Publishable summary Silicon-Light; Period II

Executive summary (max 1 page)

Silicon-Light is a European FP7 project aiming at the development of high efficiency thin film silicon solar cells on foil. The project focusses on a) improved light management through implementation of nano-imprint lithography; b) improved silicon material and c) novel TCO materials made by sputtering. Implementation of these three developments has led to significant improvement of cell efficiencies on foil and record (stable) efficiencies of almost 12 % have been obtained. The feasibility of large scale production of all developed technologies could be demonstrated on pilot scale production tools. Life cycle analysis showed that large scale production of modules based on the technologies developed in Silicon-Light would have an Energy Payback Time of 0.85 years in Central European countries.

Project context and main objectives (max 4 pages)

Silicon is a superb feedstock material for solar cells. To make cells with high efficiencies, though, it is important to make the silicon as pure as possible. This purification is an expensive process, and therefore it is necessary to make the solar cells as thin as possible. In Silicon-Light methods are being investigated and improved to fabricate thin silicon layers with thickness of about 1/1000 of a millimeter out of a gas phase on foil by means of Plasma Enhanced Chemical Vapor Deposition (PECVD). The purpose is to make high quality amorphous and micro-crystalline silicon at relatively low process temperatures (typically below 200 ºC), allowing the usage of cheap plastics as substrate foil. To collect all sunlight into such thin layers of silicon, special structures need to be incorporated in the solar cells which trap the light. In Silicon-Light we investigated methods to create light-scattering textures at the rear side of the cell. For the fabrication of these textures, with structures on nanometer scale, methods from the semiconductor industry like e-beam lithography were applied. To demonstrate that these textures can be manufactured on large scale, these methods were combined with large scale production methods for nano-imprint lithography (NIL) which are used in the holographic industry .

Another aim of the project was to develop new Transparent Conductive Oxide (TCO) layers for thin film silicon solar cells. TCO layers are needed to collect the generated current at the front side of the solar cell. Indium Tin Oxide (ITO) is technically a good candidate but the scarceness of Indium requires to investigate alternative materials. Zinc-Oxide (ZnO) is a possible alternative but has certain disadvantages related to its stability in humid environments. In Silicon-Light new TCO were developed that combine the advantages of ITO with those of ZnO.

Integration of the novel light management techniques and new TCOs into high efficiency solar cells was one of main objectives of the project. We achieved thin film silicon solar cells with initial efficiencies of 13.2%.

Finally, the project demonstrated the industrial scale feasibility of the developed technologies and materials. Cost of Ownership calculations showed that implementation of these technologies on large scale would enable the production of these high efficiency solar modules project at manufacturing cost of 65 Eurocents per kWh.

Main S&T results/foregrounds (max 25 pages)

Work package 1: Management

This work package deals with the overall technical and scientific management of the project. The main objectives in this WP are:

1. Overall technical and scientific project management
2. Financial management
3. Reporting to the EU
4. Public relation, dissemination and ensuring exploitation of results

Work package 2: Light trapping:

Light trapping is of uppermost importance for thin film silicon solar cells in order to obtain high cell efficiencies. So far, only ad-hoc solutions have been applied in n-i-p type solar cells. In this work package we pursued a fundamentally new scientific and technologic approach through the following steps:

1) Design of ideal periodic nano-textures for efficient scattering that take into account the actual change of interface-morphology associated with the growth of the devices.

2) Fabrication of ideal textures through lithography and imprint on large area,

3) Implementation of textured back contacts in n-i-p cells (a-Si, μc-Si and a-Si/μc-Si tandems) on foil and feedback to the design.

The novelty of this approach is that full control of the texturization is obtained. Theory and experiment are thus combined successfully for designing better light trapping strategies.

Main results obtained:

- Ideal periodic textures for back reflectors in n-i-p silicon solar cells have been identified by theoretical modeling
- Feasibility of fabrication of these periodic textures, using e-beam lithography, laser interferometry and replication methods has been shown
- Masters for UV nanoimprinting of periodic textures, with feature size of less than 1 micron have been made.
- Large scale production of foils with nano-imprinted textures has been demonstrated by fabricating dozens of meters of (steel and PEN) foil with light-trapping textures on 30 cm width.

