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A Review on 5 Years Cell Development within the European Integrated Project Crystal Clear

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ABSTRACT

The integrated project (IP) Crystal Clear has been finalized in June 2009 and thus a chapter of more than 5 years successful collaboration between European solar cell research institutes and industry is closed.

This paper reviews the achievements within the 4th subproject (SP4) of Crystal Clear dealing with the development of advanced solar cell concepts. Within SP4, 12 of the 16 partners have participated and have formed a productive consortium. The goal of this subproject was the further reduction of the cell production costs to enable the psychological important Si PV module price below 1 Euro/Watt. This should be reached by novel cell designs and manufacturing processes in order to achieve a process cost reduction of 40% (cost per Wp). One major effort was put in the development of novel cell concepts and processes suited for thin wafers in industrial fabrication. Three cell concepts were distinguished and developed by the participating institutes: i-PERC, MWT with full Al, and solar cells with laser fired contacts (PERC-LFC). In addition to the effort to implement these concepts into an industrial type of process with large area wafers, excellent results have been achieved on EFG and RGS ribbons. World record results with laboratory-type processes could be reported, with efficiencies of 18.2 % on EFG ribbons and 14.4 % on RGS ribbons. The defect mechanism of these materials has been studied in detail and efficiency limits have been indicated. The paper will refer to the separate contributions submitted to the conference by the different partners on specific topics.

1 INTRODUCTION

Over the past three decades industrial crystalline silicon PV technology has shown impressive growth towards technological and economic maturity. This is evidenced by the fact that the experience curve for PV modules, which is almost exclusively determined by crystalline silicon, is characterized by a progress ratio of approximately 80% [1] over the same period. In other words, typical selling prices have decreased by 20% for every doubling of the cumulative global sales.

The all over objective of the CRYSTALCLEAR project is to enable a price reduction to a level of 1 €/Wp, which roughly corresponds to electricity generation costs of 15 to 40 eurocents per kWh, depending on location in the EU *(Roughly assuming a performance ratio of 85%, 3% real interest rate, 20 years economic lifetime, and 1% operation and maintenance costs per year)*. This is an improvement of 40 to 50 % over the present situation and brings the costs into the range of consumer electricity prices, which is often considered to be the first major hurdle to overcome in order to realize large-scale application of photovoltaics.

Solar cell manufacturing is a key issue in cost reduction strategies for photovoltaics. There are many different ways to tackle production costs per watt-peak of module power, and most of those relate in some way to cell manufacturing: enhancing cell efficiency, using thin and large silicon wafers, processing low-cost material, increasing process quality, yield and throughput, and implementing cell designs to allow for low-cost module assembly (such as back-contact schemes). Each of these topics is investigated in the subproject 4 (SP4) of the Crystal Clear project.

Work has been performed on advanced cell concepts, on the high-efficiency potential of novel low-cost silicon materials, and on next generation cell options.

Advanced manufacturing technologies such as plasma processes, rear side passivation, local Al BSF, front side metallization, selective emitter formation and laser drilling and ablation have been further developed and evaluated. Industry has accompanied the work of involved institutes and universities to guarantee a fast technology transfer. An evaluation matrix for all concepts and processes including cost reduction calculations aids in effective focusing on the most promising technologies.

Dedicated production techniques, concepts and processes for very thin (<150 µm) and large (156 x 156 mm^2) wafers have been developed using the following cell concepts:

Solar cells based on the PERC concept with a passivated rear and local Al-BSF (i-PERC).

Solar cells based on a MWT concept with full Al

Solar cells based on the PERC concept with laser fired contacts (PERC-LFC).

The combined activities of SP4 and related SP's can lead to a decrease of production costs per watt peak of typically 50%.

