Presented at Silicon for the Chemical and Solar Industry X, Ålesund - Geiranger, Norway, June 28 - July 02, 2010

WAFER-BASED CRYSTALLINE SILICON MODULES AT 1 €/WP: FINAL RESULTS FROM THE CRYSTALCLEAR INTEGRATED PROJECT

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1. GENERAL PROJECT OVERVIEW

CrystalClear [1-5] was a 5½-year Integrated Project carried out in the 6th Framework Program of the EU. It was finished in June 2009. The project aimed at developing technology for wafer-based silicon solar modules at 1 € per watt-peak manufacturing costs and a strongly improved environmental profile. The project was a joint effort of a consortium of 16 European companies, research institutes and university groups involved in wafer-based crystalline silicon PV technology. The project has shown that wafer-based multicrystalline-silicon solar modules can be produced at 1 € per watt-peak at a world-record efficiency of 16% and an energy pay-back time of less than 2 years in Southern Europe.

The Crystal Clear project consortium consisted of:
Companies: BP Solar (ES), Deutsche Cell (DE), Deutsche Solar (DE), Isofotón (ES), Photowatt (FR), REC (NO), REC Wafer Norway (NO), SCHOTT Solar (DE), SolarWorld Industries (DE).
Universities: Utrecht (NL), Konstanz (DE), UPM-IES (ES);
Research institutes: InESS-CNRS (FR), ECN (NL, project coordinator), FhG-ISE (DE), IMEC (BE).

The project aims 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 very ambitious, but essential to get world-class technology. Manufacturing cost reduction is essential to bring prices of modules and turn-key complete systems down.
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.

The CrystalClear project has tackled all aspects from the raw materials up to the completed solar module. Key activities concerned:

- strongly reducing the consumption of expensive materials (especially silicon, but also others) as well as introducing the use of 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.

Since many combinations of options for cell and module design, processing and materials potentially fulfill the project aims, a selection of 6 distinctly different overall technologies has been developed, underlining the many faces of wafer-based silicon PV and the variety of approaches found within the industry. The feasibility of these technologies to comply with the projects aims has been verified by detailed cost and environmental analyses. CrystalClear has chosen technologies which might be demonstrated as full-scale modules already at the end of the project as well as technologies which still need to be developed further after the project.

The project has been organized in Subprojects 1-7, covering the parts of the value chain as well as integrating aspects (environmental analyses, cost calculations, etc.):

1. Feedstock;
2. Wafers;
3. Wafer-equivalent approaches;
4. Cells;
5. Modules;
6. Environmental sustainability;
7. Integration.

In Chapter 2, a summary is given of the results obtained in Subproject 2, feedstock.

2. SUMMARY OF SUBPROJECT 1. FEEDSTOCK

2.1 Feedstock situation

Among Subprojects 1-7, the feedstock project SP1 is probably the one for which the business environment has gone through the most dramatic changes in the span of the 7 years from the planning to the project conclusion.

At the time of planning (2002-2003), the PV market was strongly growing, but it was still much below the GW size, silicon consumption was significantly lower than the polysilicon installed production capacity, semiconductor market was weak, feedstock had been predominantly made of reclaims from semiconductor industry and virgin polysilicon had just started to be extensively mixed as a supplement to the reclaims.

Silicon was affordable at a price in average below 20 US$/kg, virgin polysilicon specifically made for solar or not was traded at just above 20 $/kg.

A major shift occurred during 2004 a few months after the official kick-off of CrystalClear. Because of a strong concomitant demand from both semiconductor and PV industry offer and demand of polysilicon appeared quite in balance and it became more evident – although not for everyone - that a potential shortage of silicon feedstock might occur in a near future. Polysilicon prices strengthened and recovered levels as of before the last downturn of 1998. But silicon remained still both available and affordable.

Boosted by the remarkable growth of the PV industry silicon demand continued to increase. At the midterm assessment of the CrystalClear program in June 2006, shortage had become a reality and that year the consumption of virgin polysilicon by the solar industry sector was for the first time equivalent or had even surpassed the consumption by the semiconductor market. Both the polysilicon and the PV industry had to face this historical shift and measure the consequences of it. That triggered numerous initiatives on both immediate expansions and accelerated R&D projects on new solar grade (SoG) silicon processes. Beside polysilicon, upgraded metallurgical silicon (UMG-Si) became more widely and seriously considered as a long term solution. In addition to that, other forms of SoG silicon have been investigated as alternatives. Meantime, silicon prices had started escalating.

This trend continued until the 4th quarter of 2008, when the world wide financial crisis hit all sectors of the world's economy, semiconductor, PV and silicon industry included. The following slowdown in the PV activities reflected in the trade of modules and other materials. A useful indicator is the spot price of polysilicon which was down to 120-150 $/kg in March 2009.

