SOLAR CELL PROCESS DEVELOPMENT IN THE EUROPEAN INTEGRATED PROJECT CRYSTALCLEAR

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ABSTRACT: CrystalClear is a large integrated project funded by the European Commission that aims to drastically reduce the cost of crystalline Si PV modules, down to 1 Euro/Wp. Among the different subprojects, the one dealing with the development of advanced solar cells is relatively large (with 11 partners out of the 15 Crystal Clear partners taking part) and has a crucial role. The goal of the subproject is to develop cell design concepts and manufacturing processes that would enable a reduction in the order of 40% of the cell processing costs per Wp. In this paper, we give an overview of all the development work that has taken place in the CrystalClear solar cells subproject so far. World class results have been achieved, particularly on high efficiency cells on Si ribbons, and on industrial-type solar cells on very thin (120 µm thick) substrates.
Keywords: crystalline silicon solar cells ; processing

1 INTRODUCTION

CrystalClear (CC) is a large, 5-year joint effort of a large consortium of European companies, research institutes and university groups involved in crystalline silicon PV technology [1], see also www.ipcrystalclear.info. It is an Integrated Project carried out in the 6th Framework Program of the EU. The project covers the whole value chain of Si PV up to module level. It therefore deals with feedstock, crystallization, wafering, solar cell processing and module assembly. Apart from these main activities, there are two additional ones, one dealing with sustainability of the Si PV production, and another one dealing with the wafer equivalent concept, a thin-film alternative to the traditional bulk Si solar cells but which nevertheless show important similarities with conventional Si PV.

Within CrystalClear, the subproject on solar cell processing is one of the largest, and involves 11 out of the 16 partners. The objectives of this subproject are 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. Activities are focused on high efficiency cell processing on low-cost materials and very thin wafers, and on innovative solar cell structures.

2 OVERVIEW OF THE ACTIVITIES WITHIN THE CELL SUBPROJECT OF CRYSTALCLEAR

The Subproject includes a variety of R&D activites with different implementation horizons (Figure 1). The activities range from quite fundamental research to large batch processing with part of the processes carried out in industrial production lines. The activities are determined to feed the roadmap technologies that have been determined in an integration effort within Crystal Clear [2,3]

3 PHOTON CONVERSION FOR SI CELLS ENHANCEMENT

The most long-term activity investigates 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. 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.

To achieve photon shifting (shifting of very high energy photons towards lower energies for a better usage in the cell) silicon nanoparticles have been synthesized in a silicon nitride (SiN:H) host matrix and in a silicon dioxide/silicon nitride multilayer. The experiments have demonstrated that high temperature annealed samples with excess of 30% lead to the formation of percolated silicon particles of nanosize in width but very long chains. Bright photoluminescence has been observed on some samples, and these layers have been used in solar cell structures.

