AN INDUSTRIAL PROCESS FOR BIFACIAL SOLAR CELLS BASED ON SCREEN-PRINTING TECHNIQUES

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ABSTRACT: The aim is to show the feasibility and optimization of an industrial process for p+nn+ bifacial solar cells on thin substrates, based on screen-printing techniques of both emitters and the metal contacts. The experiments were carried out on n-type Cz silicon wafers of different resistivities. It is important to note that p^+ and n^+ emitters have been developed simultaneously by means of a co-diffusion step in a belt furnace.
Keywords: screen-printing, bifacial, industrial

1 INTRODUCTION

Space reduction is a goal on the photovoltaic research that puts us on the way of bifacial solar cells, its relevance underlined by the feedstock problem. Part of the silicon shortage can be overcome if thin substrates are used, and if the n-type material rejected by the semiconductor industry is made suitable for PV. This view leads to the p+nn+ thin bifacial solar cells.

Besides, low cost requirements needed in industrial environments are leading the manufacturers to use totally in-line processes, and as a consequence, screen-printing is extending its presence in the manufacturing process not only for the metallization but also for the creation of the emitters.

These two key factors have been taken into account at TiM in order to develop a process for industrially manufacturing thin bifacial solar cells by means of screen-printing techniques.

2 EXPERIMENTAL

The objective of the work is to develop thin cells of 12.5×12.5 cm^2 with a SiNx layer as an antireflection coating. N-type Cz silicon substrates have been used to manufacture bifacial p^+nn^+ cells.

Preliminary steps have been taken using n-type 0.8 Ωcm Cz wafers of 350 µm width to manufacture small cells of 2.25 cm^2. Surfaces were textured without any AR coating. Emitters were done by screen-printing boron and phosphorous pastes and carrying out a co-diffusion in a belt furnace at 1000ºC, for 8 minutes, resulting in a boron front emitter in the range of 30-45 Ω/sq. In order to metallize the emitters, a matrix of different firing times and temperatures was designed. This way, the evolution of the electrical parameters was studied.

Next stage has been carried out with thinner and more resistive substrates. N-type 4 Ωcm Cz wafers of 140 µm width have been used to create both small and large area cells. Co-diffusion step has also been modified. First of all, the process for small area cells was optimized, so that larger ones could be manufactured obtaining reasonable results.

In all cases, several types of measurements have been done to characterize the structures before and after the metallization. In this way, bulk lifetime has been estimated by QSSPC [1] and PCD [2] measurements and its analysis using *teffsim* [3] program. The electrical parameters of the cells have been extracted from I-V measurements and using the fitting program *MultIV* [4]. Finally, it has been measured the EQE of the manufactured cells.

3 RESULTS

3.1 Preliminary results over thick substrates

The first manufactured cells (0.8 Cz n-type, 2.25 cm^2) showed around 65 µs of bulk effective lifetime after the co-diffusion of the emitters performed at 1000ºC for 8 minutes. Once the emitters were created, the work focused on the optimization of the contact formation step. The table below shows the series resistance values corresponding to the different firing points studied.

Table I: Evolution of the series resistance Rs (Ωcm^2) with the firing point. The best diagonal (in red) shows the lowest values for R_s.

	Firing temperature (ºC)					
Time	725	750	775	800	825	850
32’’	0.846		1.75		4	
25’’		0.738		1.05		1.66
17.9’’	1.79		0.421			
10.6’’		1.53		0.413		0.394

It can be seen that there is a diagonal where the series resistance is lowest and therefore, those are the best firing points in terms of series resistance. Besides, the lowest shunt conductance and recombination at the junction belonged to the lowest temperatures. That makes the low temperature and long process (725ºC, 32’’) the best. With this process, for monofacial cells fill-factors close to 78% have been obtained, and for bifacial cells close to 75%, but the bifacialities are quite low (around 18%).

Using thinner and more resistive substrates bifacialities are expected to increase.

3.2 Results over thin substrates

In order to show the performance of the thin cells created (around 140 µm), four samples are analyzed by varying different steps in their process. Some of the variations introduced in the experiment were related to the diffusion of the emitters, the firing of the metal pastes and the deposition of a passivating and antireflective SiNx layer.

Table II: Summary of the process.

