contacts. Table I shows the light IV parameters for the three processes measured under STC and Figures 4-7 the LBIC measurements with 1mm resolution.

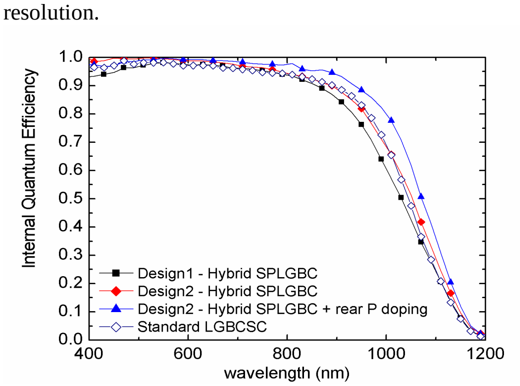

Figure 3. Internal quantum efficiency measurement

	Hybrid SPLGBC cells (design 1)	Hybrid SPLGBC cells (design 2)	Hybrid SPLGBC cells (design 2) with rear P doping
Voc(mV)	590	614	624
Jsc(mA/cm^2)	32.53	34.57	34.71
FF(%)	76.47	76.6	73.6
Efficiency(%)	14.68	16.25	15.94
Shadowing(%)	8.94	5.4	5.4
Cell Area(cm/s)	80.9	134.6	134.6

Table I. I-V parameters measured at STC

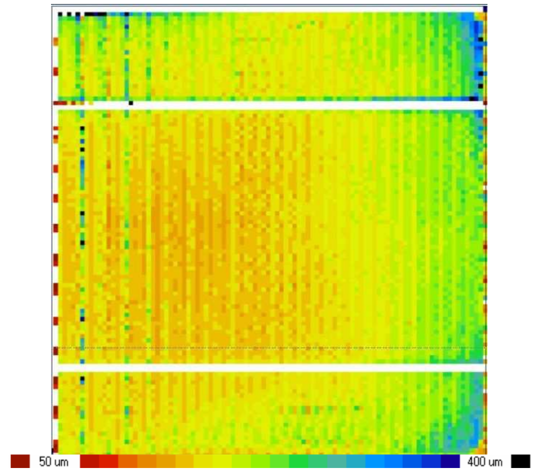

Figure 4 – LBIC scan on Design 1 cell.

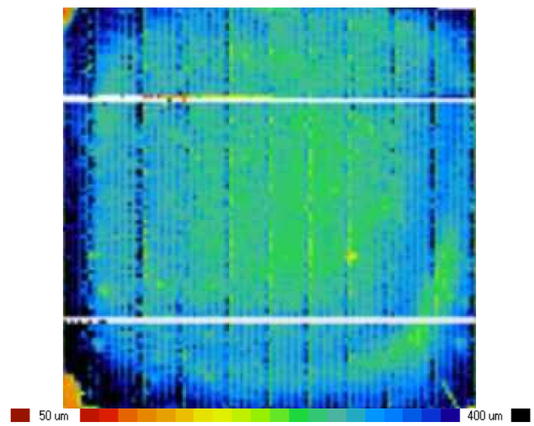

Figure 5– LBIC scan on Design 2cell.

Cell type/process	Hybrid SPLGBC cells (design 1)	Hybrid SPLGBC cells (design 2)	Hybrid SPLGBC cells (design 2) with rear P doping
Best measured diffusion length (µm)	181	310	438
IQE modelled diffusion length (µm)	160	200	408
IQE modelled RSRV (cm/s)	1800	646	200
IQE modelled BSF thickness (µm)	4.5	5.1	5.7

Table II - Average diffusion lengths measured compared with cell parameters modelled from IQE data.

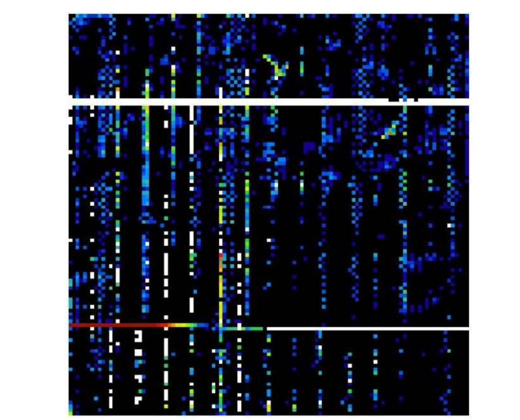

Figure 6– LBIC scan on Design 2 cell with rear phosphorous doping.

