Project no. SES6-CT-2003-502583

# CRYSTALCLEAR

***Crystalline Silicon Photovoltaic:***
***Low-cost, highly efficient and reliable modules***

Integrated Project
Sixth Framework Programme, Priority 6.1.II, Sustainable Energy Systems

# Periodic Activity Report on 2008 / 2009

(publishable executive summary)

Period covered: *from month 49 to month 66* Date of preparation: *June 2009*

Start date of project: *1 January 2004* Duration: *66 months*

Project coordinator name: *Prof. Dr. W.C. Sinke*
Project coordinator organisation name: *Energy research Centre of the Netherlands (ECN)*

Revision: *[vs0.9]*

# Publishable executive summary

***Introduction***
Solar energy is clean, can be used almost anywhere, and has a huge potential. The main reason it is not yet applied on a much larger scale is the relatively high price of current systems. CrystalClear aims to bring down the production costs of the central system component, the solar module, by more than 50%. This is a key to the success of solar energy and of the European solar industry in this rapidly growing world market.

***Nature and scope of the project***
CrystalClear is (was) a research and development project dedicated primarily to cost reduction of solar (PV) modules. At the same time the projects aims at increasing the efficiency (electricity yield), improving the environmental quality and improving the applicability of such modules. CrystalClear is about crystalline silicon module technology. This comprises about 90% of today's world market and can still be improved substantially.

The CrystalClear consortium has 16 partners: 9 companies and 7 research institutes and university groups. It represents over 25 years of experience and excellence in this field, covers all aspects from raw material to final product, and, most importantly, is fit to challenge the powerful competitors from Asia and the USA. Therefore it supports the European PV industry sector to maintain its strong position on the global market.

*Companies:* BP Solar España (ES), Deutsche Cell (DE), Deutsche Solar (DE), Isofotón (ES), Photowatt (FR), REC (NO), REC Wafer Norway (NO), SCHOTT Solar (DE), SolarWorld Industries Deutschland (DE).

*Universities:* Utrecht (NL), Konstanz (DE), UPM-IES (ES);

*Research institutes:* InESS-CNRS (FR), ECN (NL, *coordinator*), FhG-ISE (DE), IMEC (BE).

***Project contact details***
CrystalClear has a public website providing information to the interested specialist and non-specialist: www.ipcrystalclear.info.

Project manager is Wim C. Sinke (Energy research Centre of the Netherlands, ECN); the project management office (PMO) can be reached at pmo@ipcrystalclear.info (after 30 September 2009, use sinke@ecn.nl) or +31 224 564539.

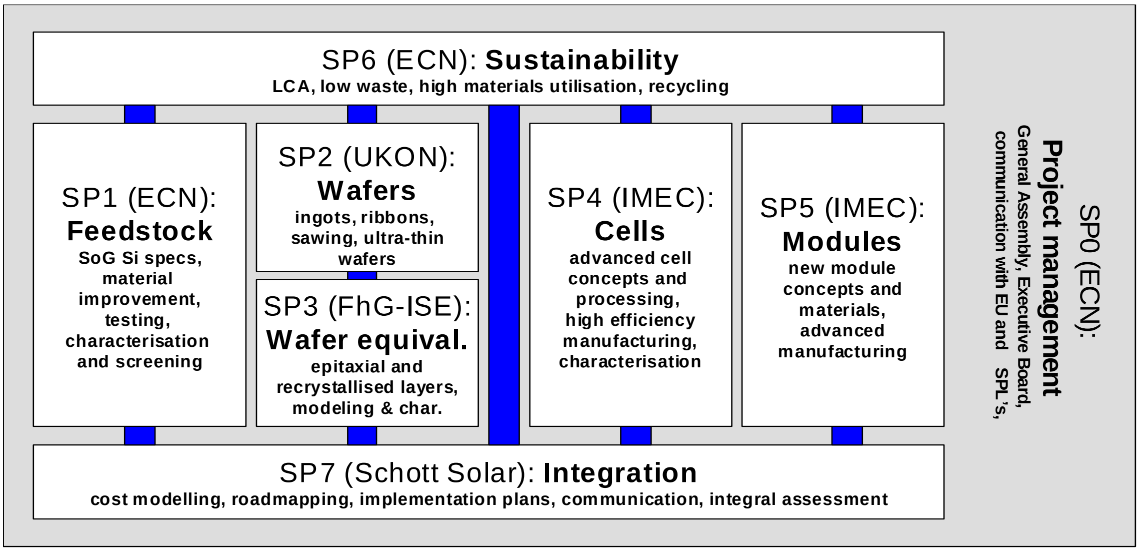
***Project lead time and budget***
From January 2005 to June 2009 (66 months)
Total project cost: M€ 28
EC contribution: M€ 16