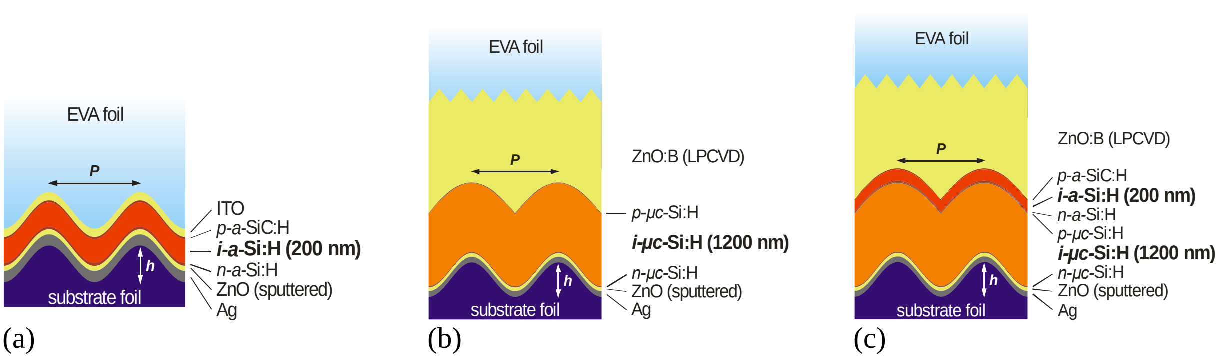

Figure 1 Schematic representation of the structures of analyzed (a) a-Si:H, (b) μc-Si:H and (c) a-Si:H/μc-Si:H solar cells.