	Sample 1	Sample 2	Sample 3	Sample 4
Cleaning & texturization	✓	✓	✓	✓
SP Boron	120 mesh	120 mesh	120 mesh	120 mesh
SP Phosphorus	120 mesh	120 mesh	325 mesh	325 mesh
Co-difusion Temperature (ºC) / Time	1000ºC / 8’	1000ºC / 8’	950ºC / 36’	950ºC / 36’
HF	–	✓	✓	–
Deposition SiNx	–	✓	✓	–
p+ contact paste	New Ag/Al	Ag/Al	Ag/Al	New Ag/Al
n+ contact paste	Ag	Ag	Ag	Ag
Firing Temperature (ºC) / Time	725ºC / 32’’	825ºC / 10’’	825ºC / 10’’	725ºC / 32’’
Area (cm^2)	2.25	100	100	2.25

First of all, the process for small area cells (2.25 cm^2) was optimized. These are referred as samples 1 and 4 in Table II. In this first approach the aim is to improve the bifaciality of the cells in base of different phosphorous emitters, therefore different diffusion temperatures and times have been tried out: 1000ºC, 8’ and 950ºC, 36’. In order to achieve a more doped n+ emitter, two screens with different meshes have been used to screen-print the dopant pastes; one with a mesh of 325 wires per inch (typically used for the n+ emitter) and one of 120. This means that the second one lets more paste to be deposited and to get more doped less resistive emitters [5].

One should take into account that the amount of dopant paste existing in samples 1 and 2 is greater than the placed in samples 3 and 4, due to the different mesh used during the SP process, which will give different superficial doping as a result. This, altogether with the different diffusion processes, will provide different sheet resistances for the emitters.

Henceforth, the samples codifused at 1000ºC for 8’ are referred to as type 1 and the ones codifused at 950ºC for 36’ are type 2. Type 1 boron emitters present a sheet resistance of 50 Ω/sq and phosphorus emitters of 22 Ω/sq. Type 2 emitters show sheet resistances of 30 Ω/sq for boron and of 70 Ω/sq for phosphorous.

Emitters with higher sheet resistance, besides answering better to passivation, show greater bifaciality than the ones with lower sheet resistance, which, on the other hand, are easier to contact. Thus, the amount of dopant paste and the co-diffusion thermal budget are relevant for the emitter profiling.

The cells were fired at two peak temperatures and different belt-speeds: 725ºC, 32” for the small area samples (number 1 and 4) and 825ºC, 10” for the large area cells (samples 2 and 3).

Suns-Voc and I-V measurements allow to extract of the most important electrical parameters of the cells. Table III summarize these parameters for samples 1 and 4.

Table III: Electrical parameters of small area bifacial cells (samples 1 and 4) fired at 725ºC for 32’’measured by the front side.

	Sample 1	**Sample 4**
V_{oc} (mV)	581.23	591.11
$J_{sc\text{-}active}$ (mA/cm^2)	22.07	29.04
FF (%)	71.37	71.05
Gsh (S/cm^2)	6.35e-4	5.97e-4
Rs (Ω·cm^2)	0.68	0.89
η (%)	10.19	12.54

The I-V analysis revealed sample 4 (cell with deeper emitter and lower superficial doping) outperforms sample 1 in terms of Voc and Jsc.

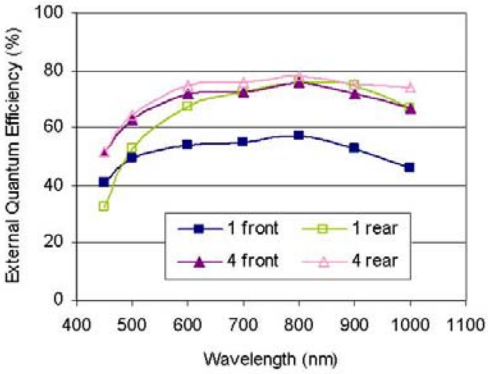

Figure 1: Front and rear external quantum efficiency (EQE) of small area samples 1 and 4.

The poor short circuit current measured on the front side of sample 1 can be due to the residual layer on the boron emitter, which causes a shading effect. Thus, the light trapping could be improved removing this layer by an HF etch after diffusion.

