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Efficiency and material issues for thin film photovoltaics

HELATHIS
High Efficient Very Large Area Thin Film Silicon Photovoltaic Modules

Grant Agreement No.: 241378

Final Report

Period covered from 01/01/2010 to 31/12/2012

Start date of project: 01/01/2010

Dr.-Ing. Michael Vetter
T-Solar Global S.A.

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Project data overview

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Name of the scientific representative of the project's co-ordinator, Title and Organisation:

Dr.-Ing. Michael Vetter

T-Solar Global S.A:

Tel: +34 988 011 300

Fax: +34 901 022 756

E-mail: michael.vetter@tsolar.eu

Project website address: www.tsolar.com/helathis

1 Final publishable summary report

Executive summary

Photovoltaic (PV) solar energy generation already is the third renewable energy source after hydropower and wind power in Europe. The thin film silicon PV module is one technology which could achieve a wide market application due to easy production at large area and low cost and low environmental impact of production. To improve thin film silicon PV modules, optical confinement was identified as a major source of efficiency improvement by the 5 partners of the HELATHIS project. T-Solar Global S.A. (TS), silicon thin film PV module producer using Applied Materials SUNFAB technology, AGC Glass Europe (AGC), flat glass producer and three research institutions, the Forschungszentrum Jülich (FZJ), the Utrecht University (UU) and the University of Barcelona (UB) had formulated the Work Program of the HELATHIS project including the following 5 Work Packages (WP) to promote R&D of very large area (5.7 sqm) thin film silicon PV modules. The Work Packages (WPs) (apart from the WP1 for the Project Management) were organized by research dedicated to the -Front Surface- (WP2), the -Glass/TCO (Transparent Conductive Oxide) Interface- (WP3), the -Intermediate Reflector- for tandem cells (WP4), the -Back Reflector- (WP5) and -Advanced Characterization Methods- (WP6). The objective of the project was to push the implementation of optical layers as part of adapted thin film silicon solar cells into large scale production facilities, including most of the optical confinement strategies that are state-of-the-art in highest efficiency silicon thin film laboratory cells. In the time frame of 3 years a stabilized large scale 2.6 m x 2.2 m (5.7 sqm) module efficiency of 8% for single junction amorphous silicon (a-Si:H) and 11% for a-Si:H/microcrystalline silicon (mc-Si:H) tandem modules were scheduled. These module efficiencies together with cost reductions in the raw materials, as e.g. the TCO glass substrate supplied by AGC, was expected to lower the module production cost clearly under the 1 €/W level at the end of the project.

In the frame of the HELATHIS project AGC has improved its TCO glass from initially standard TCO glass AN10 to ANS10ME TCO glass, latter providing about 2% higher optical transmission. The solar cell fabrication process was optimized by TS for the ANS10ME substrate, resulting in an increase of stabilized efficiency of 5.7 sqm a-Si:H modules in production average from about 6.7% (382W) at the beginning of the project to about 7.3% (420 W) at the end of the project and achieving in the best R&D module an efficiency of 7.95% (455W). Production cost was about 0.7 €/W in middle of 2012 and was estimated to reach 0.6 €/W in 2013 including latest R&D steps and new implemented automation. During the operation of the project, the whole module production of Applied Materials SUNFABs in Europe (initially 5 factories with a nominal TCO glass volume of approx. 3 Mio. sqm/year) had changed from formerly in Japan produced NSG/Pilkington TCO glass to TCO glass produced by AGC in Moustier, Belgium, which presents a big impact on the European economy.

For further improvement of the TCO glass, TiO_2 layers were identified at AGC and UB as suitable candidates to produce graded index layers between the SnO_2 TCO layer and the amorphous p-layer of the solar cell to reduce optical losses at this interface. However, within the project a suitable layer for the implementation in modules could not be successfully developed for the TS production process. Nevertheless, the interesting result obtained on small scale samples suggest, that this research should be pursued further. Furthermore, the application of a sol-gel anti-reflection coating (ARC) on the front surface of the TCO glass was investigated by AGC and UB and it was shown that the transmission of the ARC covered TCO glass could be increased by about 2%. The ARCs developed at UB and AGC were subjected to standard durability test conditions as e.g. in IEC 61646 norm and were found to be very stable. However, the implementation of a production process for sol-gel ARC resulted to be not cost effective at the actual low level of module price and efficiency.

Intermediate reflector (IR) technology was investigated and developed in 1 sqcm tandem solar cells and laboratory modules up to a size of 30 cm x 30 cm. For this purpose properties of microcrystalline silicon oxide (mc-SiOx:H) layers deposited by PECVD were studied and optimized. A 30 cm x 30 cm tandem module with mc-SiOx:H IR with a record initial efficiency of 12.2% was fabricated by FZJ very close to the 12.5% efficiency aimed at the beginning of the project. The deposition technology of n-type mc-SiOx:H IR layers was implemented in the TS production process. With top cell and the mc-SiOx:H IR layer deposited in TS and bottom cell prepared in FZJ, a maximum initial efficiency of 11.9% has been achieved in 1 sqcm tandem cells. With the top cell and ZnO:Al IR layer prepared at TS and the bottom cell prepared at FZJ a maximum initial efficiency of 11.6% has been achieved in 1 sqcm tandem cells and 10.1 % for a 10 cm x 10 cm mini module for which, FZJ has developed an innovative laser scribe design for conductive ZnO:Al. Tandem module development could not be extended to 5.7 sqm module since TS could not make the expensive upgrade of the PECVD deposition system which was required in order to deposit device-quality intrinsic mc-Si:H, as a consequence of the photovoltaic market development with extremely low module prices and the global financial situation.
ZnO:Al layers for the back reflector (BR) sputtered from rotatable targets were successfully optimized and implemented by FZJ on 30 cm x 30 cm scale. In a-Si:H/mc-Si:H tandem solar cells prepared with this BR, an initial efficiency of 11.3% was achieved. Ga-doped ZnO layers (ZnO:Ga) were implemented and optimized by UB. However, these two approaches finally were not considered for an implementation in TS production for cost reasons. The key issue in improving the BR performance is the use of an Ag layer instead of Al as BR which could improve the efficiency by about 5%. The increase of the Ag price and the decrease of overall module production cost in last years were shown to present a strong negative impact on the cost effectiveness of the implementation of the Ag layer and therefore the implementation was not considered by TS.
To support the TCO glass and solar cell development, the surface morphology of industrial and laboratory TCOs was determined by SEM, AFM, XRD spectroscopy, optical transmission spectroscopy and angular resolved spectroscopy. Electrical properties were determined by Hall-effect measurements. Electrical and optical properties were determined of a-Si:H, mc-Si:H and mc-SiOx:H layers. The local transmitted light intensity distribution on TCO glass and TCO glass covered with a-Si:H p-i-n structure was obtained experimentally by near-field scanning optical microscopy (NSOM) and theoretically by rigorous solution of Maxwell's equations using the finite-difference time-domain method. A CCD camera inspection system was developed and successfully implemented in the TS production line for the detection of infrared radiation emitted from the module when stimulated by a forward current and so indicating defective areas, providing an excellent assessment of the electrical quality of each module at the end of the production process.

Project context and objectives

Project context

The European Union's new energy and environment policy, agreed by the European Council in March 2007, establishes a forward-looking political agenda to achieve the Community's core energy objectives of sustainability, competitiveness and security of energy supply. To make this a reality, the European Union (EU) is committed to the "20-20-20" initiative [Communication from the Commission, COM (2008) 781 final, Brussels 13.11.2008, p. 2.]. To adapt the research activities to the recent difficult economic situation in Europe triggered by the financial crisis starting in 2008, the EU has created the new Framework Program for Research and Innovation - Horizon 2020 [http://ec.europa.eu/research/horizon2020/index_en.cfm?pg=h2020]. It is expected that around 35% of the Horizon 2020 budget (approx. € 80.000 Mio.) will be climate related expenditure e.g. in renewable energies [Communication from the Commission, Horizon 2020 - The Framework Programme for Research and Innovation, COM (2011) 808 final, Brussels, 30.11.2011, p. 5.]. Photovoltaic solar energy generation (PV) will play a relevant role in the future renewable energy production presenting with 58% annual growth rate from end 2006 to 2011, the highest growth rate of all renewable energy sources worldwide [Renewables 2012 Global Status Report, (Paris: REN21 Secretariat, Renewable Energy Policy Network for the 21st Century) p.13.]. With about 52 GW of PV installed in 2011 in Europe, PV [Global Market Outlook for Photovoltaics until 2016, p. 12 (EPIA, www.epia.org)] already is the third renewable energy source after hydropower (260GW) [International Hydropower Association Activity Report 2011 (IHA, London) p. 13.] and wind power (98 GW) [Renewables 2012 Global Status Report, (Paris: REN21 Secretariat, Renewable Energy Policy Network for the 21st Century) p.57.] in Europe.

When creating the HELATHIS consortium (www.tsolar.com/helathis), the 5 partners had jointly identified optical confinement as a major source of efficiency improvement for thin film silicon PV modules. To promote this development, a work program had been formulated based on the expertise of 2 companies with high volume production and the know-how of 3 widely recognized public research organizations.

- **T-Solar Global S.A.**, (TS) is a company producing very large area a-Si:H modules having increased its production capacity within the project from nominal 40 to about 70 MWp/year. The 5.7 sqm PV modules fabricated by TS with "SUNFAB" technology from Applied Materials are the largest modules in the world market.
- **AGC Glass Europe** (AGC) is the European branch of the worldwide biggest producer of flat glass with long time experience in fabrication of transparent conductive oxides (TCO) on glass, the substrate for silicon thin film modules.
- The involved research centre **Forschungszentrum Jülich**, (FZJ, **Institute of Energy and Climate Research 5**, IEK-5, Germany), the **University of Barcelona** (UB, **Dept. of Applied Physics and Optics**) and the **Utrecht University** (UU, **Debye Institute for Nanomaterials Science**, located now in High Tech Campus Eindhoven) are performing research in silicon thin film technology since several decades and provide detailed knowledge on laboratory scale high efficiency thin film silicon solar cell technology, on deposition technology of thin film silicon and TCO layers and micro and nanotechnology.

Objectives

The objective of the project was to push the implementation of optical layers as part of adapted thin film silicon solar cells into large scale production facilities, including most of the optical confinement strategies that are state-of-the-art in highest efficiency silicon laboratory cells. In the time frame of 3 years a stabilized large scale 5.7 sqm module efficiency of 8% for very large area single junction amorphous silicon (a-Si:H) and 11% for very large area a-Si:H/ microcrystalline (mc-Si:H) tandem modules were scheduled. These module efficiencies together with cost reductions in the raw materials, as e.g. the Transparent Conductive Oxide (TCO) glass substrate supplied by AGC, was expected to lower the module production cost clearly under the 1 €/W level at the end of the project. To achieve these objectives a Work Program containing 5 Work Packages (WP) dedicated to research and development activities was organized apart from the WP1 –Management- for the project coordination.
The present project identifies optical light confinement as a key point to increase efficiency in silicon thin film modules. The optimization of the properties of TCO layers deposited on front glass as front contact of the solar cell and the back reflector have to be achieved for large area deposition. Additionally, methods for the reduction of reflection losses at the front glass are developed. This optimization has to be done, on the one hand, for modules with a-Si:H single junction (SJ) and, on the other hand, for modules with a-Si:H/mc-Si:H tandem junction (TJ), where, in the latter case, also an intermediate reflector for light management between top and bottom cell is considered.
The project developed innovative schemes for application in very large area industrial modules. This finally included most of the optical confinement strategies that are presently state-of-the-art in highest efficiency thin film silicon laboratory cells. The objective of the project was the implementation of optical layers as part of adapted thin film silicon solar cells into large scale production facilities. In the time frame of 3 years a stabilized large scale module (5.7 sqm) efficiency of 8% for very large area single junction and 11% for very large area tandem modules was scheduled. Furthermore, in 30 cm x 30 cm a-Si:H/mc-Si:H tandem mini modules an initial (stabilized) efficiency of 12.5% (11.5%) and in a-Si:H/mc-Si:H tandem solar cells of 1 sqcm of 13.5% (13%) and was projected. The module of the TS production consists of a glass/Poly Vinyl Butyral (PVB)/glass laminate in which the front glass is the TCO covered glass substrate (in the following TCO glass) where TS deposits the solar cells structure. The TCO glass is fabricated in a float glass line by AGC on very large area (about 6 x 3 sqm) and then cut to the 5.7 sqm size. The back glass of the module has a hole where the electrical contact is provided by a junction box glued on the back glass. On the back glass also metal profiles are glued to fix the module on the ground structure. The a-Si:H/mc-Si:H tandem structure was also under investigation in the frame of this project. a-Si:H/mc-Si:H TJ solar cells and modules have been intensively studied on laboratory level at the laboratories of the FZJ, UU and TS with the objective to optimize tandem structures with intermediate reflectors (IR) and high efficient tandem cells and mini modules were fabricated with ZnO layers and newly developed microcrystalline silicon oxide (mc-SiOx:H) IR layers. The main objectives will be presented in the following by Work Packages (WP).