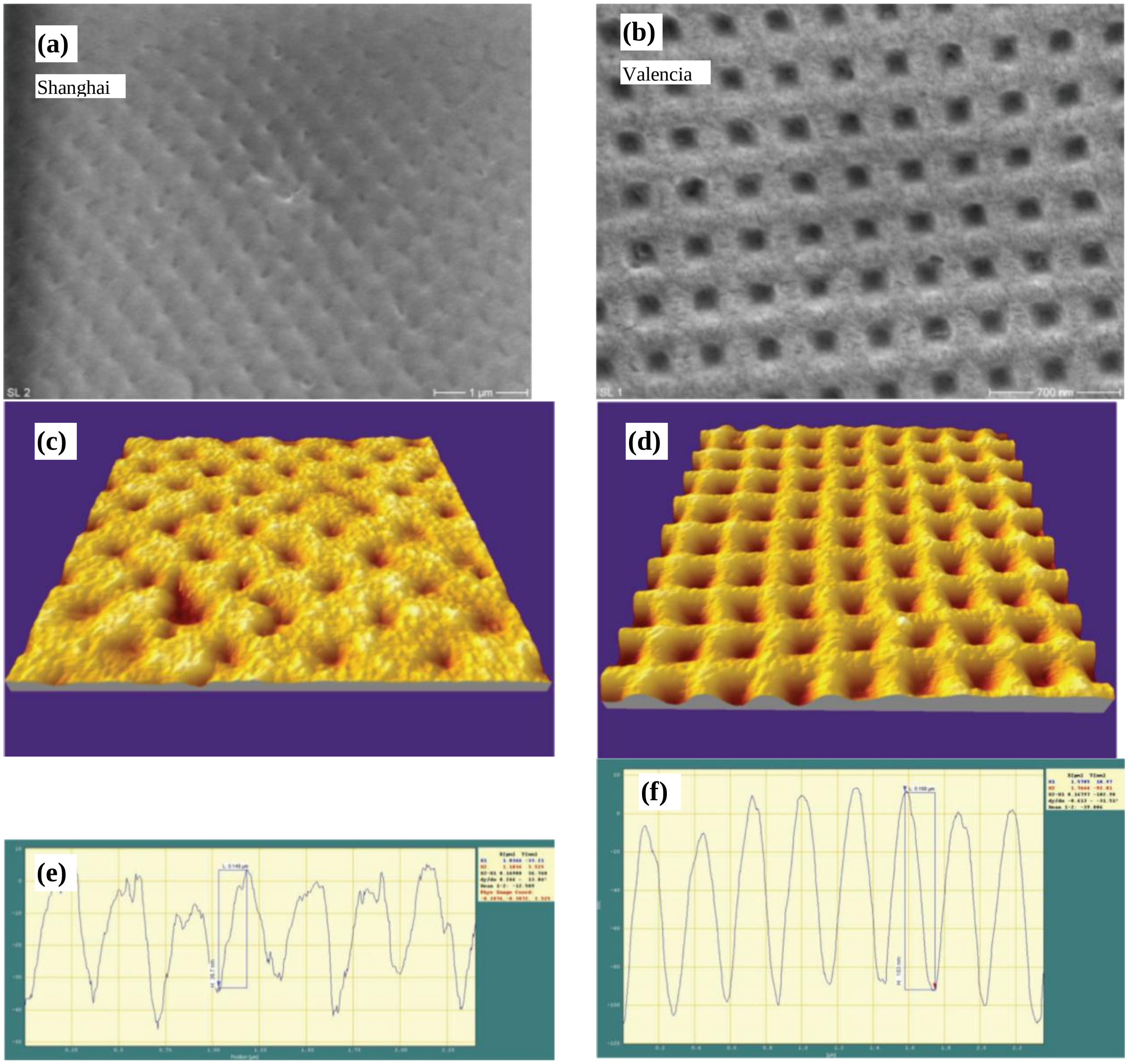

Figure 2: (a)-(b) SEM images of the two analyzed textures (negatives) as embossed on PET flexible substrate, (c-f) corresponding AFM images and texture characterization.

Figure 3: Large area (30x60 cm2) nickel master (father) with random ZnO Z5 texture after electroforming