In the following we will focus on the learning by the industry from the feedstock subproject activities. We will also enlighten why and how the goals and priorities had to be changed in the course of the program.

2.1.1 Goals

The goals of the feedstock subproject were twofold:

- to assess new feedstock materials, which were supposed to soon come onto the market;
- to assess the role and the limit acceptable for various frequent impurities, as it was assumed that new silicon sources may include higher concentrations than virgin polysilicon.

To develop new silicon processes was not a goal; at the time of planning several companies and research groups were strongly involved in proprietary confidential projects and it was assumed that new materials were just about to emerge and enter into the commercialization phase.

The methodology chosen was:

- produce ingots from baseline-, new- and synthetic- (virgin polysilicon contaminated on purpose by a controlled level of impurity) feedstock;
- make wafers and cells from ingots according to a standard defined procedure;
- characterize wafers and cells by all chemical and physical methods available to the consortium.

2.1.2 Results

2.1.2.1 New feedstock candidates: selection, acquisition

Several new types of feedstock were about to emerge. It was mainly granular polysilicon made by the Fluidised Bed Reactor (FBR) technique for the thermal decomposition of silane (REC) or chlorosilane (Wacker), instead of hot filament deposition as in the conventional Siemens reactor. Another interesting process was the Vapour-to-Liquid Deposition process of Tokuyama, in which chlorosilane is decomposed at higher temperature on a liquid surface of silicon. Free Space Reactor (FSR) technique decomposing silane into powder silicon (Joint Solar Silicon, a joint venture German company) was also a promising alternative. Upgrade Metallurgical Grade Silicon (UMG-Si) was first not envisaged as a candidate material to the subproject as it was perceived as a more long term alternative. Developments in the industry made us to change our mind in course of the project. Other new (or revitalized) processes were brought to our knowledge during the project, but at a stage too late to allow serious assessment. The acquisition of new feedstock trial materials appeared to be more difficult than anticipated. There are several reasons for that: one is that both producers and users preferred to work on a bilateral and confidential than a semi-open multilateral basis; another one is that the development at the companies was not as advanced as supposed, this has been later confirmed by delays of many of these projects. Overall, companies were very reluctant to communicate any information, not only on the process but also on analytical values.

2.1.2.2 New feedstock tested

Because of the difficulties and limitations mentioned above, only two new feedstock materials were extensively studied by the subproject, i.e. Wacker and REC granular polysilicon, both being produced in pilot plants but assumed representative of the forthcoming commercial process. Granular polysilicon from MEMC is an already established process and material, which has gained recognition by the industry and can provide a good model for similar granular materials. Therefore, some but less extensive studies were carried out with an ingot made of MEMC granules acquired commercially by one of the industrial partners.

The intention was for the industry to learn how to use, to handle and to melt the new feedstock and to understand the long term consequences of using it. Learning from ingoting and wafering on one side and cell characteristics on the other side should induce process adjustments and eventually defect engineering at some points of the value chain.

The industry in the project reported that they could use the granular material 100% in the charge, without noticing advantages or disadvantages on the cycle time and yield of melting-solidification as compared to their normal charges. Issues brought up were the longer melting time and the oxygen content.

No quantified information was given by the partners on these issues which seemed to have been solved by learning-through-practicing. Analysis of oxygen in ingots made of granular silicon did not show significant deviation with baseline material. Since granular and lumpy polysilicon will co-exist in the future we understand that a mix of both materials should be beneficial to the overall yield and cycle time of the process.

Cell characterization at the institutes showed also that the cells produced according to the same standard procedure as for the base line perform as base line cells. The conclusion of the subproject team and the industrial partners is therefore that granular material from a purity point of view can totally replace lumpy (chunks) polysilicon.

2.1.2.3 Impurity understanding and change in priorities

An important aspect of the subproject work was to study the role and the acceptable limit to individual or groups of impurities [6]. The program started with an ambitious activity plan involving specifically “contaminated” float zone wafers and cells. Surprising results were achieved with the two first selected impurities, i.e. iron (Fe) and molybdenum (Mo). The results taught that fairly high amounts of these metals can be tolerated as single impurity (far higher than the current assumed specification). The results showed also major differences in the respective impact of each element on the final performances of the cells. Unfortunately, further investigations with float zone material and other impurities were stopped by the withdrawal of the ingot supplier. Meantime, because of persistent material shortage the interest for UMG-Si was strengthened. Industry made in-house evaluations and influenced the subproject consortium to look at specific issues, which might arise when using such materials. We assumed metallic impurity levels above the parts per million by weight (ppm(w)) and we could evaluate in multicrystalline ingots a long series of individual impurities i.e. Ni, Cr, Ti, Al, Cu and their combination. The selection of these impurities was debated within the subproject. Criterions of selection were both academically and industrially relevant. Particular attention was put on the industrial sources of contamination (e.g. raw materials, equipment, process, handling, etc), see Figure 1.