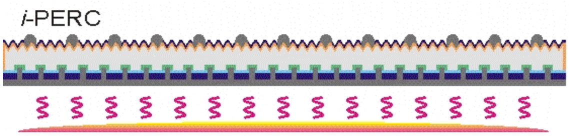
2 EXPERIMENTS AND RESULTS

In order to reach the project goals of decreasing the cost per watt different approaches has been investigated: Cell concept study, Inline characterization benchmarking, low cost material study, photon inversion study.

2.1 Cell concepts

Three cell concepts have been defined to provide the technology demonstrator for thin cells (<150µm) large area (156x156 mm^2) in modules:

2.1.1 *i-PERC*



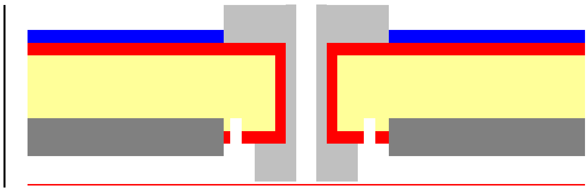
Plasma texturing (front)
One-side diffusion (CVD POCL$_3$)
Rear surface Passivation (SiO$_x$/SiN$_x$)
ARC deposition (PECVD SiN$_x$)
Rear laser ablation
Rear metallization (Al sputtering)
Front metallization (Ag SP)
Contacts co-firing

120µm thin, 15x15 cm^2, mc-Si

Best cells	Area [cm²]	Jsc [mA/cm²]	Voc [mV]	FF [%]	Eff [%]
Al BSF	225	33.1	603	76.5	15.3
***i*-PERC**	225	34.3	618	76.0	16.1

Figure 1: Schematic cross section, process flow and cell results of the i-PERC 120µm thickness, area:15x15 cm^2.

2.1.2 *.MWT concept with full Al rear (PUM)*



Flow chart PUM processing
Hole lasering
Isotexture
Emitter diffusion
P-glass removal
Front SiN$_x$
Ag front, *hole*, rear metallization
Al rear metallization
Co-firing
Hole and edge isolation

79 cells 120um	**Jsc(mA/cm^2)**	**Voc(V)**	**FF(%)**	**Eta(%)**
average	**35.0**	**0.619**	**77.2**	**16.8**
best	**35.4**	**0.624**	**77.6**	**17.1**

80 cells 160 um	**Jsc(mA/cm^2)**	**Voc(V)**	**FF(%)**	**Eta(%)**
average	**35.8**	**0.626**	**77.7**	**17.4**
best	**36.0**	**0.629**	**78.0**	**17.6**

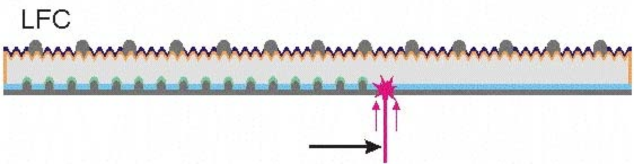
Figure 2: Schematic cross section and process flow of the PUM process. 120µm thickness, area 15.6 x 15.6 cm^2.

Results batch of ~80 cells 120 µm thickness: best 17.1% (for best 36 cells: average 16.8%)

Results batch of ~80 cells 160 µm thickness: 17.4%; best cell 17.6% (for best 36 cells: average efficiency 17.5%)

With the 160 µm cell the world record module has been made.

2.1.3 *LFC-PERC*



Alkaline Texturisation
Diffusion 60/80 Ω/sq.
PSG etching / cleaning
ARC Deposition
Wet Etching Rear Emitter
Cleaning
Thin Thermal Oxidation
PECVD Deposition Rear
Ag Paste Printing (Front)
Al Paste Printing (Back)
Paste Co-Firing
Laser Fired Contact (LFC)
Sintering
Light Induced Plating of Ag
Measuring

Measurements on 24 solar cells (as-diff. 85 Ohms/sq.) Median Average Stddev	A [cm²]	V_{OC} [mV]	J_{SC} [mA/cm²]	P_{mp} [mW]	V_{mp} [mV]	J_{mp} [mA/cm²]	FF	η [%]
Best cell (E081)	148.9	643.0	37.77	2707	522.0	34.97	0.752	18.3
E081 AD	148.9	641.5	37.68	2691	519.1	34.96	0.751	18.1
E081 AD CalLab	148.9	639.4	37.66	2679	518.1	37.71	0.747	18.0

Figure 3: Schematic cross section, process flow and cell results of the LFC-PERC Cz-Si, 130µm thick, 12.5 x12.5 cm^2.

