17 % mc-Si solar cell using full in-line processing

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Abstract: A simple in-line industrial process has been developed for commercial multicrystalline silicon (mc-Si) which results in solar cells with an average efficiency of 16.5%. The best cell has an independently confirmed efficiency of 17.0%. These are the highest efficiencies reported for full inline processing. Detailed characterization and computer simulation showes that implementation of already proven technologies in the current cell processing could lead to efficiencies around 18%.

Key Words: multi-crystalline Si, passivation, texturization.

1 Introduction

High efficiencies on large and thin wafers are the best way to reduce costs of multicrystalline silicon (mc-Si) PV technology. State of the art high-efficiency processes involve batch systems where wafers are placed vertically , such as for $POCl_3$ diffusion and parallel plate plasma enhanced chemical vapor deposition (PECVD) of passivating layers. For large wafers, inhomogeneity of coatings and especially high ohmic emitters is large. The work presented in this paper clearly shows that 17% efficient mc-Si solar cells can be made with a simple in-line (horizontal) processing scheme.

2 Experimental

156 cm^2 mc-Si wafers from two different suppliers were used to optimize the so-called ECN firing-through SiN_x:H process. We used our advanced acidic etch recipe (T2) to combine texturization and the saw damage removal in one process step.

This recipe results in a reflectivity of about 10-15% at a wavelength of 1000 nm on bare Si. This is even lower compared to our industrially applicable etch (T1) which results in a reflectivity of about 20% at a wavelength of 1000 nm on bare Si, and a 6% gain in J_{sc} compared to alkaline etched wafers [1]. Also after applying a SiN_x:H ARC, the etch T2 results in a significantly lower reflection compared to T1 (see Figure 1)

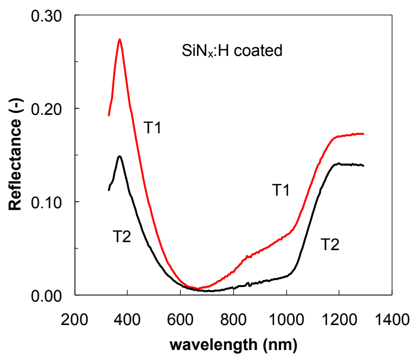


Figure 1 Reflectance of cells with either the industrial texturing process T1 or the advanced texturing process T2. Cells are coated with a SiN_x:H ARC.

A high-ohmic homogeneous emitter with a sheet resistivity of over 70 Ω/sq was made using an infrared lamp-heated belt furnace with the wafers placed directly on the standard metal belt. Passivating SiN_x:H layers were deposited with an in-line Microwave Remote PECVD system.

Cells were metallized using advanced screen-printing and firing was optimized on both contact formation and Back-Surface-Field using an infrared lamp-heated belt furnace. No post-treatments like forming gas anneal (FGA) and additional edge isolation were carried out.

p-type FZ Si wafers were processed in parallel using the same processing sequence. These FZ cells were used to elucidate the rear surface properties of the mc-Si cells as has been explained in [2].

IV measurements were performed using a class A solar simulator at ECN with six current probes per busbar. The measurements are performed according to the ASTM-E948 norm [3]. The best cell was measured at the Fraunhofer ISE Callab for confirmation. The internal quantum efficiency (IQE) was determined from spectral response measurements and reflectance measurements.These characteristics were used for PC-1D simulations. These simulations are used to identify further improvements.

3 Results and discussion

3.1 Cell results

The IV results of the different groups are given in Table 1. The best cell efficiencies are given in the upper part of the table for the various wafer types; the average efficiencies are given in the lower part of the table.

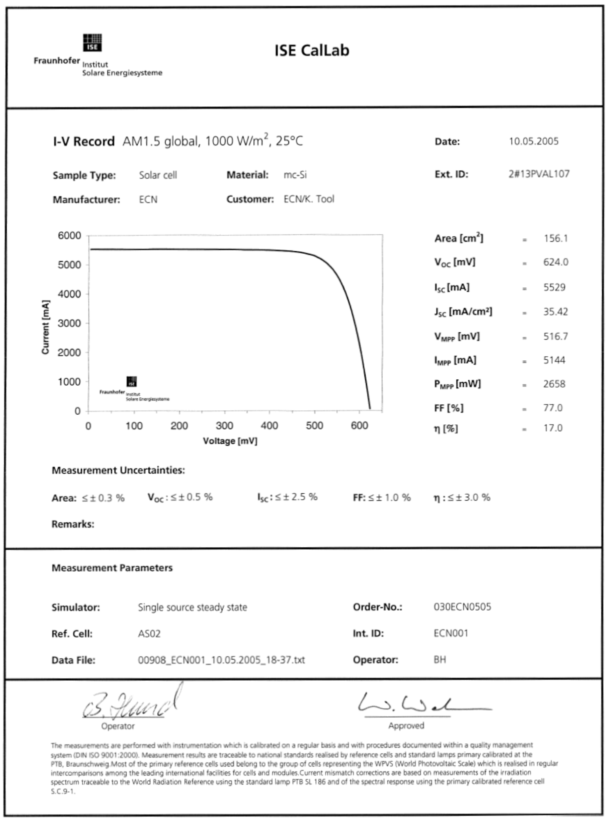
Table 1 IV characteristics averaged over the group and of the best cell for the materials used.

wafer type	J_{sc} mA/cm^2	V_{oc} mV	FF -	η -
A: best cell[a]	***35.4***	***624***	***77.0***	***17.0***
B: best cell	35.0	616	76.9	16.6
FZ: best cell	35.6	625	77.8	17.3
A: average	34.84	616.1	76.6	16.5
B: average	34.77	614.5	76.4	16.3
FZ: average	35.48	624.0	77.0	17.1

[a]: measured by Fraunhofer ISE Callab (Figure 2).