The results confirmed the surprises from the float zone studies, and enlightened the impact of other impurities on the solar cell performances.

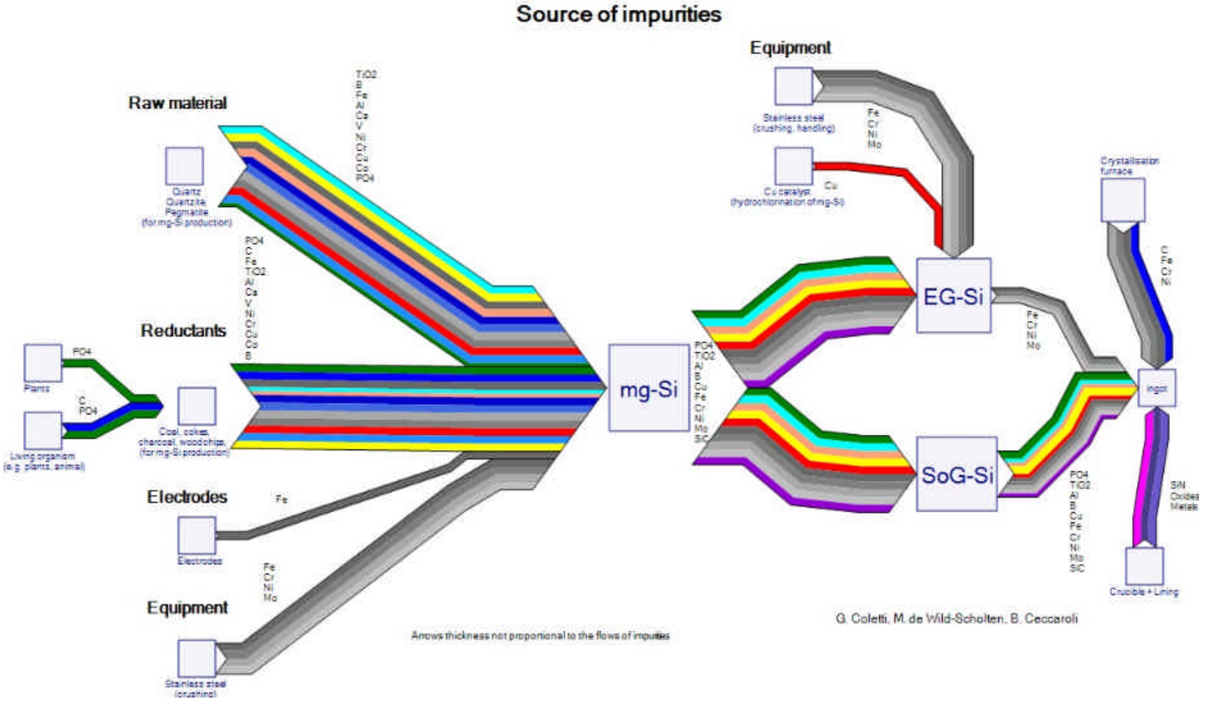

Figure 1: Schematic representation of the sources of impurities in crystalline silicon ingots (from which wafers are cut to be processed into solar cells). Graph courtesy ECN.

The learning from these studies is that good cells (high efficiency, no light induced degradation) can be achieved in spite of higher impurity contents in the feedstock. The impurities must, however, be discriminated or classified according to their ability to segregate (distribution coefficient) and diffuse (diffusivity). In addition a relationship between impurity content and extended crystal defects was found.

Furthermore, non-polysilicon feedstock is expected to contain ppm(w) amounts of boron (p-dopant) and phosphorous (n-dopant). Both modeling and experimental studies were decided to evaluate how compensation can be applied to make use of "highly" doped materials. Finally, the industry learned from the subproject work some defect engineering remedies to achieve improved cell performances with either compensated or metal contaminated feedstock materials.

In conclusion, from these studies the industry learned more about the relationship between impurities and solar cell performances. These investigations increased the competitive knowledge base, making possible to understand the limits of the state-of-the-art technology and to further develop the technology along the overall value chain (from feedstock to solar cell manufacturing). The results of these studies will be applied by the industry to optimize and develop new manufacturing techniques, not only through relaxing the material quality without efficiency penalty (as at a first glance it might seem) but also, through improved material quality to achieve very high efficiency solar cells.

3 ACKNOWLEDGEMENTS

The authors want to thank the CrystalClear partners for providing valuable input for this paper. They also want to express their appreciation for the support provided by Rolf Öström and Andreas Piontek (EC Project Officers for CrystalClear).

The EC is gratefully acknowledged for financial support to CrystalClear under Contract number SES6-CT_2003-502583.

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