WP2 Glass front surface

4% of the light reaching the surface of a solar module is reflected at the air/glass interface. Any reduction of this reflection represents a significant and assured increase of solar module output. This reflectance reduction can be achieved by antireflective coatings (ARC) that have a refractive index that e.g. decrease with their thickness from the index of glass (n=1.5) towards the index of air (n=1). This index variation is obtained e.g. by controlling the porosity of the coating throughout its thickness. Principle objectives of WP2 were:

- Development of anti-reflective coatings (ARC) on front glass surface.
- Implementation of ARC on large area solar modules

WP3 Glass / TCO interface

To get a baseline of the performance of different TCO glasses in single junction a-Si:H solar cells, at the beginning of the project benchmark tests have been performed with a variety of TCO glasses available within the consortium. Next, the objective for AGC was to further develop its TCO glass to reduce the gap between off-line and in-line industrial TCO glass and to perform the respective test-runs in the production line of TS. Objective was to produce a prototype very large area (5.7 sqm) module with 8% stabilized efficiency and a prototype large area (5.7 sqm) a-Si:H/mc-Si:H tandem junction module with stabilized efficiency of 11%. Moreover, an objective was to develop new concepts to improve the TCO functions at a laboratory scale. Furthermore, AGC and UB have investigated the application of a thin refractive index (n) matching TCO layer with intermediate refractive indices between the standard tin oxide TCO layer (n=2) and the amorphous silicon layer (n=3) to reduce the reflection losses at the TCO/a-Si:H interface. The principal objectives in WP3 were:

- Benchmarking of commercial and laboratory TCO substrates with newly developed TCOs.
- Development and improvement of new front TCOs by in-line and off-line APCVD.
- Characterization of newly developed TCOs.
- Application of newly developed TCOs on very large area.

WP4 Intermediate reflector (tandem structure)

The incorporation of intermediate reflecting layers has a great potential for the optimization of tandem solar cells with a-Si:H top cell and mc-Si:H bottom cell. Intermediate reflectors (IR) are used to provide selective light distribution for light management inside thin film silicon solar cells. The objectives for thin film silicon solar cell development are the improvement of the total energy conversion efficiency by increasing the absorption in the top cell and the reduction of the top cell thickness without losses in the total efficiency. The latter will reduce the material consumption and production costs, in addition to the improvement of the stabilized efficiency. Further objective was the development of 1D photonic layers or the so-called distributed Bragg reflector (e.g. ZnO/Si/ZnO….Si/ZnO) as IRL. The main objectives in WP4 were:

- Decreasing the thickness of the top cell by the use of a spectrally selective intermediate reflector between the sub cells and maintaining the current of the tandem cell.
- Successful development of a robust IR that can be implemented in industrial production.
- Development of novel multilayer IR that has photonic properties.

WP5 Back reflector

The state-of-the-art back reflector deposition of the TS production line is done by dc sputtering of ZnO:Al followed by an Al metal layer. The back reflector along with the front TCO layer plays a crucial role in p-i-n type thin film silicon solar cells by increasing the optical path of light inside the device resulting in short circuit current gain. The objective was to evaluate at the beginning of the project the performance of the current back reflectors (BR) of the laboratories (UU, UB, FZJ), who in particular apply an Ag-layer in the BR, to give an accelerated feed-back for the possible efficiency gain which could be achieved in large area modules using an alternative BR structure. In order to investigate new materials and techniques for producing efficient BRs, objective was to develop back reflectors with Ga-doped ZnO (ZnO:Ga) by UB and the deposition of ZnO:Al layers by sputtering from rotatable targets by FZJ. The objectives in WP5 were:

- Accelerated feedback from laboratories to improve the efficiency of industrial modules
- Development of back reflectors on the laboratory scale with potential for up-scaling to large area modules
- Evaluation and application of the optimized back reflector to industrial large area modules

WP6 Advanced characterization methods

It is the aim of the project to increase the efficiency of thin film solar cells by improving the light trapping efficiency and by reducing parasitic losses. The improvement in the light trapping is achieved e.g. by antireflection coatings at the front glass surface, the optimization of the surface morphology of the front TCO layer, the implementation of intermediate reflectors (in the case of tandem solar cells) and the improvement of the back reflector. Standard methods for the characterization of solar cells are the measurement of current voltage curves and external quantum efficiency however, more advanced methods were developed and applied to determine the properties of materials and layers and to characterize the light trapping properties of TCO layers and ARCs. The main objectives in WP6 were:

- Analysis of the surface structure and identification of optimised profiles for light trapping
- Application of advanced electrical and optical characterization methods
- Identification of the best stabilized ARC under light-soaking and environmental conditions
- Development and implementation of an IR camera inspection system in TS for module quality assessment.

Scientific and technologic results/foregrounds

Work Package 2: Glass front surface

4% of the light reaching the surface of a solar module is reflected at the air/glass interface. Any reduction of this reflection represents a significant and assured increase of solar module output. This reflectance reduction can be achieved by antireflective coatings (ARC) that have a refractive index that e.g. decrease with their thickness from the index of glass (n=1.5) towards the index of air (n=1). This index variation is obtained e.g. by controlling the porosity of the coating throughout its thickness. In Work Package (WP) 2 antireflection coatings based on sol-gel processing were developed to reduce the reflection of light at the front side of the TCO glass used as the substrate for thin film silicon solar modules.

<u>Task 2.1 Industrial very large area SiOx ARC by sol-gel (AGC) and Task 2.3 Test of ARC on large area module</u>

In this task AGC developed a process to cover the front glass on large area with a thin SiOx-containing layer based on a sol-gel process which e.g. is used also for cover glass of crystalline silicon modules. The new challenge here was that the glass was already covered with the TCO-layer at the back side and an optimization of the whole sol-gel process had to be performed. The objective of the task was to demonstrate in the frame of the project a transmission increase of 2% in the wavelength range interesting for a-Si:H single junction (300-800 nm) and a-Si:H/mc-Si:H tandem junctions (300-1100 nm) on an area of 1 m x 0.5 m. Latter was the maximum size on which AGC actually could perform the ARC process on industrial level in a pilot line. Deposition of ARCs on the front surface (tin side) of a TCO coated glass sheet has been performed at the AGC R&D centre's pilot line in Lodelinsart, Belgium. Figure 1 shows a photo of three TCO glasses covered with an antireflection coating layer after the curing process. The average reflectance in a wavelength range from 400 to 1000 nm is 7.4% (varying from 7.2 to 7.6%). On the TCO glass before AR-coating the reflectance was measured as 9.2% (average 400-1000 nm). This means that on average a reduction of reflectance (or gain in transmission) of 1.8% was obtained. In certain areas of the ARC covered TCO glass a reduction of reflectance of 2% could be obtained, most of the sample presented a gain of 1.8 to 1.9%. By further fine tuning of the process parameters a reflectance reduction of 2% over the whole area is supposed to be achievable.

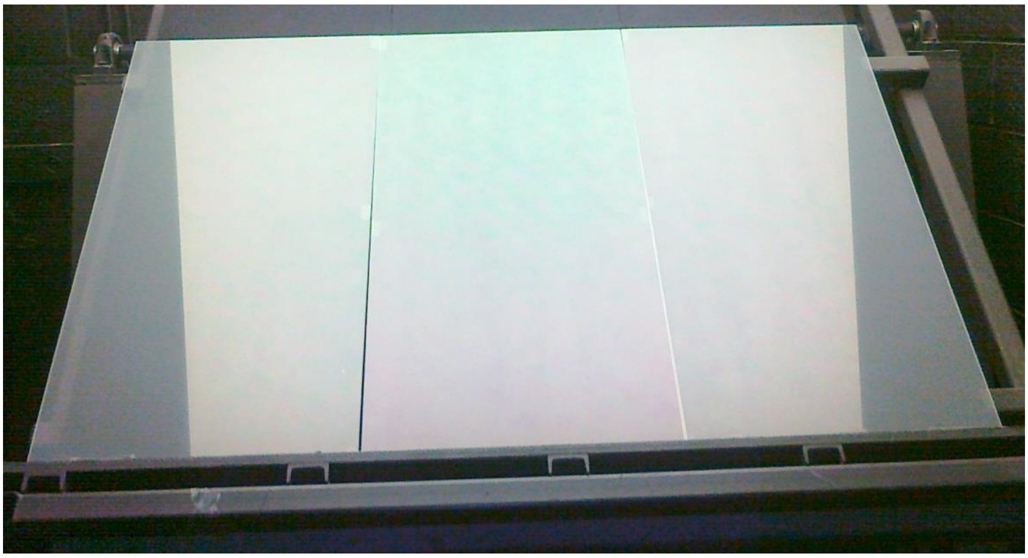

Figure 1: Picture of 3 samples of ANS10ME TCO glass uniformly coated with sol-gel AR coating.

Once to potential of the ARC was determined AGC has performed respective cost evaluations for the investment into an ARC processing line for very large area TCO substrates as used in the T-Solar module production. The calculation was based on the following numbers:

- Expected reflectance reduction (resp. transmission gain): 2%
- Expected solar panel efficiency (tandem type): ~10%
- Module price: 1 €/Wp

The power of a tandem-type silicon thin film module at 10% efficiency at that time was estimated to be 100 Wp/sqm. The estimated power gain by reduction of the reflectance by about 2% amounts to 1-2 Wp/sqm. At a module price of 1 €/Wp, the benefit of these extra 1-2 Wp amounts to 1-2 €/sqm. Admitting that this benefit would be shared 50/50 by AGC and its customer, this would mean for AGC an additional revenue of 0.5-1 €/sqm. The deposition of such an antireflective coating on a TCO involves additional costs, especially as this coating cannot be deposited in the same production line as the TCO coating (which is done directly in the float line), but e.g. the TCO-glass must be turned around and transferred to another process line. Concerning the additional costs incurred for an ARC coating process the following has to be considered:

- Investment of large-scale sol-gel coating line (a small pilot line already costs ~500 k€)
- Operating costs of coating line
- Additional transport and handling costs
- Overall yield loss

There exist some data in crystalline silicon PV technology about the additional cost incurred by a crystalline silicon module producer for using anti-reflective coated glass instead of normal glass which was reported by Centrosolar [CENTROSOLAR Group AG, Investor Presentation, November 2009] to be ~7 €/module. For a typical module size of 1 to 2 sqm this corresponds in average to 7€/1.5 sqm = 4.7 €/sqm. This is more than two times higher than the expected price difference that could be obtained for our case on a tandem-type silicon thin film module. Although the cost figure reported above for the anti-reflective coating is already 3 years old it seems unrealistic that it would have been reduced by more than 50% in the meantime. In general, on crystalline silicon modules with higher cell efficiencies the cost of ARC is more easily justified as the total gain in power due to reflection reduction is higher than on thin film solar cells. In consequence of the cost evaluation, the production of TCO glass with an sol-gel ARC coating was not implemented by AGC on large scale however, an alternative technology was identified that could be applied on a float glass line and first experiments performed within the project presented promising results. In consequence of the negative result of the cost evaluation, no prototype TCO modules including a TCO glass with sol-gel ARC could be produced in T-Solar.