2.2 Ribbons (low cost materials)

EFG ribbons and RGS material has been investigated. While solar cells made from RGS show deficits due to the high defect density of the material, EFG cells could produced showing promising potential towards high efficiency.

The combination of laser fired contacts with a plasma texturing step showed very encouraging results as the enhanced light trapping of the front surface and the high reflectivity of the rear side (evaporated Al on the SiO_2/SiN_x-stack) strongly enhance the long wavelength IQE

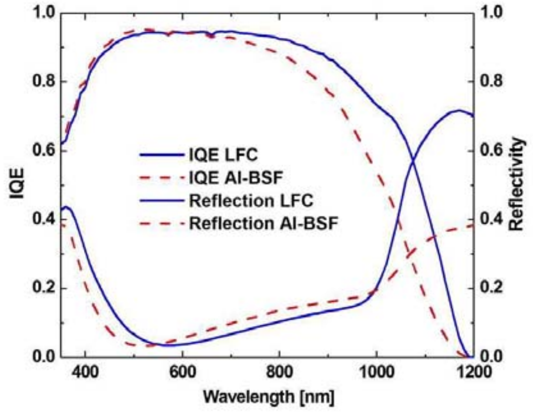
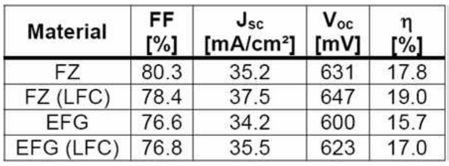


Figure 4: EFG solar cells with plasma textured front surface, one of the cells has a common Al-BSF, the other one a dielectric rear side passivation and LFCs.



Material	FF [%]	J_{sc} [mA/cm²]	V_{oc} [mV]	η [%]
FZ	80.3	35.2	631	17.8
FZ (LFC)	78.4	37.5	647	19.0
EFG	76.6	34.2	600	15.7
EFG (LFC)	76.8	35.5	623	17.0

Figure 5: EFG cell results using plasma texturing and LFC benchmarked against cells made of FZ Si. Area 2x2 cm^2. 180µm thickness.

In a high efficiency process world record results on EFG material could be achieved. The high efficiency process flow is depicted in fig 6 the cell results are summarized in table 1.

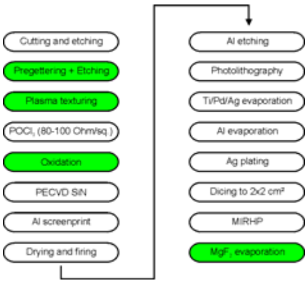


Figure 6: High efficiency EFG **process flow**

EFG 4cm^2	Jsc(mA/cm^2)	Voc(mV)	FF(%)	Eta(%)
	36.8	632	78.1	18.2

Table 1: Solar cell results of the high efficiency EFG process

In an industrial i-PERC process cell results up to 16.4% could be achieved on 140um thick EFG wafers. These results are presented in table 2.

J_{sc} (mA/cm²)	V_{oc} (mV)	FF (%)	Eff. (%)
34.8	620	76	16.4

Table 2 Solar cell results of i-PERC cells on EFG Si substrates (100 cm^2, 170 µm thick)

2.3 Inline Characterization

New characterization techniques suitable to be integrated within solar cell production lines are developed. The techniques have been tested on their capability to handle inline process velocities of 1sec / wafer in order to be consistent with up to date solar cell production throughput. The highlights of the inline characterization Techniques developed within SP4 are summarized in the following bullet points:

2.3.1 Illuminated Lock-in Thermography

Fast iLIT (illuminated Lock-In Thermography) allows the detection of local shunts spatially resolved within a measurement time of only 1 s.