Although sample 4 shows a lower bifaciality than sample 1, it’s still very high (106%) and can be due to its less doped phosphorus emitter, which increases the BSF effect, and enables a better passivation than in sample 1.

Taking into account all these results, it can be concluded that sample 4 has better performance than sample 1.

For these two samples the bulk carrier lifetimes were greater than 200 µs.

The first task with the large area cells, that is, samples 2 and 3, was optimizing the firing step of the metal pastes, since the process that had worked fine for the small area cells did not provide good results for the large ones.

After trying different temperatures and times, the finally chosen firing point was 825 ºC at a faster beltspeed (10’’ in the high temperature zone of the 3-zone IR belt furnace).

Not only the firing point but also the metal paste to contact the Boron emitter was changed for commercial Ferro 3398, which has aluminum in high concentration [6, 7].

The most important electrical parameters for this two large area samples are summarized in the Table IV.

Table IV: Electrical parameters of large area bifacial cells (samples 2 and 3) fired at 825ºC for 10’’measured by the front side.

	Sample 2	**Sample 3**
V_{oc} (mV)	583.67	574.82
J_{sc} active (mA/cm^2)	28.10	28.85
FF (%)	69.85	63.39
Gsh (S/cm^2)	2.08e-4	7.36e-5
Rs (Ω·cm^2)	0.73	1.3
η (%)	11	10.35

First of all, it can be concluded that the metal pastes could go through the SiNx and contact the emitters. Besides good short circuit currents have been obtained for the boron emitter in both cases, probably due to the deposition of a SiNx layer which passivates and makes it easier the light trapping.

Large area cell of sample 2 almost reproduces the result obtained on its correspondent small area cell of sample 1 (p^+ and n^+ emitters were co-diffused under the same conditions). Shunt conductance improves for sample 3. It seems that the lower doping in its phosphorus emitter helps diminishing edge shunting. However it can be seen that the open circuit voltage of sample 3 is much lower than the one obtained for small area cells. Besides sample 2 turned out to be more bifacial (85.31%) than sample 3 (70%) even if the opposite was expected from the results of the small area cells. Both bifaciality and Voc show that the effective lifetime has probably degraded in both cells compared to previous samples, especially in sample 3, which having a lighter phosphorus emitter is more sensitive to surface passivation. Sample 2 shows lower series resistance thanks to the good contact on its more doped rear emitter. Let be said too that the surface passivation provided by the SiNx coating was not as good as expected.

Having a look at the cell’s output, one can conclude that the sample number 2 outperforms sample 3 in terms of all electrical parameters except of shunt conductance.

Front and rear EQE of the large cells have been drawn in figure 2.

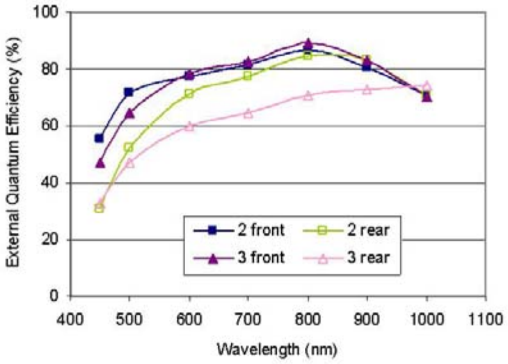

Figure 2: Front and rear external quantum efficiency (EQE) of large area samples 2 and 3.

Comparing the results of both firing processes, the best performance corresponds to sample 4, which, surprisingly does not have a SiNx coating.

4 CONCLUSIONS

A process suitable for industrial environments was proved using screen-printing techniques for the creation of both emitters and metal contacts. Co-diffusion for the emitters and the firing point of the metal pastes were optimized and good results were achieved on small area cells: open circuit voltages greater than 590 mV and bifacialities over 100% were achieved. We would like to remark the goodness of this latter result, providing short circuit current densities of 29 mA/cm^2 were measured without using any anti-reflection coating.

Large area cells also showed fine performance in terms of shunt conductance and short circuit current densities, specially sample 3, with figures circa 7e-5 S/cm^2 and over 28 mA/cm^2. Though, more experiments should be conducted towards further efficiency enhacement; being one of them the fine-tuning of different steps related to the surface passivation, such as the adequate time in HF and the firing through SiNx.

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