<u>Task 2.2 Laboratory scale textured SiOx ARC by spray</u>

At the University of Barcelona (UB) a SiOx sol-gel solution was deposited on lab scale glass substrates by spray-coating and texturing was done by hot-embossing process which consists in the replication of a master onto this polymeric or gel-like coating. Thermal curing treatment is necessary to eliminate the organic molecules and to rigidify the film. To synthesize SiO_x materials $Si(OR)_4$ and $R\text{-}(SiOR)_3$ precursors were used. The homogeneous low temperature deposition and texturing of ARC on lab-scale was achieved with a uniformity of about 5% on 10 cm x 10 cm substrates. These films show high diffused transmission, especially in the wavelength range higher than 700 nm, which is beneficial for the light scattering into the thin film solar cells. The as-deposited films were successfully textured by the hot embossing process. The deposition and embossing process parameters were optimised in such a way that this layer can be implemented into the fabrication of amorphous silicon thin film solar modules, e.g. using the autoclave process which forms part of the module lamination process. The perspective and main attraction of the here developed process is the flexibility to replicate any type of master texture to the ARC and to evaluate its improvement in the light scattering and light absorption in silicon thin film solar cells.

Work Package 3: Glass/TCO interface

To get a baseline of the performance of different TCO glasses in amorphous single junction solar cells, at the beginning of the project benchmark tests were performed by the different laboratories with a variety of TCO glasses available within the consortium. At the beginning of the project, the standard TCO glass of AGC produced in large volume production was so-called “AN10” TCO glass which was further improved in two development cycles to “ANS10ME” TCO glass mainly increasing the transmission of the TCO glass. In this framework, prototype TCO glasses from AGC were tested several times in the TS production line to find the best TCO glass and to optimize the module fabrication process to this TCO glass. In a third development cycle the introduction of an interface layer (IFL) to reduce the reflection loss at the TCO-layer/p-layer interface was investigated.

Task 3.1 Benchmarking of commercial TCOs with ZnO developed at FZJ and validation of TCOs developed in task 3.3

At the beginning of the project, a number of commercially available (Asahi-U, AN10, NSG/Pilkington) and experimental TCO-glasses provided by AGC (Asahi-VU, AN10+ARC –with anti-reflection coating (ARC)-, AN10ME –with mobility-enhanced (ME) TCO layer-, ANS10 –extra clear glass with low iron-content) were benchmarked at the different laboratories with their standard solar cell process for a-Si:H single junction solar cells. In this first benchmarking, the Asahi-U TCO-glass and the industrial TCO-glass with low iron-content (AGC ANS-type) presented the highest solar cell efficiencies. The high efficiency with the Asahi-U TCO-glass was not surprising, since the solar processes of the laboratories have been optimized for the Asahi-U TCO-glass. The good results found with the low iron-content substrate glass indicated that the implementation of low iron-content glass could be cost effective not only for a-Si:H/mc-Si:H tandem modules, but also for a-Si:H single junction modules. Furthermore, this first benchmarking showed the difficulties associated to the implementation of an ARC layer on the front side of the TCO-glass by the low efficiency of the devices suffering from contamination problems. In a second benchmarking experiment the solar cell processes of different laboratories were compared with a cell process similar to the TS fabrication process i.e. the thickness of the i-layer in the p-i-n structure was fixed to 200 nm. The objective was to find out the potential of improvement of the TS solar cell when compared to laboratory high efficiency processes. This gave a guide line for the optimization of the solar cell fabrication process in the TS production line. In a third benchmarking the effect of light-induced degradation (LID) of solar cells fabricated with the standard laboratory processes and different TCO glasses, including the new developed ones, was investigated. Here the dependence of the LID on i-layer thickness was determined. [M. Vetter et al., Proc. 27th European PVSEC 2012, Frankfurt, p. 2594] A fourth benchmarking was performed to investigate and to optimize a new type of TCO layer developed by AGC with enhanced carrier mobility (ME-type) which resulted in reduction of the TCO layer thickness and higher layer transparency. This layer then was combined with low iron content glass resulting in the ANS10ME TCO glass. Figure 2 shows the improvement of the spectral response of the solar cell implemented in the TS module at the beginning of the project and at the end of the project.

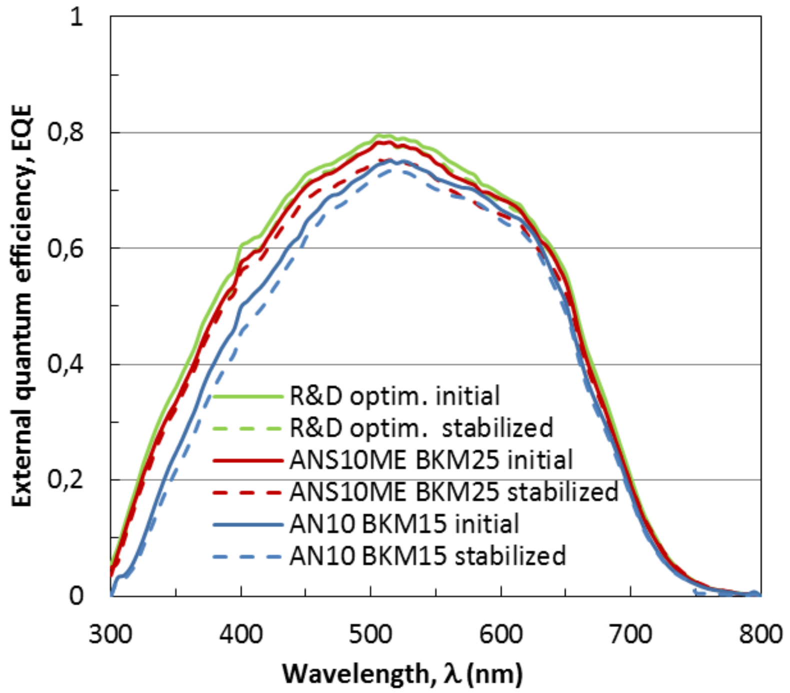

Figure 2: Initial and stabilized spectral response of best 1 sqcm solar cells deposited at T-Solar on AN10 TCO-glass at the beginning of the project (BKM15), ANS10ME TCO-glass using production conditions (BKM25) and final optimized R&D process conditions.

Table 1 presents the electrical parameters of 1 sqcm solar cells at standard test conditions (STC) fabricated in the TS production line at the beginning and at the end of the project. In the stabilized state the solar cell efficiency improved by more than 12% from 7.32% to 8.22%.

Table 1: Initial and stabilized electrical parameters at STC of best 1 sqcm solar cells deposited at T-Solar on AN10 TCO-glass at the beginning of the project (BKM15), ANS10ME TCO-glass using actual production conditions (BKM25) and final optimized R&D process parameters (Jsc_SR is the current calculated from the spectral response measurement, Jsc_SS: is the Jsc-value from the illuminated IV curve)

Panel	η_SS (%)	Jsc (mA/cm2)_SR	Jsc (mA/cm2)_SS	Voc (V)	FF (%)	Rs (Ω)	Rsh (Ω)
Initial State							
AN10 BKM15	8.50	12.29	12.97	0.912	71.9	5.48	1724
ANS10ME BKM25	9.20	13.05	13.69	0.928	72.5	5.95	2105
ANS10ME R&D optim.	9.56	13.40	14.09	0.940	72.1	6.29	11047
Stabilized state							
AN10 BKM15	7.32	11.85	12.64	0.890	65.1	7.09	1229
ANS10ME BKM25	7.97	12.62	13.13	0.894	67.9	6.40	1809
Difference to AN10	*8.9%*	*6.5%*	*3.9%*	*0.4%*	*4.3%*	*-9.7%*	*47.2%*
ANS10ME R&D optim.	8.22	13.10	13.71	0.895	67.0	6.62	1758
Difference to AN10	*12.3%*	*10.5%*	*8.5%*	*0.6%*	*2.9%*	*-6.6%*	*43.0%*

In a fifth benchmarking the performance of ZnO:Al TCO glass developed at FZJ was investigated in the a-SiH single junction device. For this purpose, ZnO-based TCO-glasses require a different device structure than SnO[sub(2)]-based TCOs, namely a p-doped mc-Si:H/a-Si:H layer stack must be included to provide a good electrical contact between the p-doped layer (p-layer) and the ZnO:Al-layer Single junction a-Si:H p-i-n solar cells have been deposited at FZJ on their in-house ZnO:Al

TCO-glass and on Asahi-U TCO-glass as reference. The device structure of both sets of cells is identical (i-layer thickness, back reflector, etc.) except for the p-layer structure. The implemented p-layer is the optimized one for each TCO-glass for single junction a-Si:H cells: amorphous single p-layer on Asahi-U and double structure p-doped mc-Si:H/a-Si:H on ZnO:Al. The efficiency of cells on ZnO:Al TCO-glass was found to be about 10%relative lower than on Asahi U TCO-glass. A lower fill factor (FF) on ZnO:Al TCO-glass was due to the unfavorable contact between the zinc oxide layer and the p-doped thin film silicon layer. This effect is well-known and the reason that a multi-stack mc-Si:H/a-Si:H p-layer is used on this TCO-glass. If a single a-Si:H p-layer had been used (like on Asahi-U), the FF value would have been even lower. A higher open circuit voltage (Voc) measured on ZnO:Al was always observed on this kind of devices. The root cause of the effect was not found and is still under investigation. Morphology of the ZnO:Al-layer may be the reason behind this increased Voc. The lower Jsc measured on ZnO:Al, comes from different effects: higher light absorption in the mc-Si:H/a-Si:H p-layer double structure, and maybe in the ZnO:Al-layer as well, and the fact that in single junction a-Si:H p-i-n solar cells, one does not fully benefit from the light trapping of the ZnO:Al front TCO-layer, since this kind of TCO-layer is optimized for mc-Si:H and a-Si:H/mc-Si:H tandem devices, where light trapping is more essential in the longer wavelength range as compared to a-Si:H single junctions.

<u>Task 3.2 Process development of front TCO by small-scale in-line APCVD and Task 3.6 Development of TCOs with graded optical properties</u>

The work in these two tasks was addressed to an important issue concerning the interface between the thin film silicon layers of photovoltaic cells and the TCO layer of the substrate. The TCO layer that is used consists of fluorine-doped tin oxide and has a refractive index of n=1.9 (at a wavelength of 600 nm). Silicon thin films however have a much higher refractive index of about 3 to 4.5 (at a wavelength of 600 nm). The result is that some of the light is reflected upon reaching this interface and can therefore not be harnessed by the photovoltaic layers. From the Fresnel formulae (which are valid only for smooth interfaces), the reflectance of the light would be theoretically zero if $n_{TCO2} = n_{TCO1} \times n_{a\text{-}Si}{}^{1/2}$ and $4 \times n_{TCO2} \times d = L$, where, n_{TCO2}, n_{TCO1} and $n_{a\text{-}Si}$ are the refractive indices of the intermediate TCO, front TCO and silicon p-layer respectively. The thickness of the intermediate TCO layer and the wavelength of incident light are presented by d and L.