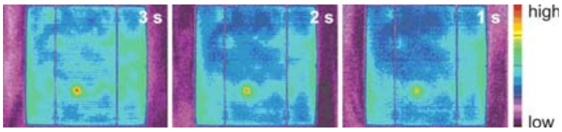


Figure 7: Fast iLIT measurements of a solar cell with a Lock-In frequency of 1 Hz.

2.3.2 Inline interstitial iron concentration

We demonstrated by means of numerical simulations that the interstitial iron concentration (*C*Fei) in standard industrial-type mc Si cells can be obtained from 2 measurements of the spectral response *SR*(E1) and *SR*(E2) (= short circuit current density / light intensity) of the solar cells at 2 different light intensities *E*1 and *E*2 at a single near infrared wavelength

The technique relies on the characteristic injection-level dependence of the diffusion length governed by the Shockley-Read-Hall minority carrier recombination due to interstitial Fei in 0.5 to 2 Ωcm *p*-type crystalline Si the measurement period of the proposed technique is potentially below 1 s.

2.3.3 Inline non-contact surface photovoltage

SPV: A measurement time of < 1 s and an accuracy of < 6 % is obtained

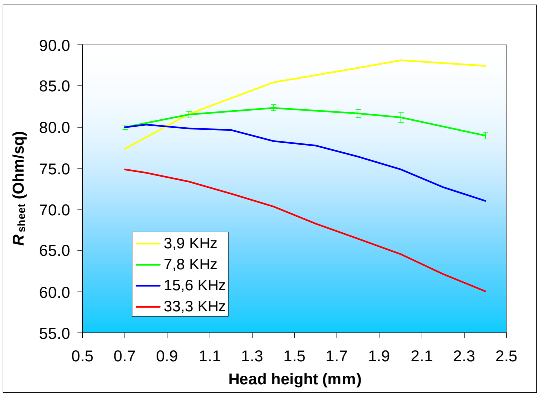
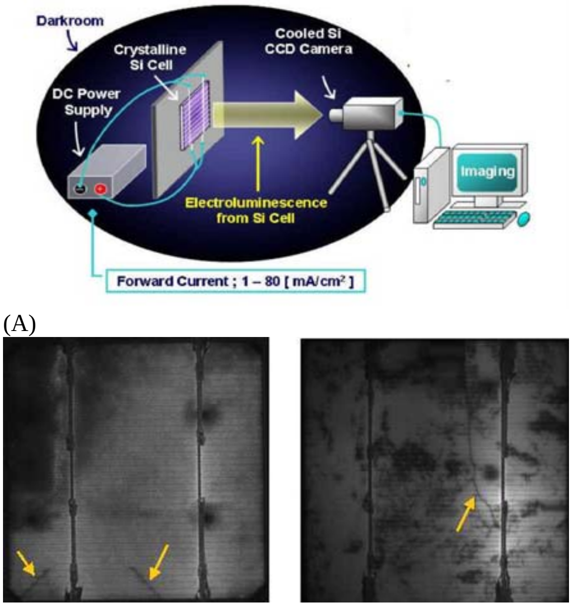


Figure 8: Impact of the calibration on measurement accuracy. Two measurements of the same sample with the same calibration settings but different coil/wafer distances are depicted.

2.3.4 *Inline Electroluminiscence*

EL: 512x512pixel, measurement time 0.8sec/cell, easy crack recognition on FZ, small cracks are difficult to distinguish from grain bounderies in mc-Si.



(A)

(B)

Figure 9: Schematic graph of electroluminescence measurement set-up (A) and EL images of CZ and mc Si cells with cracks (B).