***General overview of activities***
The CrystalClear project has tackled all aspects from the raw materials up to the completed solar module. Key activities concern:

- strongly reducing the consumption of expensive materials (especially silicon, but also others) as well as introducing the use cheaper materials;
- increasing the electricity output of solar modules;
- developing highly automated, high-throughput, low-cost manufacturing processes;
- screening materials, processes and products in relation to sustainability and suitability for large-scale use.

Within CrystalClear an average of over 50 researchers from 6 European countries worked together. For this to be effective CrystalClear has introduced a variety of communication tools and practices, in many of which internet plays a crucial role. In addition to that, face-to-face meetings are indispensable. Industry consortium partners are the natural first users of research results. Since they are very well represented the impact of CrystalClear is optimally assured.

***Project structure (SP = Sub Project)***




***Societal impact***

There is a rapidly increasing awareness and sense or urgency concerning the transition to a sustainable energy supply. The green house effect, but also dependence on energy imports, local air pollution and unavailability of energy to poor people are seen as major problems to be addressed ambitiously and immediately. For the longer term the depletion of fossil fuel reserves needs to be faced. Solar energy can play a key role in solving all these problems, but still has a very small impact today. By far the most important barrier towards large-scale use of solar energy is the current price of systems and hence, the cost of electricity generation. Therefore CrystalClear takes price (or better: cost) reduction as the central theme. CrystalClear is targeted to enable a price reduction grid-connected systems to a level that allows reaching (or passing) the point of grid parity with retail electricity. This is done by reducing the manufacturing costs of solar modules, which form the heart of photovoltaic systems, to a level of 1 € per watt-peak (Wp).

***Expected results at the end of the project***

The expected results of CrystalClear after completion of the project in June 2009 have been divided in three main blocks.

1. Availability of innovative manufacturing technologies which allow solar modules to be produced at a cost of 1 €/watt-peak (which is a reduction by more than 50% compared to state-of-the-art at the start of the project). This objective is extremely ambitious, but essential to get world-class technology. Manufacturing cost reduction is essential to bring prices of modules and turn-key complete systems down (see graph).
2. Improved environmental profile of solar modules by reduction of materials consumption, replacement of undesired materials and designing for recycling. This will strengthen the position of solar energy as a clean and sustainable alternative to conventional electricity generation.
3. Enhanced applicability of modules by tailoring to customer needs and by improving product lifetime and reliability. Since solar modules will be used in very different situations (e.g. on buildings) flexibility of use is crucial. Assured quality is a prerequisite for large-scale, professional use.

In the following, the project results achieved in 2008 and 2009 are summarized per Subproject, i.e. along the wafer silicon value chain from silicon starting material (feedstock) to the final module and beyond:

- Sub Project 1; Feedstock
- Sub Project 2; Wafers
- Sub Project 3; Wafer-equivalent approaches
- Sub Project 4; Cell technology
- Sub Project 5; Modules
- Sub Project 6; Environmental sustainability
- Sub Project 7; Integration

***Activities and results achieved in the last reporting period (Jan 2008 - June 2009)***

*Sub Project 1: Feedstock*
Of the 5 Sub Projects dealing with the different steps of the value chain, Subproject 1 is dedicated to the subject of the so-called feedstock, the silicon that solar cells are made from. For solar cells (as well as for microelectronic chips) a high grade (purity) of silicon is required. In response to the rapid growth of the PV industry, dedicated production of such high-purity ("solar grade") silicon is now in the planning, pilot, or preproduction phase in a number of countries worldwide.

In 'impurities and specification of solar grade silicon' related researched activities in CrystalClear, the role of contamination in present wafer material, the sources of such contamination, its behaviour during gettering, and the changes in electrical properties of the contaminants by hydrogen passivation have been researched. Some of this work is similar to research performed in the 1980's by Westinghouse Corp. Those results were however obtained with cell processing technology of the 1980's, and mostly on mono-crystalline material, and recent results in SP1 show that interesting deviating results occur for intentionally contaminated multi-crystalline silicon with Fe, Ni and Cu. It was concluded that the compared different approaches (casting vs FZ) arrive to similar results, validating the results achieved with the chosen approach of mono and multi-crystalline FZ wafers. After Fe and Mo, other relevant impurities were identified like Ni and Cr for their presence in stainless steel, and the effect and behaviour of other individual important impurities of fundamentally different character have been investigated, e.g. Titanium, Copper and Aluminium.