From literature was known that the addition of a high refractive index layer as e.g. TiO_2 (n=2.6) on top of the tin oxide TCO layer helps to reduce the reflectance at the TCO/Si interface. However, it has been found that TiO_2 presents two major issues. One is that it is not sufficiently conductive, thereby introducing an additional series resistance in the electrical circuit of the solar cell. Secondly, TiO_2 can lead to additional absorption depending on deposition conditions.

At UB, Nb-doped TiO_2 (NTO) films were deposited at room temperature by rf and dc magnetron sputtering over Corning 1737F substrates in order to optimize their properties before using them as second TCO layer in the graded index structure. When NTO films were annealed at temperatures higher than 350 ºC, their crystalline structure changed to anatase phase and the films became conducting. Deposition parameters (rf or dc power applied, O_2 partial pressure and doping level of the target) and different post-annealing treatments (duration, temperature, atmosphere) were explored to optimize film properties, i.e. to minimize optical absorption in the spectral range of interest for a-Si:H and a-Si:H/mc-Si:H tandem cells and to get a conductivity high enough to avoid increasing the cells series resistance. The optical transmission spectra showed negligible free carrier absorption and this gave a wide scope for the utilization of this TCO layer for different applications. The reduction of the reflection losses at the TCO/a-Si:H interface was verified by depositing on the Asahi U/NTO stack a 200 nm a-Si layer and a 200 nm Ag layer back reflector in order to reproduce, from the optical point of view, the behaviour of a real device. The electrical resistivity of the thin NTO layer (40 nm) was 2×10^{-3} ohm cm. There was only little change in sheet resistance when NTO was deposited on Asahi U substrates and hence, no significant contribution to the series resistance of the cell is expected with this additional coupling layer. The sheet resistance of the Asahi U was 8.5 ohm/sq and it was 9 to 9.5 ohm/sq for the NTO layer deposited on Asahi U substrate. A set of Asahi U samples covered with different NTO layers (NTO1 to NTO3: TiO_2:Nb_2O_3(1%), NTO4 TiO_2:Nb_2O_3(0.5%)) were prepared at UB and transferred to T-Solar to finish the solar cell structure in the production line. Spectral response measurements (see Figure 3) show an increase of the spectral response in a wide range of wavelengths, also the reflectance measured of solar cells presents lower reflectance of cells with interface layer (IFL) layer in the same wavelength range.

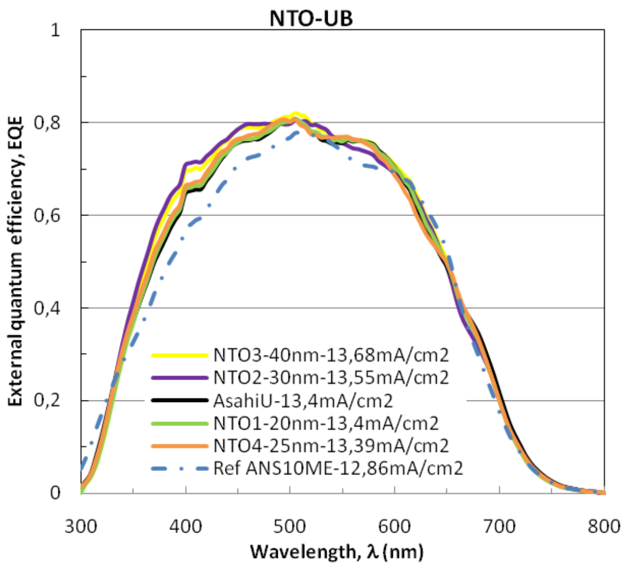

Figure 3: External quantum efficiency comparison of the NTO samples with its references. Solar cells fabricated at T-Solar. Short-circuit current density values for the cells indicated in the legend were obtained from integration of the spectral response weighted by the AM1.5G spectrum.

In Table 2 the photovoltaic parameters for these cells are shown. As it was previously shown from EQE measurements, the addition of a NTO layer slightly improves the short circuit current density, being this effect more evident for samples NTO2 and NTO3. Nevertheless, in all cases, the Voc and FF values are worse than those of ANS10ME and Asahi U references.

Table 2: Electrical parameters of the solar cells deposited at T-Solar on NTO samples and reference cells on ANS10ME and Asahi U in the initial state. (SR indicates the current calculated from the EQE, SS indicates the current from the IV-curve)

Sample	η	J_{sc} (mA/cm^2)_SR	J_{sc} (mA/cm^2)_SS	V_{oc} (mV)	FF	R_s (Ω cm^2)	R_{sh} (Ω cm^2)
Ref ANS10ME	8,98	12,86	13,45	922,7	72,4	5,59	1752
Asahi U	9,03	13,4	13,69	910,1	72,5	5,71	1759
Asahi U + NTO1	7,52	13,4	13,63	816,7	67,5	7,55	1403
Asahi U + NTO2	8,53	13,55	13,79	884,3	70	7,49	1859
Asahi U + NTO3	7,19	13,68	13,78	815,7	63,9	10,33	4298
Asahi U + NTO4	8,03	13,39	13,61	882	66,9	11	1367

AGC's work within this Work Package has been to modify the deposition chemistry of the TiO_2 interface layer in order to avoid the issues found for TiO_2 layers. Experimental trials made on the CVD pilot-scale equipment at AGC has resulted in determining deposition conditions for a TiO_2-based interface layer that reduced the reflectance between the tin oxide TCO layer and the silicon layers of the solar cell. Most importantly conditions have been found that avoid absorption and resistive losses in the interface layer. On small-scale, efficiency of a-Si:H solar cells fabricated in

AGC labs was increased in some cases by up to ~5% relative to the TCO glass substrate without interface layer. As the pilot-scale equipment is highly similar to the CVD equipment used on an industrial scale these conditions in principle could be transferred to the industrial production line after some adaptations of the trial parameters for larger scale and fine tuning for differences in temperature.
Two series of TCO glass with IFL layers were fabricated at AGC and sent to T-Solar to be tested in single junction large area modules. Table 3 summarizes thickness and electrical properties of the three most promising IFL conditions measured at AGC. Sheet resistance of these layers (Rs in the Table 3) is slightly higher than the optimal for a-Si:H single junction devices, values of around 11 ohm/sq are more adequate for amorphous/microcrystalline silicon tandem devices.

Table 3: TCO layer and IFL layer thickness and electrical properties of the 3 chosen conditions and reference sample.

Samples	TCO thickness (nm)	IFL thickness (nm)	Rs (ohm/sq)	Mobility (cm/Vs)
Reference	778	0	11,2	40,4
Test n°8	807	40	10,6	39,9
Test n°9	806	40	10,8	40
Test n°10	806	28	10,6	40,3

All samples prepared on glass thickness: 3,2 mm

Table 4 summarizes the output parameters of the single junction modules fabricated by using the IFL front TCO glasses. ANS10ME TCO glass is included as additional reference representing the standard production process at that time. Efficiency is much higher than for AN10 since the TS production process was optimized for ANS10ME substrate.

Table 4: Summary of averaged performance parameters of 2.2 x 2.6 sqm single junction modules prepared at T-Solar on IFL samples. ANS10ME is included as extra reference representing the average production performance.

Type	Experiment	RACK	Pmpp[W]	Eff	Voc[V]	Isc[A]	FF
AN10 IFL	REF	AAXPI-01-517	411,95	7,20	193,51	3,30	64,59
AN10 IFL	TEST 10	AAXPI-01-508	414,12	7,24	193,44	3,26	65,68
		vs REF	0,53%	0,45%	-0,04%	-1,10%	1,69%
AN10 IFL	TEST 9	AAXPI-01-505	416,79	7,28	193,97	3,28	65,55
		vs REF	1,18%	1,12%	0,24%	-0,54%	1,49%
AN10 IFL	TEST 8	AAXPI-01-502	418,54	7,32	194,15	3,29	65,61
		vs REF	1,60%	1,56%	0,33%	-0,30%	1,57%
ANS10ME	-	AAQYH-01-516	423,85	7,41	194,53	3,27	66,60

In spite of this, the different IFL conditions (Test 8-10) show unexpectedly low improvements when compared to their reference. The results show that the properties of these coatings evolve further during the deposition process of the single junction modules. They also indicate that certain factors such as sheet resistance have a larger impact on large size solar modules than on laboratory-sized solar cells. Given the interesting results on IFL coated TCO glasses obtained on small scale samples, this research should be pursued further. However in addition to electrical and optical properties of such a layer the stability issues and the precise production environment have to be addressed, e.g. laser scribe processes need to be optimized.

Task 3.3: Implementation of optimized TCO in in-line process by APCVD

The amount of light that reaches the active layer of a p-i-n solar cell strongly depends, among others, on the quality and properties of the front contact. The front contact consists of a glass sheet coated with a TCO layer. In this task, new developed front TCO glass was characterized and tested at industrial level. AGC's AN10 TCO glass with usual float glass as substrate was the production standard TCO glass at TS at the beginning of the project. In a first cycle of TCO glass optimization, the effect of using extra clear substrate glass (ANS-type), usually implemented in tandem modules, in a-Si:H single junction modules was investigated and a gain in integrated transmission (wavelength range: 400 – 800 nm) of 1.6% of the TCO glass was demonstrated. Processing ANS10 TCO glass through the TS production line presented an increase of 2.8% in the average module efficiency reaching the first time a module efficiency of 7% (400 W in a 5.7 sqm module). This gain in efficiency was high enough to compensate the higher cost of the extra clear glass substrate.

In a second development step, a TCO-layer with enhanced carrier mobility was added to the use of extra clear glass resulting in so-called ANS10ME TCO glass. Before, a series of ME-type TCO glasses with different sheet resistance and TCO layer thickness was tested to find the best trade-off between optical and electrical properties for a-Si:H modules. The optimum was to reduce the TCO layer thickness from about 1000 nm to 750 nm and to keep the sheet resistance of the TCO layer in the range of 8-9 ohm/sq. This resulted in a TCO layer with about 0.5% higher transmission and 1% higher module efficiency. Figure 4 shows transmission spectra of AN10 and ANS10ME TCO glasses and respective substrate glasses where the TCO layer has been removed, the increased transparency of ANS10ME TCO glass (leading to increased short-circuit current (Isc) in the modules) is clearly seen. Average integrated transmittance (400-800 nm, the range where single junction a-Si:H solar cells respond) over a significant number of batches used in production was 85.8% for ANS10ME TCO glass (270 glasses) vs. 83.8% for AN10 TCO glass (25 glasses). The increase of the TCO glass transmission of 2% translates to an increase of the module power of about 5%, (including also an optimization of p-i-n structure to the TCO glass).

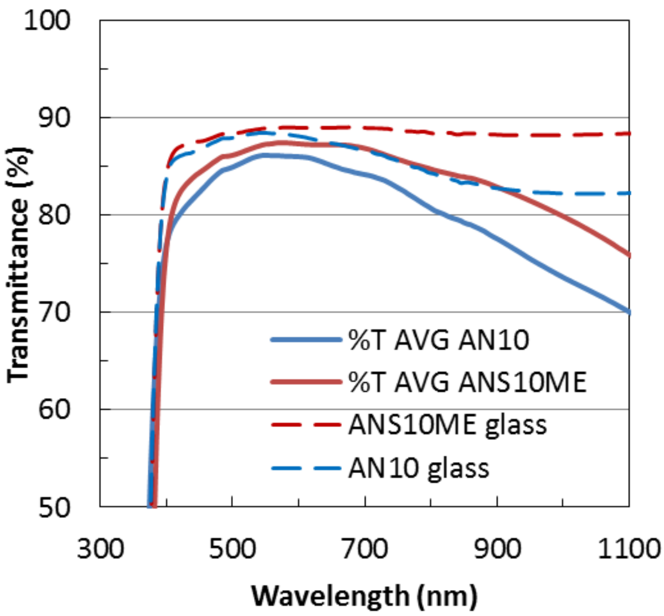

Figure 4: Transmission spectra of AN10 and ANS10ME front TCO glasses and the substrate glasses (3.2 mm thickness) without TCO layer (measurement with index matching liquid CH_2I_2 and quartz cover glass.