2.4 Photon conversion

The purpose was to investigate novel concepts that can lead in theory to efficiencies exceeding the Shockley-Queisser limit for silicon solar cells. The scope was narrowed down to photon conversion applied to Si solar cells, evaluating the potential and the efficient integration in fabrication processes. The idea is to convert the incoming photons in a specific part of the spectrum into photons with different energies so that they can be absorbed or converted more efficiently by the Si solar cell. One distinguishes between photon conversion towards lower energies (which includes quantum cutting and photon down-shifting) and up-conversion. These photon converters can in principle be easily implemented on Si solar cells, by adding a layer on top (for conversion towards lower energies) or at the bottom of the cell (for up-conversion). This is viewed as a big advantage as there is no need to modify the semiconductor; one can use the well-established crystalline Si technology as a base. Within SP4 research is conducted on photon-shifting using nanoparticles on several matrices (based on silicon nitride and/or silicon oxide layers) and up-conversion using rare-earth doped compounds.

2.4.1 *Photon Shifting*

The internal quantum efficiency of the cells is shown in Figure. The cells with high R exhibits a higher response in the UV part. A high IQE was measured for the sample showing the highest luminescence, higher than that of the cell with a conventional PECVD silicon nitride. The measured IQE above 80 % at 400 nm is actually remarkably high considering the very deep emitter of 40 Ω/sq. The room temperature photoluminescence measured on the cell itself was substantially larger for that sample than for the other samples (figure 7). Therefore there are strong indications that it might be related to a down shifting effect.

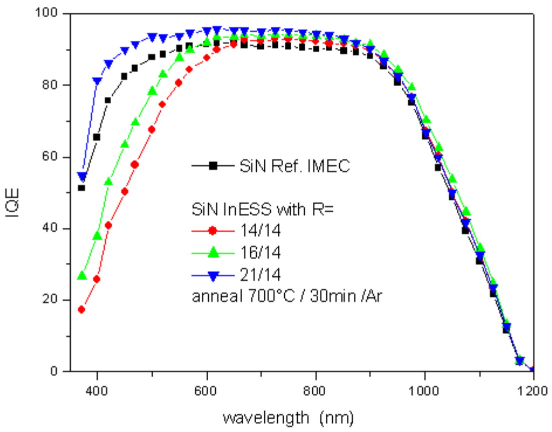
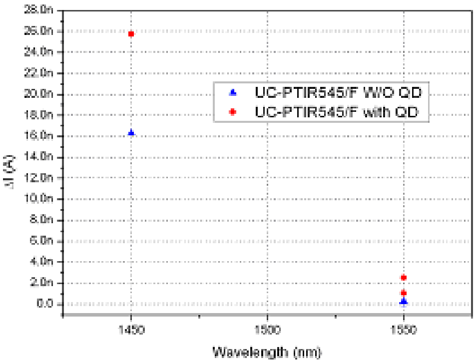


Figure 10: IQE curves of solar cells made with silicon nitrides developed for photon shifting.

2.4.2 *Up conversion*

Er-doped phosphors, from the company Phosphor Technology (PTIR-545F) and from the company MaxMax (IRUCG and IRSG), have been tested. Bifacial solar cells have been fabricated and the up-converters have been attached to the rear side by two simple methods: either by dissolving it in a spin-on oxide, or by doing that in a silicone.

The result of the measurements is shown in the next figure 11, where in all cases an increase in the photocurrent gained by combining the Er-doped phosphor with the quantum dots is seen. Although further characterization is needed to give more precision, it seems that the quantum dots are very effective in shifting light power to the range where the up-converter responds.