The results on behaviour of impurities and mitigation of their effects have been communicated to the industrial parties, also those involved in other subprojects, at the plenary workshops of CrystalClear and at international conferences and workshops. Furthermore, a workshop was organised in Amsterdam in November 2008 by the consortium with the title: 'Arriving to Solar Grade Silicon Feedstock specifications'.

The feedstock needed to test newly developed SoG-Si feedstock in CrystalClear was with much difficulty acquired by the partners, and assessed under industrial conditions. As it has become clear that feedstock for the last 2 years of the project will be only available to the CrystalClear consortium in either very limited quantities or on bilateral terms, SP1 decided to refocus its activities. Further research on this topic focused on the relationship between possible features of new potential feedstock and the wafer/cell characteristics. Currently, new SoG-Si feedstock from various metallurgical purification techniques is entering the PV-market, offering an alternative to the very pure poly-Si material. Also, Si-feedstock from Fluidized Bed Reactor processes has been introduced to the (currently very heated) market for solar grade Si. Feedstock based on metallurgical routes, has the challenge of removing doping elements, such as P and B, which require long high-temperature steps, increasing the thermal budget of the purification. As addition to the removal of a specific dopant is the admixture of a complementary element in order to achieve the right ingot resistivity, which is required for a good solar cell performance. The effect of this compensation has been chosen as a very interesting topic to investigate.

Feedstock from FBR-routes has generally smaller particle size then the eg-Si dominantly used. Based on research in the previous period, further topics for investigation arise, to understand and predict the behaviour of small particle sized feedstock, e.g. the effect of longer melting time and oxygen content on the wafer/cell level.
The industry actively took part in these above mentioned research topics, as it is crucial for them to know, what the consequences could be, when deviating from their current feedstock requirements.

*Sub Project 2: Wafers*
Sub Project 2 deals with the preparation of solar silicon material by ingot growth applying directional solidification. Further it deals with wafering of these materials by multi wire slurry sawing (MWSS) as well as by diamond wire cutting. The general aim is to reduce the wafer cost by increasing the throughput of ingot fabrication and by reducing the silicon consumption per wafer.
Activities on crystallization of two kinds of ribbon growth carried out in the past within SP2 have been stopped according to the detailed implementation plan in M48 (EFG) or have been shifted into another SP (RGS activities shifted towards SP4).

Several upper size ingots of 450-600 kg i.e. up to 130% more weight than standard were grown by two industrial partners and analysed by several SP2 partners. Their electrical quality was found to be similar to the standard of today's production, although for some ingots reduced as grown lifetimes especially close to the bottom of the block could be observed. The productivity could be increased by around 85% for both industrial partners active in the topic of increasing ingot size, and costs per ingot mass could be reduced to 50% for the 600 kg ingot compared to the standard one.
The increase of as grown lifetimes due to the use of pure coating material could be demonstrated by another industrial partner, but the increase in as grown wafer quality did not lead to significantly higher cell efficiencies.
A comparison of thin (200 µm) solar cells with cells of standard thickness processed from the new 12-facet EFG technology revealed slightly higher $V_{oc}$ and slightly lower $J_{sc}$ values for the thin EFG material, but almost identical efficiencies. The use of thin EFG material therefore seems to be suited for industrial processing without decrease in efficiency.
A large amount of thin Cz and multi-crystalline wafers was wafered and delivered to SP4 for processing of solar cells for the demonstration modules.
Reduction of kerf loss was under investigation and tests with two new 100 µm thin wires of different alloys have been performed in comparison to wires of standard thickness (120 µm). Using a wire of 100 µm diameter it is possible to obtain a kerf loss of 140 µm. The 100 µm wire has a better mechanical resistance, but the sawing speed is still lower.
Tests of mechanical stability on pre-stressed wafers using different setups (twist test and 4 bar test) have been performed. Both setups lead to comparable results, but surprisingly only the dropping of a pin (0.5 g) onto the wafers from 8 or 16 cm height lead to poorer mechanical stability, whereas all other methods for pre-stressing the as grown wafers lead to the same mechanical stability as for the unstressed references.