Figure 5 presents the comparison of the diffuse transmission of AN10 and ANS10ME TCO glass and the haze calculated from diffuse and total transmission. The diffuse transmission of ANS10ME appears slightly higher than for AN10 resulting from the higher overall transmission, the haze curve of TCO layers is very similar indicating that a very similar surface morphology could be obtained by the newly developed deposition conditions even if the layer thickness of the ANS10ME TCO layer is 25% thinner.

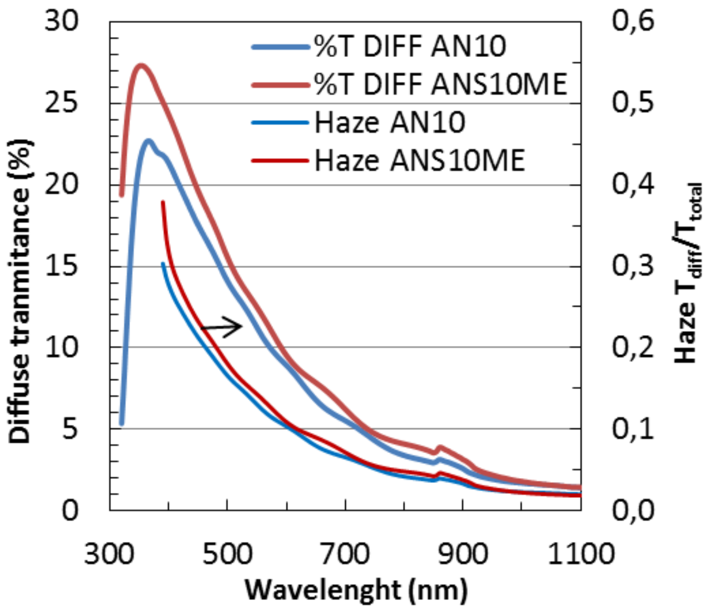

Figure 5: Diffuse transmission spectra and haze of AN10 and ANS10ME front TCO glasses.

A resume of the electrical and optical properties of different industrial TCO glasses and the laboratory TCO glass Asahi U is shown in Table 5.

Table 5: Integrated transmission (400-800 nm range), transmission gain vs. AN10, carrier density (n), carrier mobility and resistivity of the front TCO glasses.

Sample	Int. Trans. (%)	Δ to AN10	n (10^{20} cm^{-3})	μ (cm^2/Vs)	ρ (10^{-3} Ω·cm)
Asahi-U	85.4	1.5	3.19	28.6	0.69
AN10	83.9	-	3.11	27.8	0.72
ANS10	85.6	1.7	-	-	-
ANS10ME	86.1	2.2	3.08	31.9	0.64

<u>Task 3.4: Implementation of developed TCO in very large area modules</u>

In this task several front transparent conductive oxide (TCO) glasses developed by AGC have been tested in large area (2.2 x 2.6 sqm) modules at the production line at T-Solar. These TCO glasses had already been characterized, tested and benchmarked in small scale cells as described in tasks before. In Figure 6, the evolution of the average efficiency of the module production at TS can be seen. The increase in efficiency from 6.68% (382 W, BKM15) to 7.34% (420 W, BKM25) at the end of the project, almost a 10% relative increase, is the result of an improvement in the properties of the TCO glass (ANS10ME has become the standard T-Solar production TCO glass in the meantime) together with an improvement of the device (optimization of the different layers and adaption to the new TCO glass, laser process improvement, etc.). Table 6 summarizes the average electrical parameters of the production modules at T-Solar. Electrical parameters of the champion production module are also included.

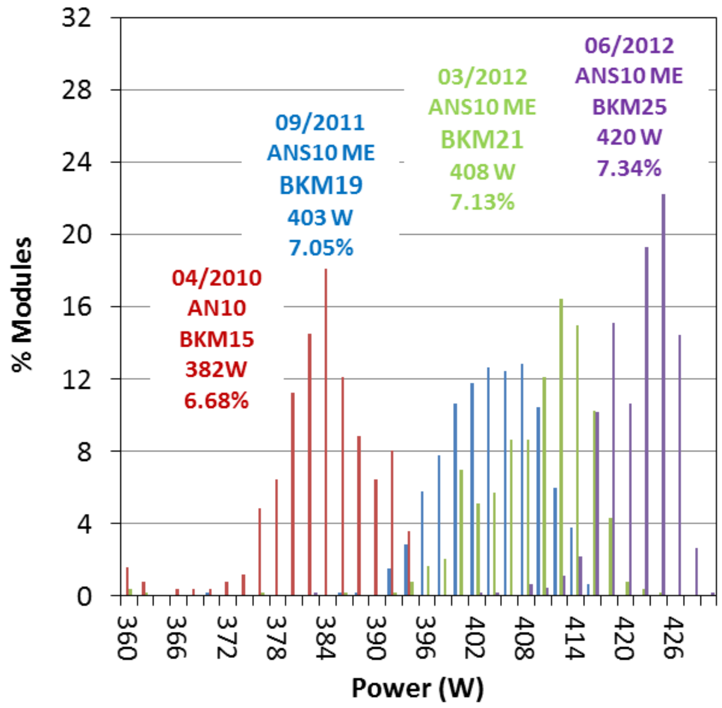

Figure 6: Evolution of the module production efficiency at T-Solar during the project.

Table 6: Average production and production champion module electrical parameters at the end of the project.

ANS10ME	Pmpp (W)	η (%)	Voc (V)	Isc (A)	FF (%)
Prod. Av.	420.1	7.34	192.6	3.27	66.6
Champion	428.0	7.48	193.6	3.31	66.9

One of the module parameters that had increased the most with the overall improvements is the short circuit current (Isc). Factors impacting this parameter are the quality and transparency of the TCO glass (increased from AN10 to ANS10ME), the total active area in the module, increased upon improvement of the laser scribing process that allows a much narrower (200 µm vs. 350 µm) distance between laser scribe lines and optimization of the p-i-n structure (layer thickness, i-layer quality, etc.). The latest R&D developments (use of microcrystalline n-doped layer, improved p-layer and low deposition rate i-layer) lead to an even further increase in Isc (3.8% improvement in stabilized current vs. the last production process). Table 7 shows the initial and stabilized electrical parameters of a standard production module (BKM25, ANS10ME TCO glass) and the initial data of the champion R&D module (fabricated on the same type of TCO glass). Our standard production module showed an initial efficiency of 8.49% and a stabilized one of 7.37% after 300 kWh/sqm of light-soaking. The current R&D champion showed an initial efficiency of 9.14% (523 W) and had not finished light-soaking at the end of the project. Nevertheless, assuming the same 13% LID measured for our production modules, the expected stabilized efficiency is 7.95%.

Table 7: Electrical parameters (initial and stabilized) of a standard T-Solar production module (BKM25) and initial electrical parameters of T-Solar champion R&D module. Stabilized power and efficiency of R&D champion is estimated using the current 13% LID coefficient.

	BKM25 (Production)		R&D Champion	
	Initial	Stabilized	Initial	Stabilized
P_{mpp}(W)	485	422	523	455
η (%)	8.49	7.37	9.14	7.95
I_{sc} (A)	3.44	3.28	3.54	
V_{oc} (V)	199	194	203	
FF (%)	70.9	66.3	72.6	

Figure 7 shows the behavior of the electrical parameters during light-induced degradation of a module deposited on ANS10 TCO glass (prototype) in the first year of the project (BKM15) and of a module deposited under the same conditions as TS current R&D champion with slightly lower power, exposed to ambient conditions at the module outdoor test station of the TS factory in Orense, Spain.

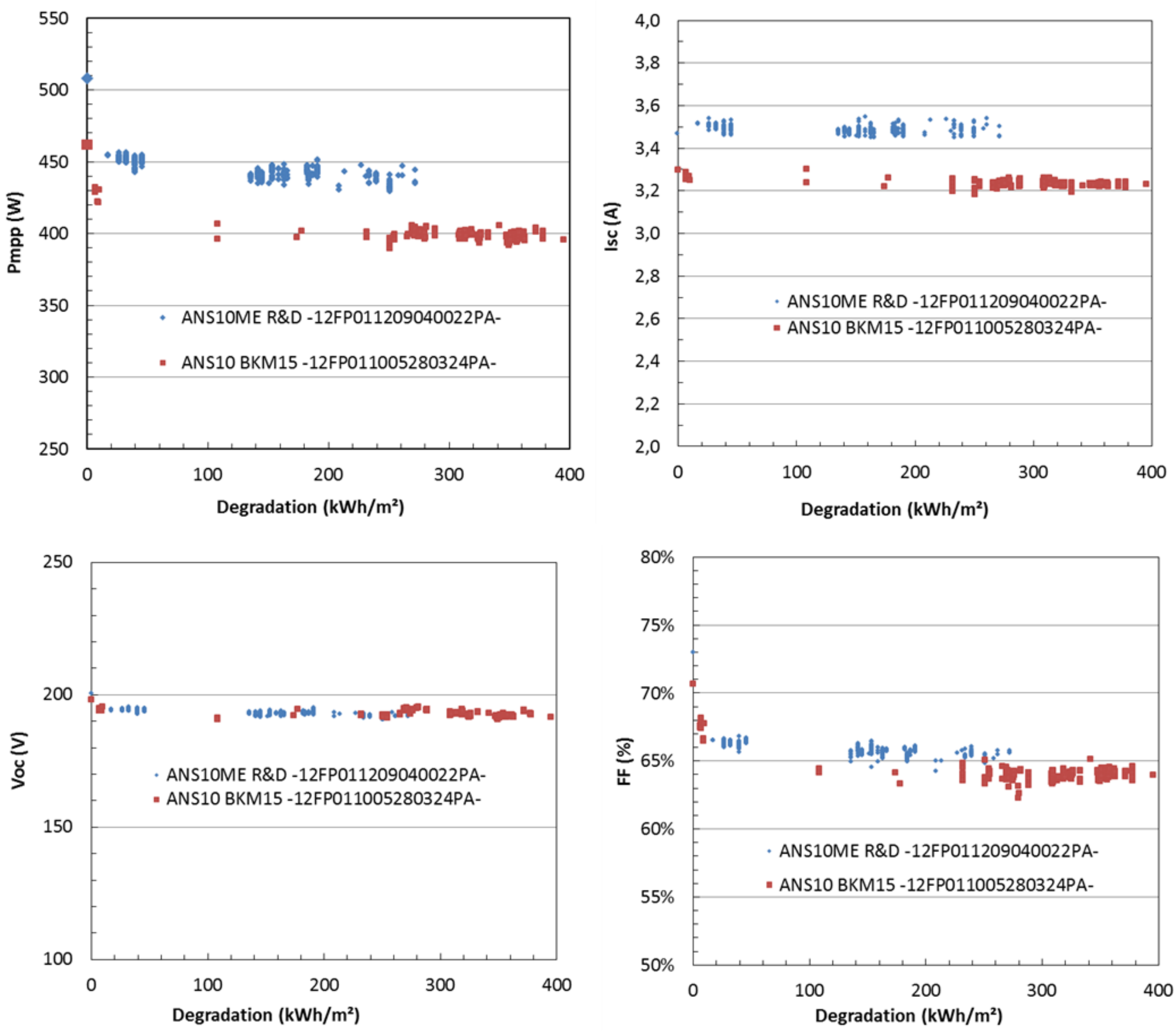

Figure 7: Evolution of electrical parameters during light-induced degradation of a module deposited at the beginning of the project (BKM15) and a current R&D module with the latest developments.