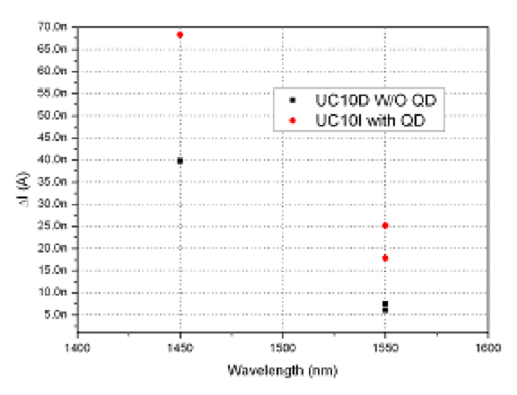


Figure 11: Photocurrent versus wavelength for PTIR545/F embedded in the oxide (left) and in the silicone (right) with and without Quantum Dots.

This is the first time this phenomenon has been experimentally shown for silicon solar cells.

3 BENCHMARKING

In the following chapter SP4 objectives are benchmarked against the *project results:*

Objective: To demonstrate the concept of photon conversion for Si solar cells and improve the performance of the photon converting structures
Photon shifting with silicon nanoparticles of silicon nitride was further explored, and the use of photoluminescent material for the enhancement of up-converting systems was demonstrated for the first time

Objective: To demonstrate stable, high efficiencies on solar cells on low cost materials
With an industrial-type process on thin EFG ribbons, efficiencies up to 16.4 % were achieved (170 µm thick, 100 cm2)
In a high efficiency process 17% on 180µm thick EFG Ribbons

Objective: To process high efficiency, industrial-type solar cells on thin (150µm or less) substrates
An efficiency of 16.8% (156 cm2), 16.1%(225cm2) was achieved on a large-area very thin (120 µm) mc-Si solar cell with an industrial-type process featuring dielectric passivation at the rear and locally alloyed contacts.
Very thin mono-crystalline solar cells were produced, with top efficiency of 18.3 % (12.5 x 12.5 cm2, 135 µm thin).

Objective: To develop innovative structures particularly adapted for large and thin wafers and easy module manufacturing
MWT cells were made on very thin, large-area mc-Si wafers, showing high efficiencies : 17.1 % (120 µm, 243 cm2), 17.6 % (160 µm, 243 cm2). World record MWT module made.

Objective: To develop and test new in-line characterisation tools suitable for novel materials and cells
A fast characterization technique for the determination of the interstitial Fe atoms was developed and demonstrated to be applicable for in-line measurements
Inline Illuminated Lock-in Thermography (iLIT)
Inline Electroluminescence (EL)
Inline non-contact Surface Photovoltage (SPV)
Inline Quasi Steady State Photoconductivity (iQSSPC)

Objective: To test large scale processing of new cell concepts
A large amount of mc-Si and cz-Si solar cells with dielectric rear surface passivation were processed in industrial environment. (i-PERC, LFC-PERC and ASPIRe)

Objective: To produce a sufficient amount of high efficiency large-area cells on very thin substrates for the fabrication of demonstration modules
56 Superslice (iPERC) cells (120um thin,243cm2,mc-Si)
79 MultistaR (PUM) cells (120um thin, 243cm2,mc-Si MWT)
86 MultistaR (PUM) cells (160um thin, 243cm2, mc-Si MWT) World record module made from these cells.
133 Multistar (LFC-PERC) cells (130um thin,147cm2,cz-Si) were delivered to SP5

4 ACHIEVEMENTS

The main achievements in SP4 of the crystal clear project are the following:

4.1 Novel processes

Novel processes for thinner cells have been developed like :
Plasma texturing
Rear side passivation
Local BSF
Front side metallization
Selective emitter formation
Laser drilling/ablation

4.2 Low cost substrates

Different low cost substrates have been screened:
EFG (Edge-defined Film-fed Growth)
RGS (Ribbon Growth on Substrate)

4.3 Cell concepts

Next generation cell concepts dedicated for thin wafers have been identified: *i-PERC, PUM and Aspire, LFC PERC*

4.4 Characterization techniques

Novel inline characterization techniques have been investigated and tested under real conditions in solar cell production lines:
EL, QSSPC, SPV, iLIT, Interstitial Fe concentration

5 REFERENCES

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