*Sub Project 3: wafer equivalent approaches*
Sub Project 3 deals with R&D on crystalline silicon thin-film solar cells, which are compatible to state-of-the-art wafer technologies but aim at a significantly lower cost and an alternative resources supply. The respective approach is called "wafer equivalent approach". Initially SP3 started with 3 concepts:

- The free-standing lift-off concept (Subject 3.1), where very thin layers are detached from a substrate by means of a porous silicon separation layer, and processed after epitaxial thickening to very thin solar cells. Due to major problems and investment needs concerning handling of the thin layers, this subject was stopped already after month 24.
- The epitaxial wafer equivalent (EpiWE), a sole silicon epitaxy on low-cost silicon substrates. This concept turned out to be the one which fitted best into the timeline and aims of CrystalClear. It was therefore pursued in CrystalClear as Subject 3.2 from month 18 to the very end of the project.
- The Recrystallized Wafer Equivalent concept, which is based on recrystallized silicon layers on mechanically supporting substrates to produce Wafer equivalent solar cells. Investigated in Subject 3.3, it showed its economic suitablility for the CrystalClear cost aims. However the experimentally achieved efficiency was behind the milestones, which made clear that more fundamental development effort was needed. Therefore the activity was stopped after month 48.

During the actual reporting period, we worked on the major topics "optical confinement", "silicon epitaxy" and "cell and module processing".
Optical confinement was realized by implementing two features: a surface texture made by plasma etching, and a reflector located on the rear of the epitaxial layer. We focused on plasma etching in large in-line tools for homogeneous texturing of the damage free epitaxy layer. We managed to texture wafers in a commercial tool (800 mm process width) with weighted reflectivities of 16%, >99% diffuse incoupling of light and only 2 µm etching depth.
Rear reflectors were realized by so-called chirped photonic bragg reflectors. These structures allow for wide-band reflectors of very high reflectance. We achieved total reflectances higher than 90% for wavelengths from 900 nm to 1150 nm. Applying these reflectors to EpiWE resulted in best solar cells on mc-Si substrate of 15.2% efficiency, with a current gain of 2-3 mA/cm$^2$ in a 20 µm thick epitaxial layer. A similar cell on monocrystalline substrate even achieved 16.1% efficiency.
As one approach to increase productivity and eventually cell efficiency we developed the in-situ epitaxy of base and emitter of the solar cell, saving the elaborate separate process of phosphorus diffusion. We were able to prove that the emitter deposited in-situ on the base layer

is as good as conventionally processed high-efficiency emitters, and in addition has a tremendous advantage in process time and cost.
Large-area epitaxial deposition was investigated in an inline prototype tool, the so-called ConCVD. We managed to increase the useable substrate size from 100 x 100 $mm^2$ to the nowadays standard size of 156 x 156 $mm^2$. Stability of the process was improved significantly, allowing deposition times of several hours before maintenance was necessary.
By assembling several demonstration modules, we were able to show the suitability of the wafer equivalent solar cells for standard module processing. The best module consisted of 32 EpiWE solar cells, resulting in a module aperture efficiency of 13.0%.

*Sub Project 4: Cell technology*
The goal of Sub Project 4 is to develop cell designs concepts and manufacturing processes that would enable a reduction in the order of 40% of the cell processing costs per Wp. The major objectives of the subproject within the reporting period were:

1. to demonstrate the concept of photon conversion for Si solar cells and improve the performance of the photon converting structures.
2. to demonstrate stable, high efficiencies on solar cells on low cost materials
3. to process high efficiency, industrial-type solar cells on thin (150µm or less) substrates
4. To develop innovative structures particularly adapted for large and thin wafers and easy module manufacturing
5. to develop and test new in-line characterisation tools suitable for novel materials and cells
6. to test large scale processing of new cell concepts
7. to produce a sufficient amount of high efficiency large-area cells on very thin substrates for the fabrication of demonstration modules