In frame of this task initially it was planned also to develop a process for large area (5.7 sqm) a-Si:H/mc-Si:H tandem modules in the T-Solar production line. Unfortunately, tandem module fabrication has not been possible at TS since an expensive upgrade of the PECVD deposition system was required in order to be able to deposit device-quality intrinsic microcrystalline silicon layers. As a consequence of the photovoltaic market development with extremely low module prices and the global financial situation, this investment was not possible during the current project. Nevertheless, development of a-Si:H/mc-Si:H tandem solar cells and mini modules with the amorphous top cell and intermediate reflector deposited at T-Solar and the bottom microcrystalline cell deposited at FZJ has been carried out successfully, and the results are reported in WP4.

Task 3.5 Textured TCOs by embossing of sol gel coatings

In this task the UB has explored the possibility of using spray technology to deposit ZnO layers from sol-gel solutions, and then applying hot embossing to transfer a surface texture to the films. The novelty of this method is to obtain TCOs with a tailored surface morphology in order to optimize their optical performance as front contacts in thin silicon solar cells. Unlike conventional spray pyrolysis of TCOs that involves spraying of a solution containing precursors onto a substrate heated above 400 °C, here the approach is to prepare a sol-gel of ZnO and deposit the film at low temperature (85 °C) to allow the embossing of the film. Additional thermal treatments may be needed after embossing to remove organic solvents. The master used for the hot embossing was a nickel hologram plate (5 x 5 sqcm) with randomly distributed periodic texture. Figure 8 shows the surface morphology of a hot-embossed ZnO film observed by interference microscopy (IM). Figure 8 (a) shows the embossed ZnO film, where the texture of nickel master is well replicated. The trace of some droplets, pin holes and a few protrusions can be observed on the surface, which might have occurred during the removal of master. Figure 8 (b) shows a slightly smaller area and Figure 8 (c) and (d) illustrates with a higher magnification the different patterns that can be obtained from the nickel master.

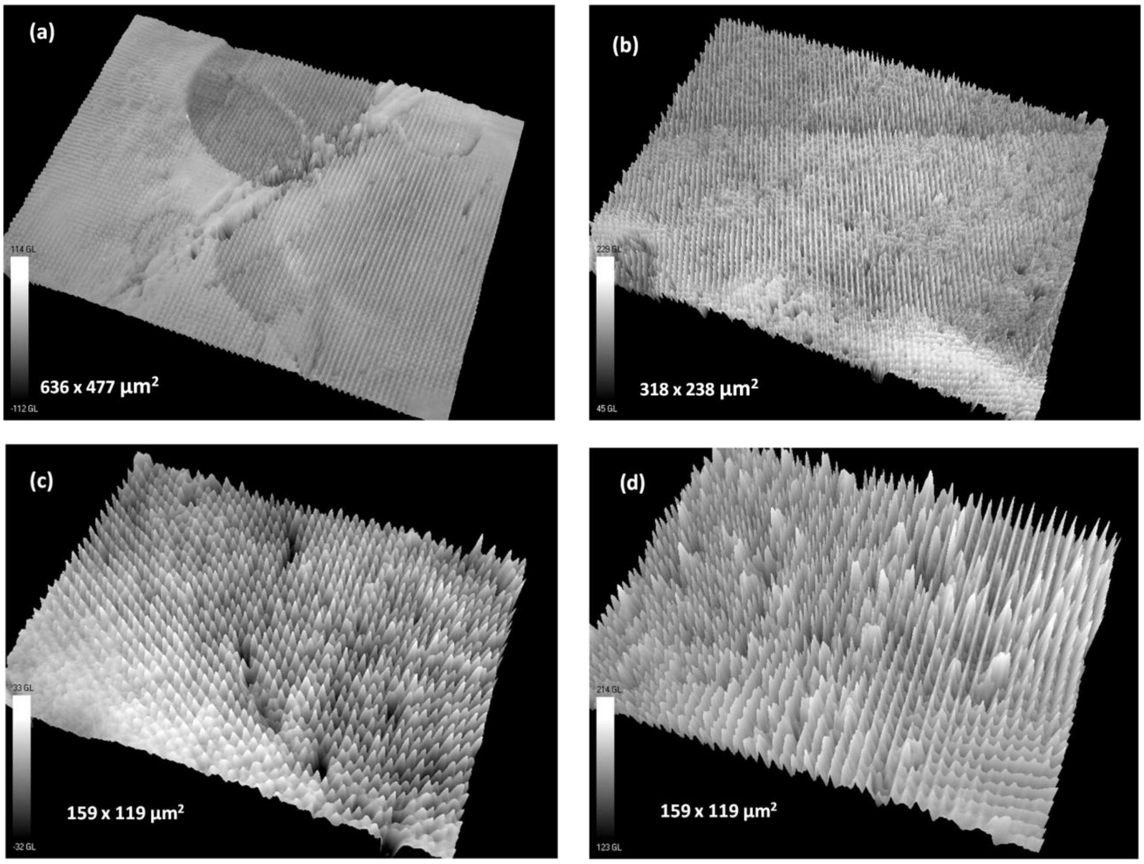

Figure 8: Images obtained at different magnifications by IM of a hot-embossed ZnO film. In (c) and (d) different patterns of the nickel master can be observed.

The XPS analysis of the film indicates the formation of ZnO. The optical band gap of the ZnO films was found to increase from 3.22 eV to 3.42 eV with aluminium doping. For Al-doping only low doping efficiency in the ZnO layers was found resulting in a resistivity of 2×10^4 ohm·cm whereas that of non-doped ZnO layers could not be measured. Further optimization of the sol-gel synthesis is needed to obtain low resistive ZnO films. In addition, the post annealing conditions have to be optimized to remove residual organic contaminants and to obtain crystalline ZnO films.

Work Package 4: Intermediate reflector (tandem structure)

The incorporation of intermediate reflecting layers (IRLs) has a great potential for the optimization of tandem solar cells with a-Si:H top cell and mc-Si:H bottom cell. Intermediate reflectors (IR) are used to provide selective light distribution, one of the three important mechanisms (the other two are light diffusion by the front TCO and reflection at the back reflector) for light management inside thin film solar cells. As the incorporation of IRL influences both the optical and the electrical properties of the whole device, the impact on the solar module performance is a complex topic. Due to the higher band-gap energy of a-Si:H, a photon, which is absorbed in the top cell provides a higher electrical power as in the bottom cell. Intermediate reflectors are incorporated in the tandem structure to reflect photons with energies near the optical band-gap of a-Si:H, which were absorbed in the bottom cell without IR. The objectives for thin-film solar cell development are twofold. First, the improvement of the total energy conversion efficiency by increasing the absorption in the top cell. Second, the reduction of the top cell thickness without losses in the total efficiency. The latter will reduce the material consumption, production costs and LID.

<u>Task 4.1 Demonstration of small tandem modules with intermediate reflector</u>

The first step of the incorporation of intermediate reflectors in very large area thin-film technology was the demonstration and optimization of IR materials on laboratory scale. At FZJ, silicon oxide layers were used as IR in a-Si:H/mc-Si:H tandem structures. The material parameters of microcrystalline silicon oxide (mc-SiOx:H) layers were investigated and were optimized. Figure 9 presents a compilation of the material properties found and an indication by the red ellipses of the interesting range for IR. The optimum properties are an electrical conductivity (s) in the range s=10^{-4} -10^{-2} S/cm, a refractive index (n) in the range of n=2.2 – 2.6 and an optical band gap (E_{04}) of E_{04}=2.2-2.4 eV. The optimum layer thickness for the IRL is around 30-100 nm.

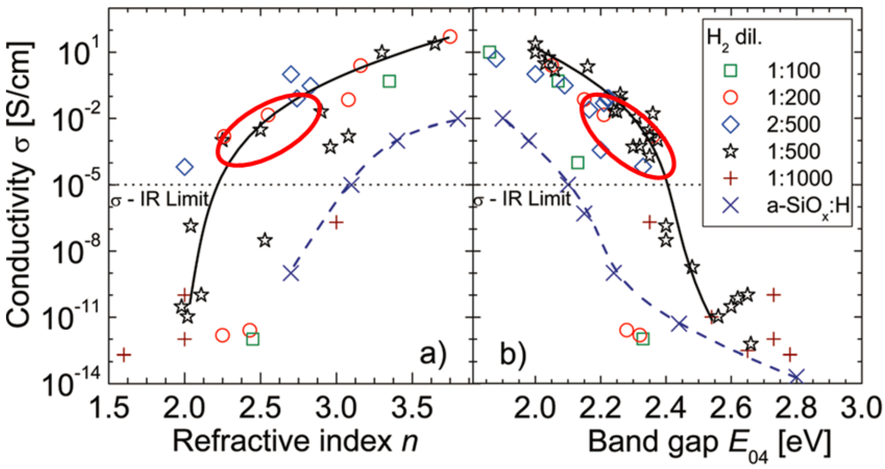

Figure 9: Compilation of material properties of n-type mc-SiOx:H layers published by FZJ representing the most important material properties for the IR application. IR Limit is the conductivity limit for a 100 nm thick layer resulting in 1 Ω·sqcm series resistance in a tandem cell (figure from: A. Lambertz, T. Grundler and F. Finger, J. Appl. Phys. 109, 113109 (2011)) The red ellipses indicate the range of interest.

Next n-doped mc-SiOx:H layers were incorporated in 1 sqcm a-Si:H/mc-Si:H tandem solar cells and it was demonstrated that the incorporation of the IR into tandem solar cells leads to an improvement of the top cell current by 13%. It was shown that the top cell thickness can be reduced by more than 40% to achieve current matching of the top and bottom cell with the same total current density (see Figure 10).

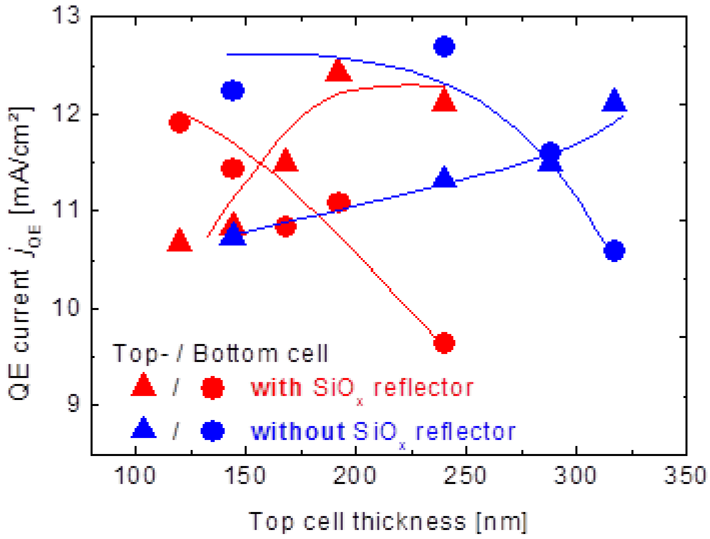

Figure 10: Photocurrent generated in the top (triangles) and bottom (circles) cells for a series of tandem cells with varying top cell thickness. Results are shown for tandem cells with (red) and without (blue) SiO_x:H layer (A. Lambertz, T. Grundler and F. Finger, J. Appl. Phys. 109, 113109 (2011)).