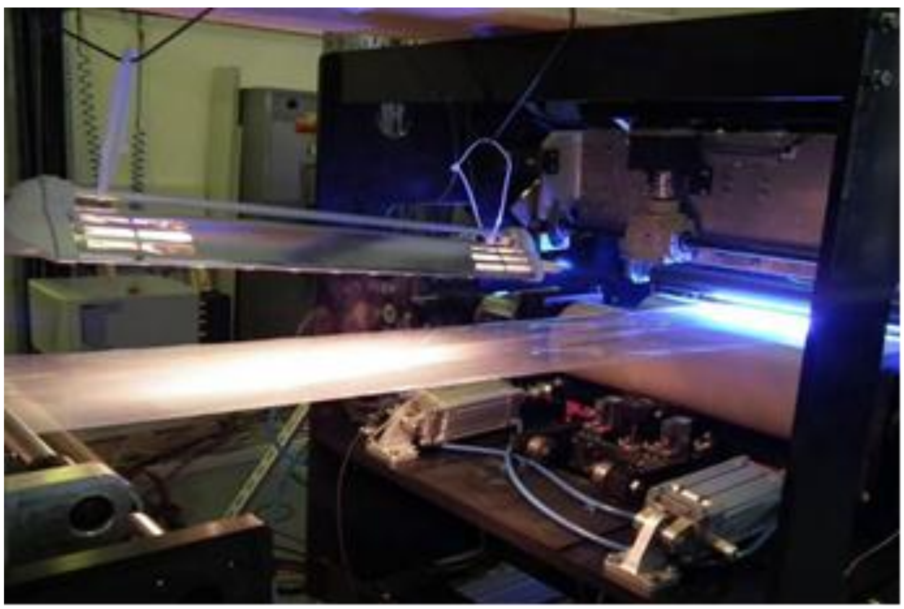

Figure 4: roll-to-roll nano-imprint tool at Nanoptics

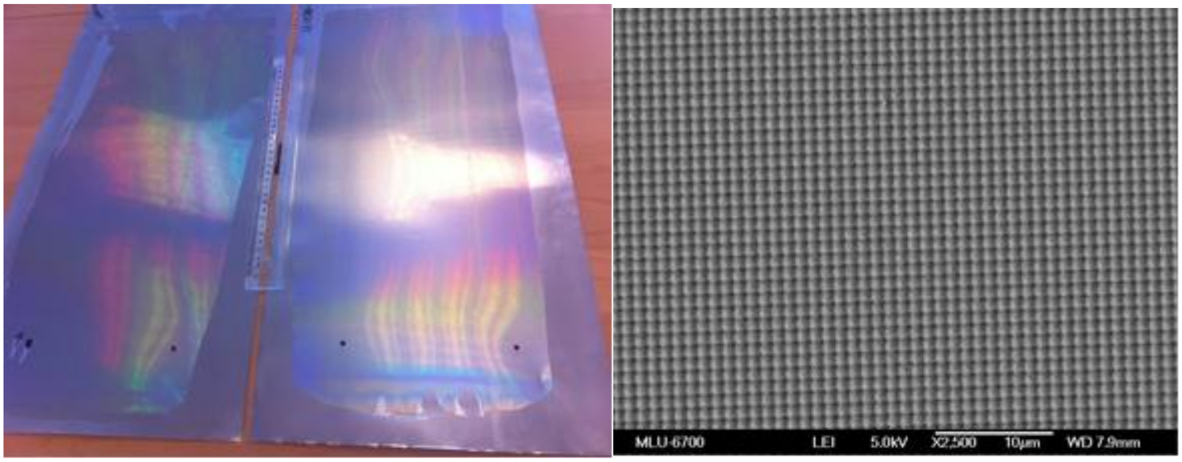

Figure 5 Steel foil (two pieces each with a width of 30 cm) with a periodic texture (left) and SEM image of the texture (right).

Work package 3: Silicon layers

Current state of the art thin film silicon solar cells have efficiencies which are still far below the theoretical limits. A crucial means to increase these efficiencies is to implement improved light scattering schemes. These schemes were developed in WP2, whereas WP3 was devoted to study effects of their implementation on device efficiency since texturization of the substrate can lead to the formation of defective regions in the silicon layers. One main objective of this work package was therefore to develop silicon deposition processes which prevent or mitigate crack formation in microcrystalline silicon, when grown on texturized substrates. A crucial interface in this respect was the n-i silicon interface. Further, the potential harm of p-layer growth on the i-p silicon interface was investigated..

Main results obtained:

- a-Si n-i-p cells with V_{oc} larger than 930 mV have been made
- High resolution TEM was successfully applied to investigate conformity and crack formation of layers grown on periodic textures with high aspect ratios
- A mechanistic model, describing the relation between crack formation in micro-crystalline silicon and the morphology of the substrate on which the micro-crystalline silicon is grown, has been developed.
- As a side product of the high resolution TEM analysis, a new dopant profiling method was developed based on EELS.

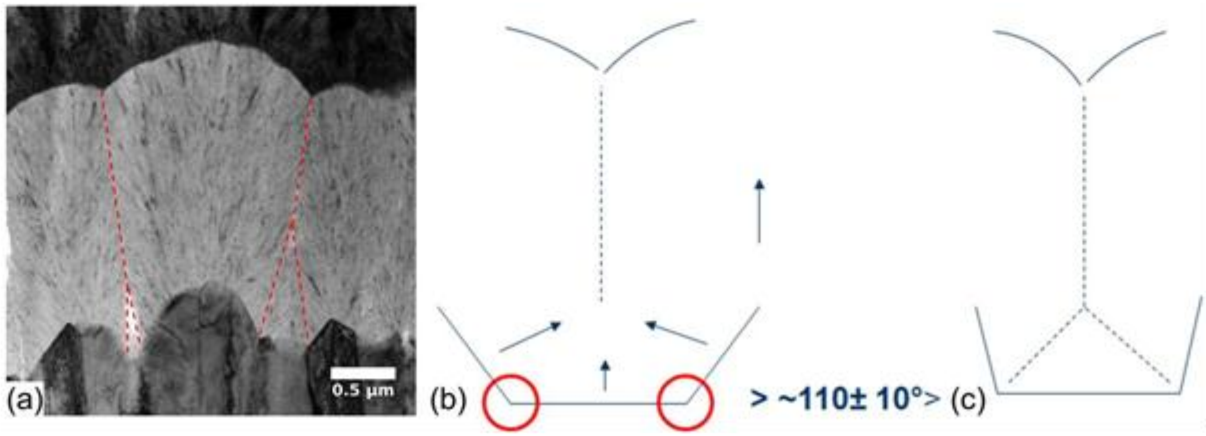

Figure 6: (a) Bright field TEM images of Si layer grown on textures above the angular threshold of ~110o. (b)Voids appear near corners with unfavourable opening angles and opposing opening angles are > 110°; the crack formation is delayed and is the result of the overall opening angle of < 110°. (c) The opening angels are < 110°; the first two sub-cracks are formed in addition to the main crack