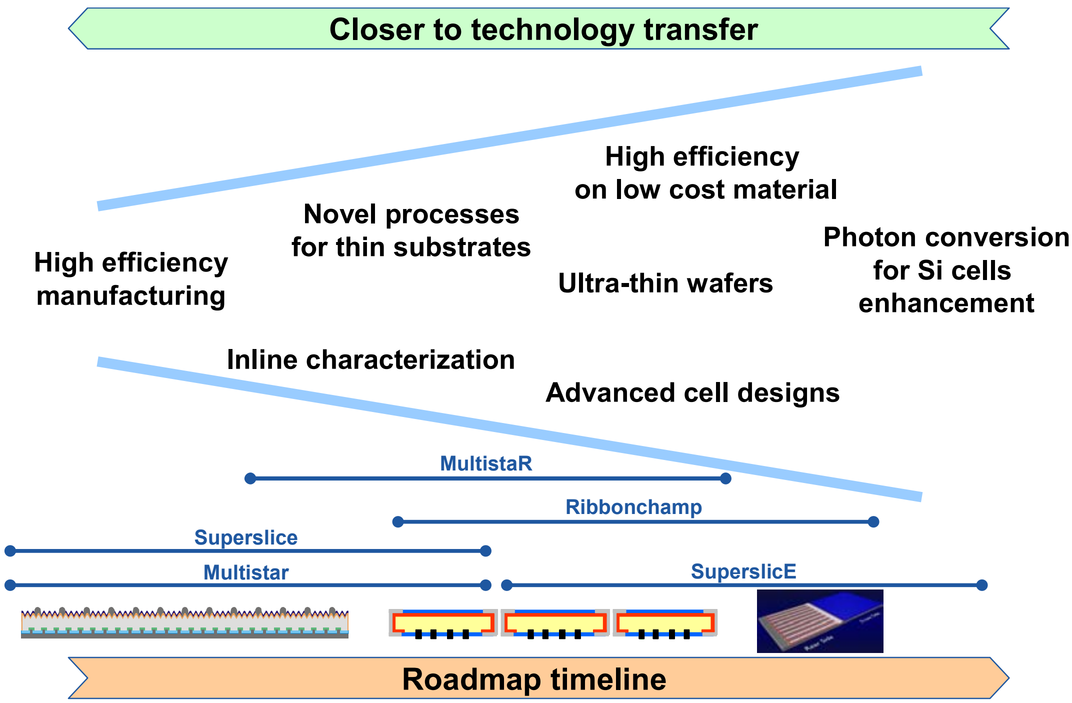


Figure 1: Overview of the activities within the subproject and positioning of these activities with respect to the CrystalClear roadmap technologies

Various Er-based upconverting materials have been tested at the rear of high efficiency bifacial cells. The most efficient up-converter was found to be $NaYF_4:Er^{3+}$, with an EQE of up to 0.3% under excitation at 1522 nm with about 3 mW power. A new up-convertor, Er-doped barium chloride was developed and prepared in the project [4].

4 HIGH EFFICIENCY ON LOW COST MATERIAL

An important task in the subproject is to evaluate the potential of low-cost materials like RGS, EFG and block cast mc material from alternative feedstock sources.

For RGS material a record efficiency for 2x2 cm2 solar cells of 14.4% could be confirmed at FhG-ISE CalLab. To check the influence of grain size on efficiency potential, a special reference material was used for cell processing. Multicrystalline wafers grown with the float zone (FZ) were used and compared with RGS wafers. It was concluded that that grain size in current RGS material does not limit efficiency in principle to values below 15.5%. Intragrain defects (extended defects like dislocations, impurities) are expected to be the limiting factor [5].

On EFG, a high efficiency process has been developed and further improved. A record efficiency of 18.2% (confirmed at FhG-ISE CalLab) was achieved (Figure 2) [6]. This cell featured a thin SiO_2 layer underneath the SiN at the front, and an Al BSF. The LFC process is being tested on such cells, promising even better performance [7]. A screenprinting process has also been implemented on EFG substrates, leading to an efficiency of 16 % (100 cm^2) on a 170 µm thick ribbon [8].

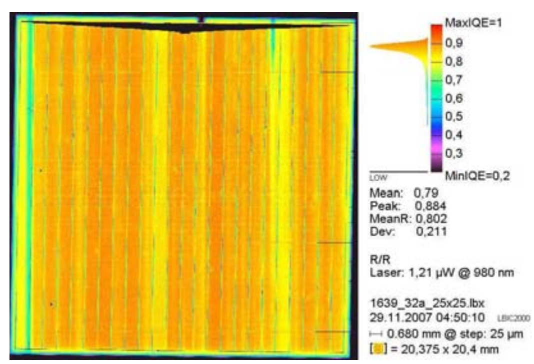


Figure 2: Internal Quantum Efficiency (IQE) at 980 nm of the best EFG solar cell (efficiency=18.2%). The cell shows good material quality, including some grain boundaries.

5 NOVEL PROCESSES FOR THIN SUBSTRATES

A major effort in the subproject is the development of new processes and solar cell structures. In the earlier part of CrystalClear, some very high efficiencies on relatively thick samples were demonstrated, including a 18.1 % large-area multicrystalline Si cell [9,10]. This cell featured a texture based on mechanical grooving, laser grooved buried contacts, and an Al BSF. However, for a few years now, the focus has been on industrially applicable processes adapted for very thin substrates, and the consensus has grown that another type of surface passivation than the conventional full Al BSF needs to be used. Over the course of CrystalClear, three solar cell concepts (*i*-PERC concept, bifacial structure with fire-through contacts, and Laser Fired Contacts based solar cells) have emerged as very promising for the next generation of solar cells (Figure 3).

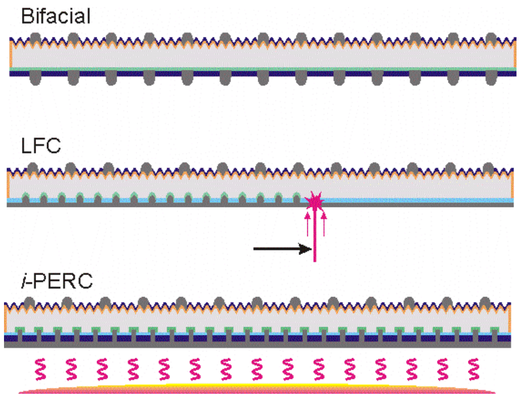


Figure 3 : The passivated rear surface solar cells on low cost substrates can be classified in three groups: bifacial solar cells with fire-through contacts, laser fired contact solar cells, and selective alloying, thermally fired LBSF solar cells (i-PERCs)

These concepts have the potential for high efficiency. This was illustrated by a laboratory cell of 21.7 %, obtained with a passivating stack consisting of an a-Si layer and a PECVD SiO_2 layer, and LFC firing [11].