Then, the technology of tandem modules was developed and optimized with respect to the achieved energy conversion efficiency. For the production of such tandem modules, several layers have to be deposited by either plasma-enhanced chemical vapor deposition (PECVD) or physical vapor deposition (PVD). Both, the top cell and the bottom cell consist of a layer stack of p-doped, intrinsic and n-doped silicon. As back reflector, a layer stack of ZnO:Al/Ag is commonly used in tandem modules. Instead of the n-doped layer of the top cell, an n-type mc-SiOx:H layer is used which has the function of the n-layer as well as intermediate reflector that reflects the light in the spectral range of 550-700 nm back to the top cell to improve its spectral response.
Table 8 shows the average values of a series of 30 cm x 30 cm modules with IR in the initial and stabilized state. Before light-soaking, an average efficiency of 11.4% and a record efficiency of 12.2% were found, very near to the 12.5% efficiency expected at the beginning of this project for this module size. After LID, the efficiency decreased to 9.7% in average with a record value of 9.9%. This value is lower than the expected 11.5%, most probably due to the relatively thick i-layers with 300 nm in the top cell. The reason for implementation of this relative thick i-layer is that the optimization of tandem junctions demands a very high effort of personnel power and machine capacity. Since the focus of FZJ first was the optimization of the tandem cell with intermediate reflector in the initial state, a thickness of 300 nm for the amorphous i-layer was chosen and finally no optimization of i-layer thickness of the top cell could be performed within this project

Table 8: Resume of the average electrical parameters in the initial (stable) state of 17 (10) 30 cm x 30 cm tandem modules.

	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	η (%)
Initial	1.372	11.46	72.6	11.4
Stable	1.355	11.29	62.7	9.7
Difference	**-1.2%**	**-1.5%**	**-13.6%**	**-14.9%**

Task 4.2 Development of suitable materials by PECVD

At the beginning of the project an exchange of tandem cells and IR structures between UU and FZJ was performed within this task. The purpose of this exchange was to implement a baseline for IR at UU by using n-type SiOx IR already developed by FZJ and to adapt this IR structure to the best tandem cell produced in UU. After testing several top cell i-layer thicknesses and two different IR thicknesses the best UU tandem cells with IR were obtained for 150 nm i-layer, 1.5 μm bottom cell and a 32 nm or 65 nm IR layer. These cells showed almost matched top and bottom cell currents due to the IR and thus the best values for the efficiency. In this frame, a tandem cell fabricated in UU with IR deposited in FZJ achieved an initial efficiency of 9.22% with 65 nm thick IR while the respective cell without IR presented a lower efficiency of 8.48% (150 nm i-layer thickness in the top cell and 1500 nm i-layer in the bottom cell) demonstrating that the IR concept works well in the UU tandem cell. The sample exchange process also showed that such sample transfer and multiple depositions at different laboratories with intermediate air breaks and sample handling has no significant effect on the cell performance due to robust nature of the device structure with IR and this was used as a guiding principle for sample exchange in Task 4.3. ZnO as IR was also tried in the UU tandem cell structure. ZnO layers, optimised for this purpose, showed significant reflection to the top cell, however, further development was needed to reduce the optical absorption loss in the ZnO IR layer.

In the next step, n-type microcrystalline SiOx:H was developed at UU, based on the exchange of knowhow of the project partner FZJ. To be able to deposit also the IR in the laboratory of the UU, they took the n-type mc-Si:H material formerly developed in the ASTER deposition system as the base material and then adapted the deposition parameters of this layer with increasing amount of CO_2 in the gas mixture. The performed experiments allowed to identify the deposition conditions to prepare microcrystalline silicon oxide layers that meet the requirements of IRs for a-Si:H/mc-Si:H tandem cells. The samples made with deposition condition of SiH_4 gas flow of 6 sccm, CO_2 gas flow of 6 sccm, PH_3 gas flow of 0.13 sccm and H_2 gas flow of 270 sccm in a VHF PECVD deposition process satisfy the criteria, however, there was still room for optimization of deposition parameters for achievement of even better material characteristics. The next step would have been to prepare layers with higher H_2 dilution, CO_2/SiH_4 ratio and PH_3 flow. However, due to a decision of the UU governing board at beginning of 2012 to move the Utrecht Solar Energy Laboratory (USEL) for strategic reasons to the High Tech Campus (HTC) in Eindhoven and in this process to join their activities with other research groups of The Netherlands, the experimental work had to be stopped in April 2012 and the laboratory was moved in May 2012 to Eindhoven. Even undertaking strong efforts to recover the functionality of the laboratory in Eindhoven, the deposition laboratory was not fully operational at the end of this project. Hence, no further deposition of mc-SiOx layers and solar cells could be made by UU after April 2012. In consequence, the objective to fabricate tandem solar cells with 13.5% initial efficiency in this task could not be fulfilled within the frame of the project. However, the here performed pre-work will find its application and implementation in the near future in the frame of the FP7 EU Project Fast-Track where the USEL laboratory is involved.

Task 4.3 Testing of intermediate reflector developed at laboratory scale at TS production line

The objective of this task was to test the intermediate reflector layer concept in a-Si:H/mc-Si:H tandem structures at an industrial level. Two types of intermediate reflector materials have been considered in the project. One of the materials considered as IR is sputtered ZnO, a material which is the production standard in the back reflector structure in TS single junction modules and, therefore, was already available on large scale in the TS production line. ZnO layers, when moderately doped, are highly transparent in a wide wavelength range and provide sufficient transverse conductivity to conduct the current flow from the top cell to the bottom cell. They present a refractive index (n) of n=2 which results in a high reflection when incorporated between a-Si:H and mc-Si:H layers (n=3-3.5). ZnO layers have been shown to be very well reflecting layers however, the relatively high lateral electric conductivity, even in non-doped layers, makes it necessary to change the design of the laser scribe sequence in modules.

Doped mc-SiOx:H layers before have been shown to be good candidates for IR. These layers are highly transparent in the visible and near infrared wavelength range (300–1100 nm) when deposited in optimized process conditions since they consist of a mixture of a doped mc-Si:H phase and an amorphous SiOx:H phase. The doped mc-Si:H phase provides transverse conductivity for the current flow and the amorphous (nearly insulating) SiOx:H phase provides an electronic passivation of the doped mc-Si:H material and gives the possibility to tune the optical properties of the mixture. The optical band gap (E_{04}) can be tuned between E_{04}=2-3 eV and the refractive index between n=1.5 (a-SiOx:H) and n=3.5 (mc-Si:H). Due to these properties, high transparency and variable refractive index can be achieved to optimize the amount of the reflected light to the top cell. Contrary to the case of doped ZnO layers, deposition of doped mc-SiO_x:H layers was not possible at TS with the production configuration of the PECVD machine at the beginning of the project (these layers were not used in the standard industrial production of single junction a-Si:H modules) and an upgrade in one of the chambers of the PECVD machine had to be done (new gas lines and RF power system) for the deposition of doped mc-SiO_x:H layers.

As the incorporation of IR influences both the optical and the electrical properties of the whole device, the impact on the solar module performance is a complex topic. Before transferring the IR concept to very large area modules, the IR and the tandem layer stack were optimized on a laboratory scale to improve the efficiency of the tandem solar cells. Process conditions of mc-SiO_x:H were studied in the TS PECVD system and layers with the most adequate properties to be used as IR and ZnO:Al, both deposited at T-Solar, were tested as IR in a-Si:H/mc-Si:H tandem devices. As it was not possible to deposit device quality intrinsic mc-Si:H at T-Solar, these tandem devices were made partially at T-Solar (top a-Si:H cell and IR) and finished at FZJ (laser scribing, mc-Si:H bottom cell and back reflector). Table 9 shows results obtained for 1 sqcm tandem cells with 40 nm mc-SiOx:H IR and Figure 11 the respective spectral response. Thickness of the bottom cell is 2600 nm in all tandem cells.

Table 9: Electrical parameters of 1 sqcm tandem cells with top cell of various i-layer thickness (first column) and 40 nm mc-SiOx:H IR deposited in TS and bottom cell prepared in FZJ.

mc-SiOx:H IRL i-layer thickness	Eff. (%)	FF (%)	Isc (mA/cm^2)	Voc (V)
150	10.3	76.6	9.7	1.4
200	11	76.4	10.3	1.39
300	11.9	75.7	11.4	1.39

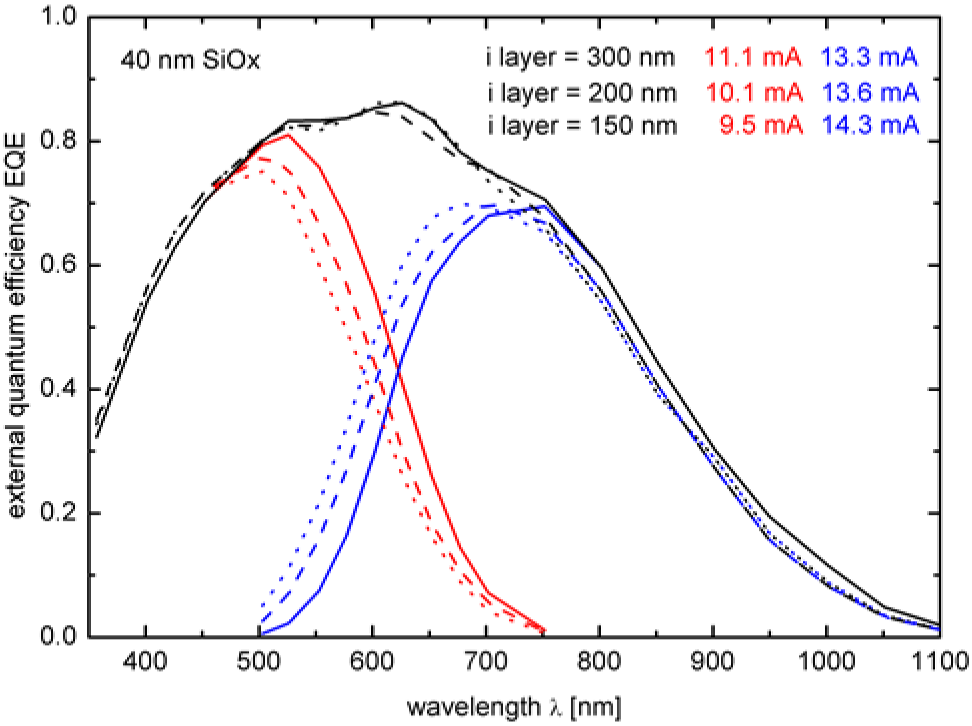

Figure 11: EQE of tandem solar cells with different top cell i-layer thickness and using 40 nm mc-SiO_x:H layer as IRL

Table 10 shows results obtained for 1 sqcm tandem cells with 90 nm ZnO IR and Figure 12 the respective spectral response.

Table 10: Electrical parameters of 1 sqcm tandem cells with top cell of various i-layer thickness (first column) and 90 nm ZnO IRL deposited in TS and bottom cell prepared in FZJ.