Work package 4: TCO layers

Transparent Conductive Oxide (TCO) layer play an essential role in the functionality of thin film solar cells in general, and thin film silicon solar cells in particular. Commonly used TCOs are presently ITO and doped ZnO, but both materials have certain disadvantages either with respect to cost or to performance. In this WP, we investigated the fabrication of alternative TCO layers with improved performance/cost ratios. We used DC magnetron sputtering, an industrially relevant deposition process. In this WP we developed new TCO layers of single doped or multiple doped oxides based on the elements Sn, Zn and In which have lower cost, high work function and high environmental stability. Further, we investigated multilayer TCOs with the objective of reaching higher resistance against moisture and graded work-function profiles to improve current collection.

From the beginning, care was taken to use processes that are compatible with scaling from lab-scale (with planar sputter targets) to industrial scale processing (with rotary sputtering targets) in WP6.

Main results obtained:

- An extensive survey was made of ITO, made by reactive sputtering, using different target compositions in combination with reactive sputtering with oxygen. We were able to increase the work function (Wf) of ITO significantly. Unfortunately, the application of these new ITO materials as top TCO in a-Si n-i-p cells result only in moderately increased V_{oc} of these cells. We could explain this finding by further refining the underlying theoretical models..
- The production recipes for novel single and double doped TCO material compositions based on In_2O_3 and ZnO were developed and lab scale sputtering targets were produced. Best materials were selected for implementation in solar cells and for damp heat tests. As a result we were able to identify at least one new TCO material which has the same environmental stability and a better optical and electrical performance than conventional ITO but with a significantly lower Indium content than ITO.
- Industrial scale deposition of these new TCO materials was demonstrated by fabrication of rotary sputtering targets with a width of 60 cm, and using these targets successfully in a pilot scale sputtering system.

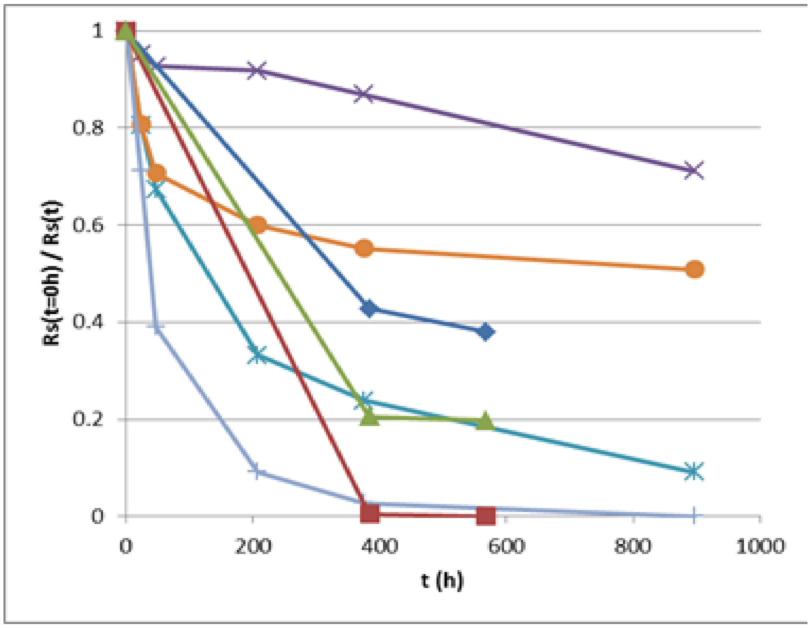

Figure 7: Dependence of resistivity ratio of different novel TCO layers based on ZnO and ITO on aging time in damp heat test. Decreasing ratio means the resistivity increases.