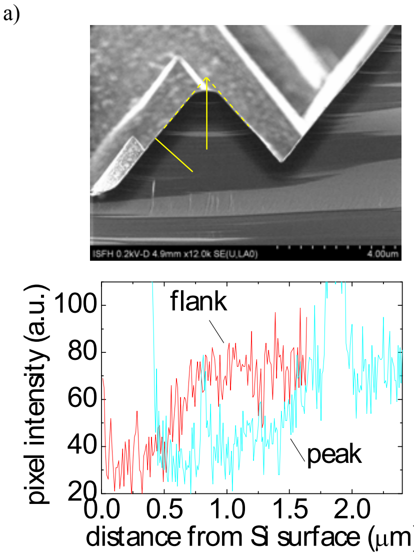
Excellent results have been achieved on very thin large-area multicrystalline and monocrystalline Si substrates (Table 1) [12,13,14].

Table 1 : Solar cell results for very thin 120 - 130 µm thick solar cells on multi- and monocrystalline Si (screenprinted cells)

Material/process	J_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]	Eff. [%]
mc-Si (156 cm^2) / i-PERC	34.7	627	77.3	16.8
Cz-Si (100 cm^2) / i-PERC	35.1	633	79.1	17.6
Cz-Si (12.5 PS) / bifacial, B-BSF	36.2	635	75.2	17.2

Various specific process steps have been developed that are especially adapted to very thin substrates. As an example, we show in Figure 4 a study of in-line diffusion based on spray-on sources. These experiments revealed that the homogeneity of the obtained emitters was similar to those achieved with $POCl_3$ diffusion.

a)



b)

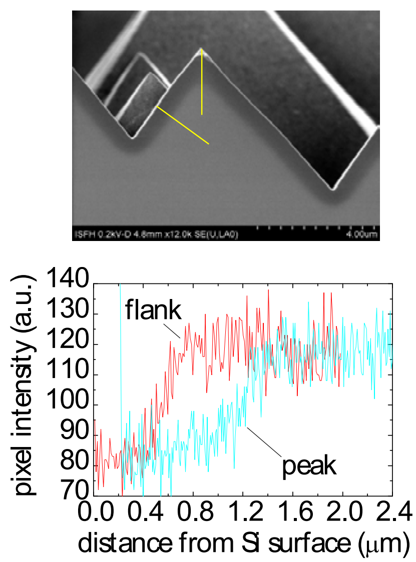


Figure 4 : Emitter profile measured by secondary electron SEM. Darker regions correspond to n-type silicon. a) spray-on in-line diffusion, b) $POCl_3$ sample. The profiles are in both case about 0.5-1 µm at the pyramid flank, and ~ 1-1.5 µm at the peaks.

The core research in solar cell processing is complemented with a study of the mechanical stability of very thin wafers (impact of different types of cracks on the breakage of wafers, before and after etching) [15,16].

6 ADVANCED BACK-CONTACT CELL DESIGNS

While the developed processes are first implemented in structures with conventional front and rear contacting, a strong activity within the subproject concerns the development of solar cells with innovative structures, featuring all main contacts on the rear surface and having the potential advantages of low-cost module manufacturing and higher efficiency thanks to higher packing density. A solar cell concept based on a bifacial structure with fire-through contacts combined with a Metallization Wrap-Through structure (ASPIRe cell) was successfully demonstrated, with an efficiency of 16.4 % (180 µm thick, 243 cm^2) [17]. On very thin (130 µm thick) large area (15.6 × 15.6 cm^2) substrates efficiencies up to 15.5 % were reached.

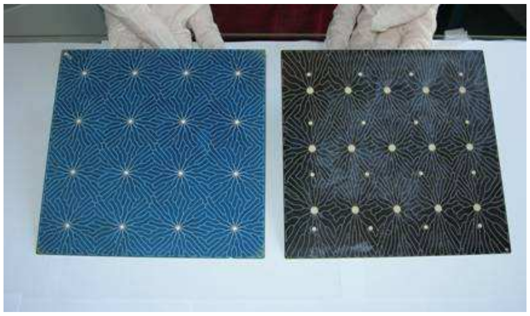


Figure 5: Photo of the front and the rear of an ASPIRe cell

An EWT cell process featuring only industrially applicable process steps was also developed and implemented on Cz, resulting in an efficiency of 17.3 % so far [18].