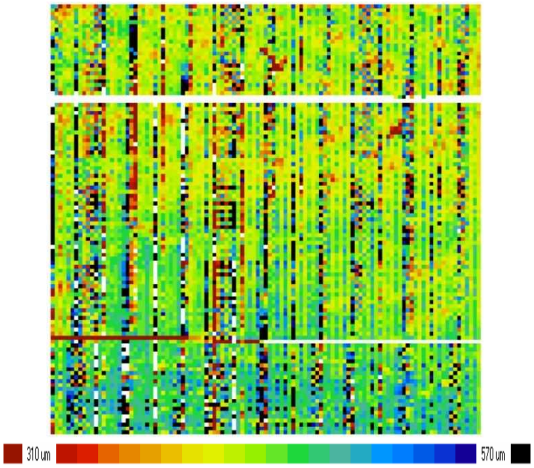

Figure 7– LBIC scan on Design 2 cell with rear phosphorous doping. The scale ranges from 210-570µm

4.2 Comparisons between cells processed as Design 1 and Design 2.

If we consider the standard LGBC process, thinning of wafers results in a decrease in performance due to the modest rear surface recombination velocity (RSRV) of 1400cm/s However using thinner wafers instead can help increase the efficiency for SP cells providing the RSRV is low enough. Indeed considering the SPLGBC cells, it can be seen that cells processed using the optimised front contact design (Design2) on thin substrates have a larger V_{oc}, J_{sc}, FF and diffusion length than those cells processed as Design 1. The FF improvement would not be expected for a design with a larger finger spacing as the emitter resistive losses will have increased. Although not reported in Table I, SPLGBC cells with Design2 front contact have produced J_{sc} values up to 34.7mA/cm^2 The maximum J_{sc} possible if this increase was due to reduction in shading alone is approximately 33.5mA/cm^2.

As a result one can conclude that part of this observed improvement is due to an improvement in cell processing, namely

a) emitter formation,
b) silver front contact paste
c) rear BSF formation/gettering.

In particular:

a) Wafers processed to front contact Design 2 went through an extra annealing step before SP and firing to drive the emitter deeper into the cell and therefore reduce the surface P doping concentrations. This has been needed to consider all the thermal treatment experienced by the wafers in the standard LGBC cells, which are avoided in the hybrid process as showed in Figure 1. It should be noted that this step could be avoided by a re-optimisation of diffusion process, in order to have the same emitter profile at the end of the extra annealing just during the normal thermal steps.

b) As previously noticed [9] the low V_{oc} was attributed to the front silver paste characteristic, quite aggressive during firing. A new paste has been used, especially designed for making contact directly on silicon. Also the use of less fingers in the front grid design has allowed the use of a snap off distance, which in turn allowed to better resolved print, and full aligned cell. This, together with the deeper emitter and optimized firing condition, led to better V_{oc} and lower contact resistivity.

c) The use of new and better performing paste for the individuated firing temperature profile yielding better BSF formation. Indeed LBIC measurements carried out yield an average diffusion length of Design 2 cells of 310µm on a 200µm thick wafer. For Design 1 cells the diffusion length is averaging 180µm on 300µm thick wafers. Also data modelled from the IQE measurements show that Design 2 cells have a lower rear SRV of approximately 640cm/s whereas the Design 1 cells have a rear SRV of around 1800cm/s.

4.4 Comparisons between Design 2 cells with or without rear phosphorus doping

Cells processed through the Design 2 process which were subjected to phosphorus doping on the rear, yielded an improvement in V_{oc} upto 624mV. This is attributed to an improvement in back surface recombination velocity and improved diffusion length from enhanced bulk gettering. Spectral response data has shown that the phosphorus doping step has resulted in an increase in IQE between 700-1200nm. Modelling of this data with an 'in-house' developed model has shown that rear phosphorus doping has indeed improved the rear surface recombination velocity from around 650 to 200cm/s with an increase in BSF thickness from 5.1 to 5.7µm respectively.

LBIC measurements have shown that this diffusion step has resulted in an improvement of average cell diffusion length by 40% from 310µm to 438µm along with an improvement in diffusion length uniformity.

4.5 Future process

Inputting the above diffusion length of 450µm and rear surface recombination velocity of 200cm/s into PC1D [10] yields (with an optimised front contact) a J_{sc} of around 36.5 mA/cm^2. Using maximum measured values from optimised front contact process and existing SPLGBC process gives a max Voc of 624mV and a max FF of 80%. This advanced process is therefore capable of 18.2% efficiency.

5 CONCLUSION

The aim for the Lab2line EC funded project is to demonstrate that a hybrid SP/LGBC p-type solar cell process is industrially feasible and able to achieve average efficiencies of 17% and best cell efficiency of 18% with cells larger than 100cm^2 in size on batch sizes of 100. To date we have demonstrated average run efficiency over 15% is possible with best cell values of 16.25% on fully screen printed process. We are currently exploring the possibility of an optmised front or a passivated rear contacted and front screen printed cell to get higher efficiency over 18%. Anyway the majority of equipment used for this work has industrial scale equipment but without the automation available to large scale production. The process is easily transferable to large scale production, and due to increased automation, the distribution of cell parameters is envisaged to be tight.

6 ACKNOWLEDGEMENTS

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