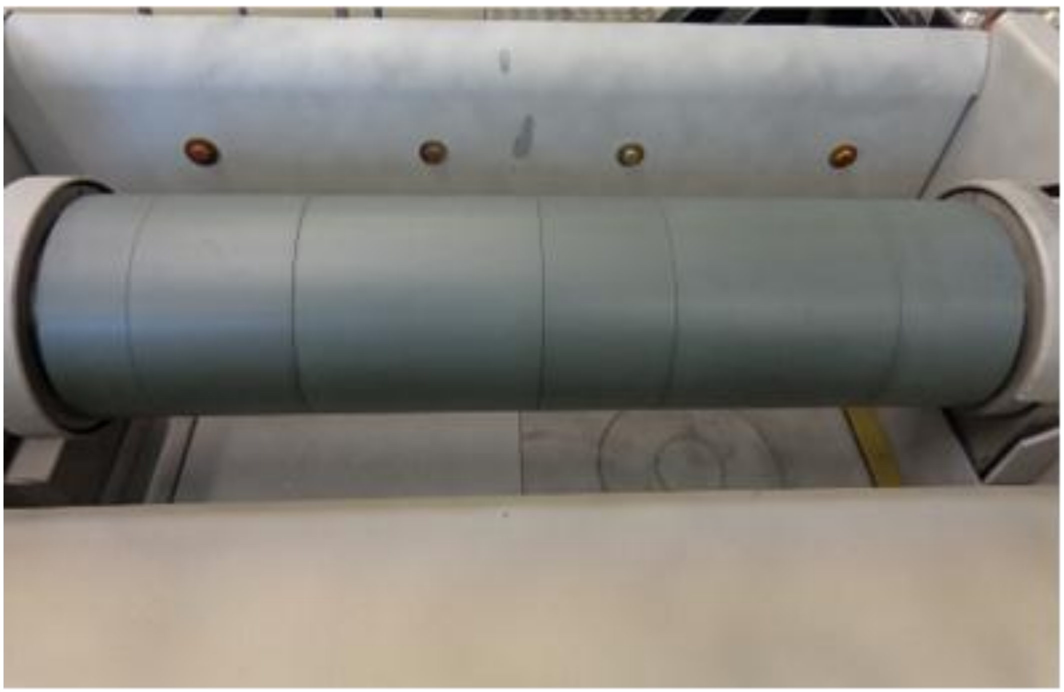

Figure 8: Tube target with a novel TCO material developed in Silicon-Light, for pilot scale industrial production.

Work package 5: High efficiency devices

The proof of the functionality of the materials and methods developed in the previous work packages has to come through demonstration of solar cells with improved efficiencies.

In this work package manufactured state-of-the art a-Si, μc-Si and micromorph a-Si/μc-Si tandem solar cells. We used either low cost plastic substrates like polyethylene or metallic foils with imprinted structure on the insulator that is required between the metallic foil and the active layers of the solar cell. The devices combined improved processing, novel light trapping structures, silicon layers and TCO layers developed in the previous work packages.

The main objectives of WP5 were: 1) single junction solar cells with stable active area efficiencies higher than 8.5% both on plastic and metal foils. 2) Tandem solar cells with stable active area efficiencies higher than 11% both on plastic and metal foils.

Main results obtained (stabilized efficiencies):

- Best single junction (μc-Si, absorber layer 1600 nm) cells: V_{oc} = 501 mV; J_{sc} = 25.9 mA/cm^2; FF = 66%; η = 8.5%
- Best a-Si/a-Si tandem cells (absorber layers: 70 nm top cell and 360 nm bottom cell: V_{oc} = 1787 mV; J_{sc} = 7.92 mA/cm^2; FF = 66.1%; η = 9.2%
- Best tandem cells (with intermediate reflector and with bottom cell thickness of 1700 nm): V_{oc} = 1415 mV; J_{sc} = 12.0 mA/cm^2; FF = 66%; η = 11.6%