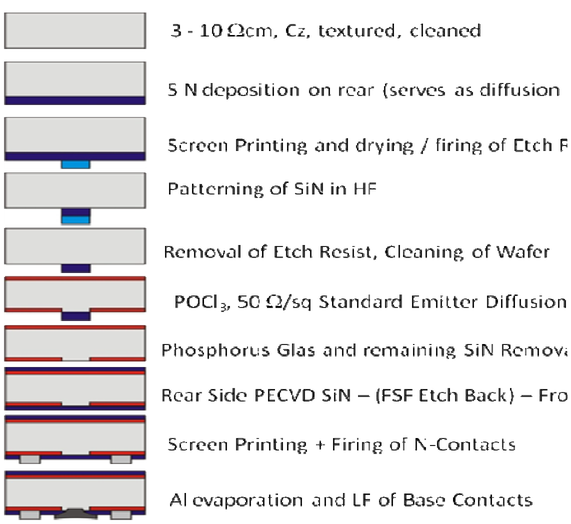


Figure 6 : Processing scheme of EWT cells

7 ULTRA-THIN WAFERS

The CrystalClear roadmap has focused on substrates with thickness of 120 µm, and defined the roadmap technologies for those substrates. Therefore, most of the R&D cell activities have been geared towards this thickness. Nevertheless, it is interesting to investigate whether the developed technologies can be pushed further to ultra-thin substrates, 100 µm and below. This somewhat longer term activity may give a hint as to how long crystalline Si will be the dominant PV technology.

Interestingly, it appears that some of the concepts for rear passivated cells can be implemented on such extremely thin wafers without major process issues. On a 4 inch round Cz wafer (p-type) with a thickness of only 80 µm, an *i*-PERC solar cell was made with an efficiency of 16.6 % (35.6 mA/cm2, 632 mV, FF 75.8 %) [19].

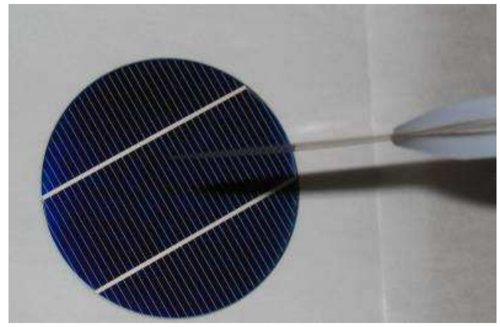


Figure 7 : Extremely thin (80 µm) screenprinted solar cell with an efficiency of 16.6 %

8 CHARACTERIZATION

The development of new characterization techniques has been an integral part of the subproject. An important focus has been the development of techniques that can be implemented in-line. For instance, the illuminated Lock-In thermography technique was successfully adapted to make it suitable for in-line characterization [20].

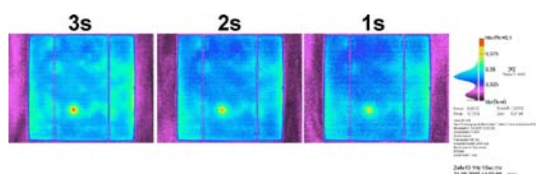


Figure 8 : iLIT measurements at 1 Hz, 1 sun and Voc for varying measurement times

Several round robins on characterization and processing have also been organized, which give a very good view on the stand of each tested technique, as the consortium is a quite large and relevant sample of the PV ‘population’. A comparison of the illuminated IV results for instance revealed a significant spread in the results obtained, though a check with a calibration laboratory revealed that the CrystalClear partners tended to underestimate the quoted cell efficiencies.

9 HIGH EFFICIENCY MANUFACTURING

The three different solar cell concepts for industrial type rear passivated solar cells are presently being implemented in joint experiments between institutes and companies. This involves large batches of wafers which are partly processed in production lines and partly in the R&D facilities in the institutes. The purpose is to start assessing the issue for industrial application, as well as producing a sufficient number of cells for module assembly research.

10 CONCLUSION

CrystalClear involves a large volume of R&D on solar cell processing. World class results and world records have been achieved, particularly with industrial cells on very thin wafers and with ribbons. The project has been effective in enhancing collaboration and communication between some major PV partners in the EU. The fruits of the research are expected to be reaped in the next few years, as the developed technologies will come on-line in industrial production lines.

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Crystal Clear is a long project. As a result, the people involved did not remain the same throughout the course of the project, as the researchers sometimes moved on to new jobs. We therefore thank all the CrystalClear alumni, who are not in the authors' list but did bring important contributions to the subproject. Particular thanks to the previous Subproject Leaders : Guido Agostinelli, Kristian Peter, Peter Fath and Eric Rüland.

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