- Photon shifting with silicon Si nanoparticles of Si silicon nitride was further explored, and the use of photoluminescent material for the enhancement of up-converting systems was demonstrated for the first time
- With an industrial-type process on thin EFG ribbons, efficiencies up to 16.4 % were achieved (140 µm thick, 100 $cm^2$)
- An efficiency of 16.8 % was achieved on a large-area (156 $cm^2$) very thin (120 µm) mc-Si solar cell with an industrial-type process featuring dielectric passivation at the rear and locally alloyed contacts.
- MWT cells were made on very thin, large-area mc-Si wafers, showing very high efficiency : 16.9 % (120 µm, 243 $cm^2$)
- A fast characterization technique for the determination of the instertitial Fe atoms was developed and demonstrated to be applicable for in-line measurements
- An second round robin of IV characterization was carried out, showing an improved consistency of results among the partners.
- A large amount of mc-Si solar cells with dielectric rear surface passivation were processed in industrial environment.
- Very thin mono-crystalline solar cells were produced, with top efficiency of 18.3 % (12.5 x 12.5 cm2, 135 µm thick). (Superslice cells)
- A large batch of Superslice cells were delivered to SP5.

*Sub Project 5: modules*
The interconnection of very thin cells using conductive adhesives as the interconnection medium as been demonstrated reliable earlier in the project has been demonstrated in the realisation of a full size module (using 120µm thin cells originating from SP4) as the Superslice I demonstrator module. Furthermore, other options for stress free interconnections of such cells based on the use of low temperature solders have been demonstrated in another full size module with these cells.

Although the PU frame (with metal inserts) do give good mechanical properties, under the influence of temperature an humidity ingredients from the polyurethane affect the metal contacts of the cells and further cells will be necessary before this product can be introduced in industry.

Large area (60 cells) laminates with back contacted cells have been manufactured and tested. Accelerated ageing tests on these laminates revealed some failures related to the cells: cells were cracking in the laminate during production (which was reinforced upon outdoor exposure) and cells were cracking under mechanical load after production. The sensitivity of such single ribbon interconnection designs has to be further investigated.

Using back contacted cells manufactured with the technologies developed in SP4 and an interconnection technology developed in the frame of SP5 based on a rear side foil with an integrated interconnection pattern and connection between this pattern and the solder pads on the rear of the cells on the base of conductive adhesives, full size (36 cell) demonstrator modules were made with world record aperture area efficiencies for multi-crystalline silicon solar cells: 16.0% for 120 μm cells and 16.4% for 160 μm cells.

*Sub Project 6: Sustainability*
In Sub Project 6, the Life Cycle Assessment (LCA) of the existing crystalline silicon production technology was updated. The CrystalClear demonstrator modules show a decrease of the energy payback time to 1.8-2.4 years (Central Europe). The reduction in the "CML 2 baseline" environmental impacts on area basis was at least 18% for the multi-crystalline silicon and at least 25% for the mono-crystalline silicon demonstrator modules compared to 2004.

A module recycling technology was developed. LCA has shown that the environmental benefit from the recovery of materials like aluminium frame, glass, copper and silicon are larger that the environmental burden created by the take-back and recycling process.

*Sub Project 7: Integration*
The main objectives of Sub Project 7 in this reporting period were:
Finalise CrystalClear Technology Roadmap
1. Finalise cost modelling of roadmap scenarios
2. Cost modelling of CrystalClear demonstrators
3. Perform overall assessment of project results
4. Dissemination CrystalClear results (open workshop, press releases)

The subproject is managed through scheduled monthly telephone conference meetings lead by SCHOTT Solar with periodic face-to-face meetings usually combined with project workshops and general meetings.

In order to communicate the CrystalClear results to a broad audience an open one-day-workshop has been organised on May 26th in Munich, Germany. The workshop was well attended by decision makers and key actors in the field of research, development and manufacturing of PV solar energy, policy makers and press.

In 2008 a CrystalClear integration workshop was held in Alzenau. The current technology status of each subproject as well as the progress towards the achievement of the project goals has been reviewed.

After finalising the CrystalClear Technology Roadmap the cost modelling for the different roadmap scenarios has been updated and also been finalised. Furthermore, the technology developments with in CrystalClear have been evaluated economically and ecologically. This evaluation is based on the data resulting from the manufacturing of the CrystalClear Demonstrators.

As an important part of the cost modelling activities a comprehensive evaluation of cost reduction due to large scale production has been performed. This evaluation is mainly based on the feedback from the industry partners. Furthermore, the integral evaluation model has been updated and current data for four CrystalClear technologies has been implemented

A journal paper on the CrystalClear cost modelling results as well as a feature article on innovative module technology has been published.