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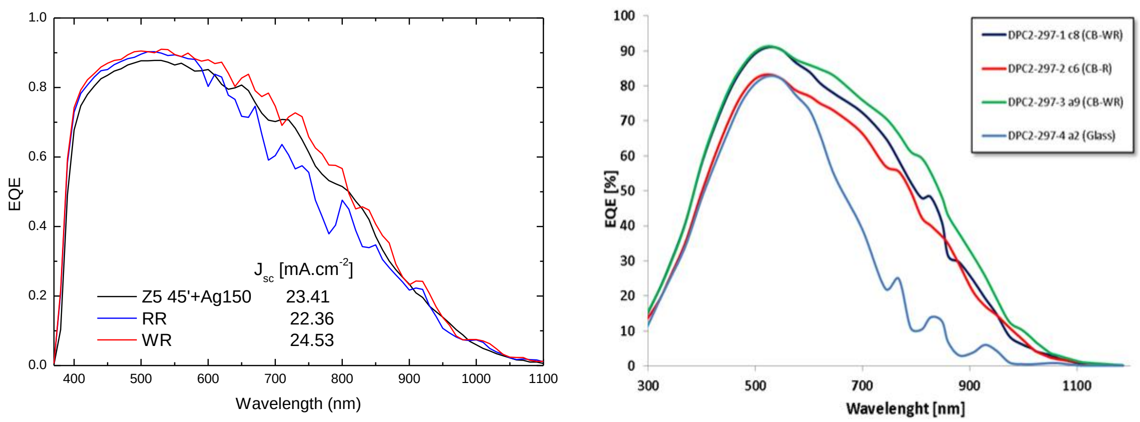

Figure 9: EQEs microcrystalline solar cells made on at EPFL(left) and at ECN (right), using replicated textures on plastic and steel substrates, respectively. In both cases, best performance is found on the WR structure.

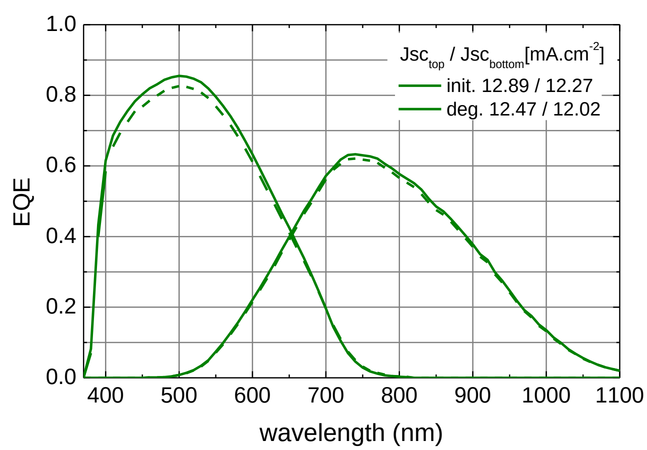

Figure 10: EQEs of the best stable device in initial (full line) and stable state (dashed line)

Work package 6: Integration and industrial implementation

The aim of this work package was transfer the lab-scale results, obtained in the other work packages, to an industrial pilot scale production. This work was carried out by VHF for the PEN-foil route and by ECN for the metal foil route.

Important sub-tasks in this Work package were up-scaling of the embossing processes and the sputtering processes.

Last but not least, an extensive economical and life cycle analysis of a thin film silicon solar cell and module fabrication process, according to the processes developed in the project, was done. The exit of VHF-Technologies in the last year of the project, due to liquidation of the company was a heavy blow for the progress in this workpackage. Some of the tasks related to industrial integration had to be skipped, but fortunately the consortium could nevertheless achieve most of the tasks of the workpackage.

Main results obtained:

- New TCO material developed in the project was successfully applied in a pilot scale production plant of VHF-Technologies,
- a-Si/a-Si tandem cells with stabilized efficiency of 8.0% were fabricated in pilot scale production of VHF-Technologies, applying rear side texture developed in the project.
- a-Si/uc-Si tandem cells on steel foil, with an (initial) efficiency of 11 % were achieved.
- Cost-of ownership calculations show that for a 100 MWp production plant the fabrication of thin film silicon solar modules on foil, using the technologies developed in Silicon-Light, the fabrication costs can be lower than 65 Eurocents per Wattpeak, even for a plant in which the production capacities of the different fabrication tools is not fully harmonized. It also confirmed earlier presumptions that the flexible encapsulant is a main cost driver and cheaper alternatives are needed to achieve module costs well below 50 Eurocents per Wattpeak.
- Life cycle analysis shows that the energy payback time (EPT) of modules based on the Silicon-Light concept can be as short as 0.85 years for Central European countries.