To quantify our progress made since the 19th EPVSEC in Paris 2004, IV results of our record cells are summarized in Table 3, and the IQEs of the cells are shown with respect to the 17.0% cell in Figure 6. The best cell presented at the Paris conference [2] has an emitter of 65 Ω/sq, that of the Orlando conference 80 Ω/sq [4], and that of the 17.0% presented here 70 Ω/sq.

The texture for the 17.0% cell presented in this paper is really much improved. This leads to a gain in current due to improved light coupling, but some losses in V_{oc} due to less effective surface passivation (emitter and texture). This is confirmed by the IQE ratios presented in Figure 3. The blue responses of the 16.5% and 16.8% cells are better than that of the 17.0% cell. However, the bulk and/or rear side of the 17.0% is somewhat better.


Fraunhofer Institut Solare Energiesysteme

ISE CalLab

I-V Record AM1.5 global, 1000 W/m², 25°C — **Date:** 10.05.2005

Sample Type: Solar cell — **Material:** mc-Si — **Ext. ID:** 2#13PVAL107

Manufacturer: ECN — **Customer:** ECN/K. Tool

Area [cm²]	=	156.1
V_{OC} [mV]	=	624.0
I_{SC} [mA]	=	5529
J_{SC} [mA/cm²]	=	35.42
V_{MPP} [mV]	=	516.7
I_{MPP} [mA]	=	5144
P_{MPP} [mW]	=	2658
FF [%]	=	77.0
η [%]	=	17.0

Measurement Uncertainties:

Area: ≤ ± 0.3 % V_{OC}: ≤ ± 0.5 % I_{SC}: ≤ ± 2.5 % **FF:** ≤ ± 1.0 % η : ≤ ± 3.0 %

Remarks:

Measurement Parameters

Simulator: Single source steady state — **Order-No.:** 030ECN0505

Ref. Cell: AS02 — **Int. ID:** ECN001

Data File: 00908_ECN001_10.05.2005_18-37.txt — **Operator:** BH

Operator — Approved

The measurements are performed with instrumentation which is calibrated on a regular basis and with procedures documented within a quality management system (DIN ISO 9001:2000). Measurement results are traceable to national standards realised by reference cells and standard lamps primary calibrated at the PTB, Braunschweig.Most of the primary reference cells used belong to the group of cells representing the WPVS (World Photovoltaic Scale) which is realised in regular intercomparisons among the leading international facilities for cells and modules.Current mismatch corrections are based on measurements of the irradiation spectrum traceable to the World Radiation Reference using the standard lamp PTB SL 186 and of the spectral response using the primary calibrated reference cell S.C.9-1.

Figure 2 Calibration report of the 17.0% mc-Si solar cell

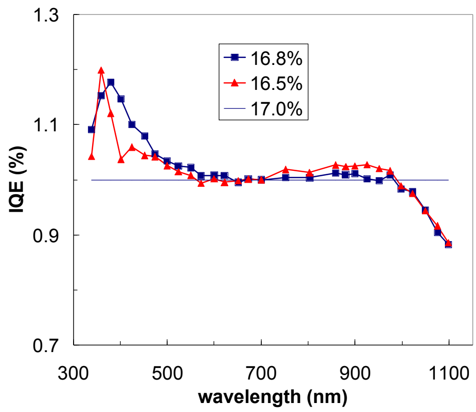


Figure 3 IQE ratios of previously reported cells with respect to the 17.0% mc-Si cell

3.2 PC-1D modeling

To determine the limitations in our processing we analyzed our results using PC-1D. We used the procedure as described in [2]; fit IV and the IQE of the FZ cell; use the obtained rear side parameters S_{rear} and R_{rear} in the fit of IV and IQE of the mc-Si cell.

The result can be seen in Table 2. Furthermore, improved parameters based on earlier observations are used for PC-1D calculations to determine the efficiency potential. Reducing the effective S_{front} to 5×10^4 cm/s which is comparable to our 16.8% cell will increase the efficiency to 17.5%. Increasing τ_{bulk} to 150 μs results in η=17.6%; reducing S_{rear} to 200 cm/s gives η=17.7% and finally increasing R_{rear} to 80% gives η=18.1%.

Lifetimes up to 150 μs can be obtained on mc-Si wafers after gettering and passivation [5]. The parameters for the improved S_{rear} and R_{rear} have been observed in separate experiments [6,7]. Both the bulk and rear side improvements are needed to obtain 18% efficiency.

Table 2 PC-1D fitting of FZ and 17.0% mc-Si cell. Improvements to obtain 18% are also included.

property/ cell output	FZ	17% mc-Si	improved (18%)
τ_{bulk} (μs)	1000	90	150
S_{rear} (cm/s)	350	350	200
R_{rear} (%)	67	67	80
S_{front} (cm/s)	$2.7\cdot10^5$	$2.5\cdot10^5$	$5\cdot10^4$
modeled V_{OC} (V)	0.624	0.624	0.636
modeled J_{SC} (mA/cm²)	35.9	35.4	37.0
modeled FF	0.777	0.771	0.769
modeled η (%)	17.4	17.0	18.1

6 Conclusions

It is shown that completely in-line cell processing using belt furnaces with a standard metal belt can be used for high-efficiency solar cell processing.

With the in-line process a 17.0% confirmed efficient 156 cm² mc-Si solar cell was made using wet chemical texturing, a homogeneous emitter and firing through SiN_x:H combined with screen printing. PC-1D modeling showes that an 18% cell efficiency could be achieved when improved processes are implemented in the current cell processing.

Acknowledgement

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