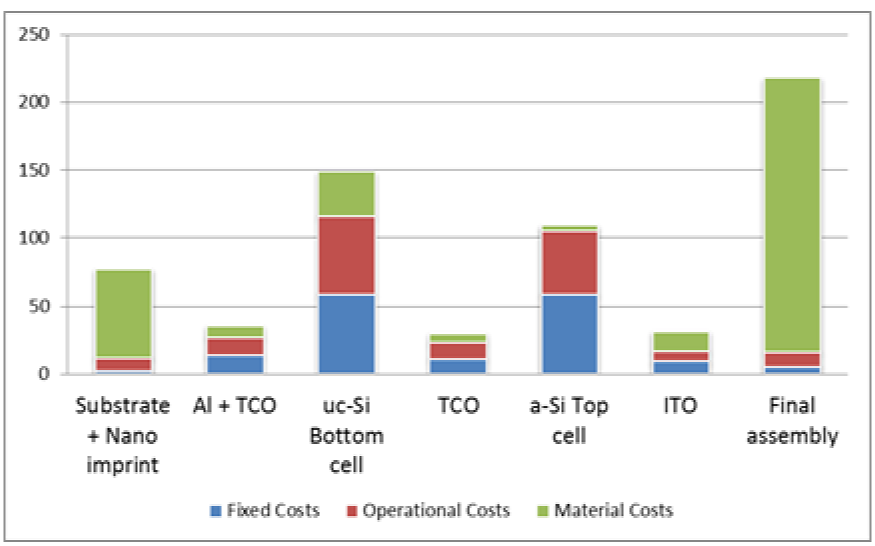

Figure 11: Cost break down (Euros per kWp) of modules of 10% efficiency with Al back reflector

Potential impacts(max 10 pages)

The project Silicon-Light had the following aims:

1) development of novel light management strategies through usage of nano-imprint technology
2) development of novel TCO materials, which should combine the relatively low costs of AZO with the good opto-electronic properties of ITO.
3) improved silicon absorber layers.

These individual developments were aimed to be integrated in a novel fabrication process of flexible thin film silicon solar modules, but they could also be exploited individually. Below we discuss the potential impacts of the individual developments and then discuss the potential impact of the integral concept.

1) Light management using nano-imprint lithography.
   We have successfully shown that by nano-imprint lithography the back contact of thin film silicon solar cells can be textured such that a significant improvement of the light trapping can be achieved, leading to 40 % increase of the solar cell current. This technology can be applied for thin film silicon solar cells on foil, but also for thin film silicon solar cells on glass. Further, the technology is not limited to thin film silicon solar cells but can also be applied for other thin film solar cells like CIGS and OPV where light management is also of increasing importance. Finally, this technology has broader potential for application, e.g. for OLEDS and displays.
2) Novel TCO materials
   TCOs are generically used in all thin film PV concepts and also in the so-called HIT concept. All these applications require high transparent, high conductive and cheap TCOs and therefore the developed materials are of interest for all these applications. Another important market for the newly developed TCOs is the display industry, where currently ITO is standardly used.
3) Improved silicon material.
   The potential impact of these developments in first instance could lead to improved cell efficiencies in thin film silicon solar module fabrication. On the longer term, also the manufacturing of silicon heterojunction cells (HIT) might benefit from the insights gained on this topic.
4) Integral concept
   Due to the sharp drop of silicon wafer prices in the recent years, one major advantage of thin film silicon solar cells, namely the small materials costs in production, has practically disappeared. In order to become cost competitive on system level (that is including BOS costs) again, cell and module efficiencies of thin film Si PV must be increased towards at least 15%. In this project we have developed some of the first elements which are needed to come to these high efficiencies. A follow-up – to some extent planned in framework of the new EU project Fast-Track - is needed to work out these elements and to realize these higher efficiencies.