ZnO IRL i-layer thickness	Eff. (%)	FF (%)	Isc (mA/cm^2)	Voc (V)
100	10.2	74.2	10	1.38
150	11.3	72.6	11.1	1.4
200	11.5	73.8	11.4	1.38
300	11.2	78.4	10.3	1.39

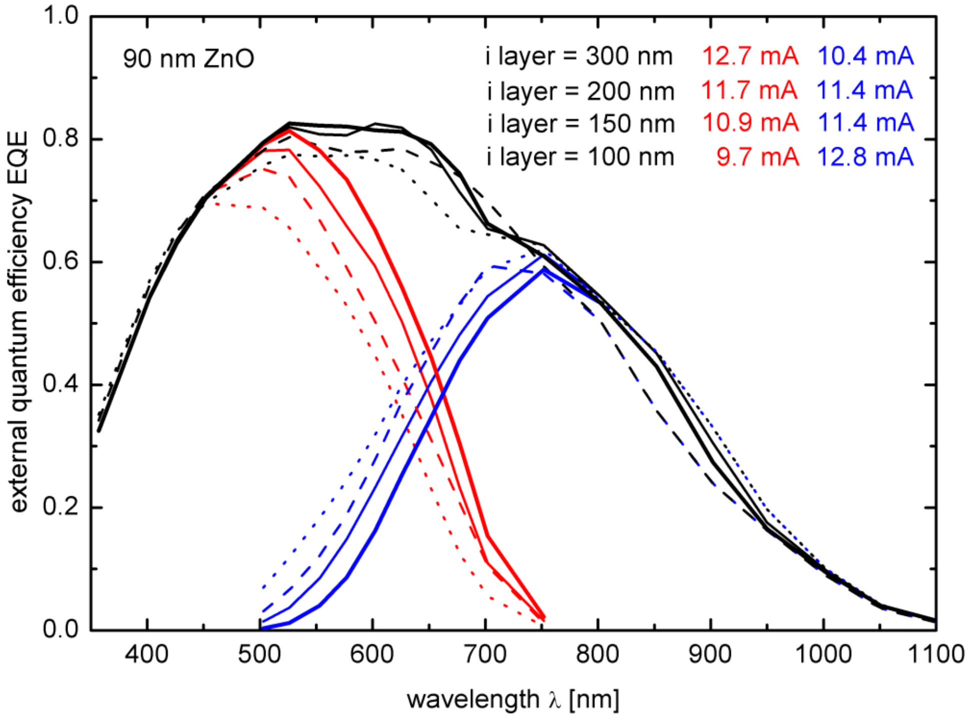

Figure 12: EQE of tandem solar cells with different top cell i-layer thickness and using 90 nm ZnO:Al as IR.

1 sqcm solar cells and 10 cm x 10 cm mini modules with the top cell and IRL deposited in TS and the bottom cell deposited in FZJ were fabricated with ZnO IR and mc-SiOx:H IR. With the ZnO IR, a maximum initial efficiency of 11.6% (Jsc=11.3 mA/sqcm, Voc= 1.39V, FF=73.5%) has been achieved in 1 sqcm tandem cells (200 nm i-layer in the top cell, 2600 nm i-layer in the bottom cell and 45 nm ZnO IR) and 10.1 % (Isc=74.8 mA, Voc= 8.12 V, FF=70.3%) for a 100 sqcm mini module (200 nm i-layer in the top cell, 2000 nm i-layer in the bottom cell and 90 nm ZnO IR). To make working tandem modules with ZnO IR, FZJ has developed an innovative laser scribe design for ZnO IR with high lateral conductivity preventing the shunting of the tandem cell.

With the mc-SiOx:H IR deposited in TS, a maximum initial efficiency of 11.9% (Jsc=11.4 mA/sqcm, Voc= 1.39V, FF=75.7%) has been achieved in 1 sqcm tandem cells (300 nm i-layer in the top cell, 2600 nm i-layer in the bottom cell and 40 nm mc-SiOx:H IR).

Work Package 5: Back reflector

The state-of-the-art back reflector deposition of the TS production line is by dc sputtering of ZnO:Al followed by an Al metal layer. The back reflector along with the front TCO plays a crucial role in p-i-n type thin film silicon solar cells by increasing the optical path of light inside the device, resulting in short circuit current gain. In the optimum doped ZnO/metal back reflector the doped ZnO layer should have low absorption and sufficient conductivity and the ZnO/metal interface should provide a high reflectivity and a low ohmic contact resistance.

<u>Task 5.1 Evaluation of the process conditions and modifications that can improve the state-of-art T-Solar back reflector</u>

The objective in this task was to evaluate the performance of the current back reflectors (BRs) of the laboratories (UU, UB, FZJ), who in particular applied an Ag-layer in the BR, in TS single junction a-Si:H cells and to give an accelerated feed-back for the possible efficiency gain which could be achieved in large area modules using an alternative BR structure. The efficiency gain due to an exchange of the standard Al-layer by an Ag-layer in the back reflector was found to be approx. 5%. However, the cost analysis showed that the Ag price of about 700-900 €/kg was too high to implement the Ag-deposition into the TS production line. Then, it was investigated if it is possible to reduce the thickness of the Ag layer e.g. by applying a stack of Ag and Al layer. The use of a very thin (50-100nm) layer of silver in a stack TCO/Ag/Al/NiV as BR could also improve about 5% the efficiency of the modules. However, reliability aspects have to be investigated in detail before implementing the stacked layer.

<u>Task 5.2 Development of ZnO:Al/Ag back reflectors for single junction solar cells by sputtering from ceramic tube targets and Task 5.5 Benchmarking of the single junction solar cells with newly developed back reflectors</u>

The aim of this task was the development of ZnO:Al layers for the back contact in thin-film silicon solar cells with an industrial compatible process and improved properties. The main improvements are expected to be a higher deposition rate and a higher optical transmittance of the layers by a reduced doping concentration. Furthermore, the rotatable target technology presents a higher material utilization rate and therefore results in less maintenance time for the target exchange in a high volume production. The better yield of the rotatable targets in comparison to flat targets results in a reduction of production cost however, it has be balanced with a higher cost of the target fabrication.

First the material properties by sputtering from ceramic tube targets were optimized by studying various process parameters like plasma power, process pressure and O_2 flow in the deposition process. Process conditions were determined to deposit layers with very low absorption, high reflectivity and sufficient conductivity. Optimization was performed in solar cells with p-i-n structure deposited in TS and BR deposited in FZJ. Table 11 presents best solar cell results found at a process pressure of 10 µbar and an O_2 gas flow of 2 sccm with a power of 10 kW. It should be noted that for the TS standard back contact, aluminum is used whereas silver is used for the FZJ back contacts. A relative improvement in the efficiency of 5.7 % was carried out. Both, the short circuit current density and the open circuit voltage are improved. It was found that the packaging and shipment of p-i-n structures from TS to FZJ lead to poorer solar cell results as it will be in an inline process which happened, as will be seen below, also for experiments performed with Ga-doped ZnO layers at UB. Therefore, a higher improvement is expected to be achieved in an inline process.

Table 11: Comparison of a-Si:H solar cell results (initial state) for the standard back contact and the optimized back contact from the ceramic tube target.

	η [%]	FF [%]	Voc [mV]	Isc [mA]
T-Solar-Std.-BC	8.88	72.9	904.8	13.45
RDM-BC	9.39	72.0	911.9	14.29
improvement abs.	+ 0.5	- 0.9	+ 7.1	+ 0.8
improvement rel.	+ 5.7 %	- 1.2 %	+ 0.78 %	+ 6.2 %

Next, the ZnO:Al layer deposited from ceramic tube targets, was implemented in tandem solar cells that are deposited on ANS10ME glass sheets with TCO developed in work package 3. This will lead to a combination of large scale TCO glass, tandem junctions and a back reflector prepared with an industrial compatible process. The results of the tandem cells with the back reflector from ceramic tube targets were compared to those of cells where the silicon layers were deposited in the same run with the standard back reflector from planar target deposited directly adjacent to the new back reflector. Therefore, the influence of inhomogeneity in the layer deposition on the solar cell performance was reduced to a minimum in order to achieve a high comparability.

Table 12 shows the electrical parameters of the tandem cell in the initial state with back reflector from ceramic tube targets and the reference cell with back reflector from planar. It can be seen that the fill factor deteriorates by 3.9%rel from 72.4% to 69.6%, besides this, the short circuit current densities of both cells are very similar with differences within the measurement uncertainty. The open circuit voltage drops down slightly by 5.3 mV in the cell with the new back reflector. Consequently, the solar cell efficiency is decreased by 4.5% from 11.83% down to 11.30%.

Table 12: Comparison of tandem solar cell results in the initial state for the standard back contact and the back contact from the ceramic tube target.

Target type	η %	FF %	Voc [mV]	Isc [mA/cm^2]
Planar target	11.83	72.4	1384.9	11.78
Ceramci tube target	11.3	69.6	1379.6	11.79
Difference	**-4.5%**	**-3.9%**	**-0.4%**	**0.1%**

In order to investigate in more detail the differences between the two back reflectors, spectral response measurements were performed resulting in the external quantum efficiency. The only significant difference was found in the long wavelength range for L>700 nm. Here, only the mc-Si:H bottom cell shows a relevant response. The cell with the back reflector from ceramic tube targets showed lower quantum efficiency compared to the cell with the standard back reflector. The reason for this is unclear, since the ZnO:Al layers from the ceramic tube targets in principle present a high transparency. It should be noted that the efficiency is still very high, in particular because the silicon deposition was performed in a system that was recently used for single junction processes only and the tandem process restarted very recently. Nevertheless, having found in the laboratory experiment a slightly lower electric performance of the back reflector deposited with ceramic tube targets, for the implementation of these back reflectors, the process still could be attractive for an industrial application due to the low material consumption and reduced maintenance time (fewer target changes per year).

Task 5.3 Development of ZnO:Ga/Metal back reflectors for single junction solar cells by rf magnetron sputtering

Ga-doped ZnO layers (ZnO:Ga) layers were characterized and optimized at the UB, where trials onto cells fabricated at UB and onto 10 x 10 sqcm coupons with the pin structure of TS were performed. Different problems arose during the project when TS p-i-n structures were used at UB or FZJ. Given that the exposure to air of an n-layer causes the oxidation of the interface, a bad device performance was unavoidably found after the standard transportation of the cells from TS and finished to solar cells in another laboratory consisting in an S-shape of the current voltage (J-V) curves near the point of open circuit voltage (Voc), giving a poor fill factor (FF), and a lack of reproducibility of the results. To overcome the problem, coupons from TS were then delivered with either a very thin protection layer of standard ZnO:Al TCO-layer over the p-i-n structure or in an inert gas environment like nitrogen or vacuum. After experimenting with the back reflector deposition from many different approaches it can be concluded that it is so far not possible to deposit a proper TCO-layer on a pin structure in a different place than where the active part of the device was fabricated. E.g. in the TS production line the time between p-i-n deposition in the PECVD machine and the BR-deposition in the PVD machine typically is between 1-4 hours and is mainly due to the time needed to cool down the panels from about 200ºC to ambient temperature. In this time the panels are stored in clean room with controlled 50% humidity. The reason is the formation of a thin oxide layer on top of the n-layer which appears when silicon is in contact with air. This thin oxide layer changed with time. Once the problem was identified, the layer was tried to be removed by chemical or reactive ion etching obtaining non-reproducible results. Also improved and quicker transportation mechanisms, such as in nitrogen or vacuum boxes, lead to non-proper working devices with lower FF, although in this case results were repeatable. Identical ZnO:Ga back reflectors deposited on top of cells fabricated at UB, gave FF as high as 0.68, even if UB solar cells were not as well optimized as the ones fabricated in TS. The deposition of a thin ZnO:Al protective layer resulted in working devices but, given that the interface was already created and that the posterior ZnO:Ga was growing on top of a nucleation layer, the resulting devices were identical although the different BR deposition condition.

Nevertheless, by spectral response measurements it was possible to get information about the short circuit current values. In general trends, ZnO:Al and ZnO:Ga back reflectors appeared to be similar to the ones fabricated in TS, except for the cells finished with ZnO:Ga and silver, where an increase of around 5% in short circuit current density was achieved, an increase similar to the one obtained in the respective study performed at the beginning of the project. No important differences were found between the behavior of ZnO:Al and ZnO:Ga suggesting that both materials behave similarly as back reflectors although the electrical properties of ZnO:Ga appeared to be better on glass.

Task 5.5 Benchmarking of the single junction solar cells with newly developed back reflectors and Task 5.6 Transfer of the optimised back reflector deposition technology to large area modules

The objective of Work Package 5 was to improve the industrial back contact structure implemented in the T-Solar production line. This back contact structure consists of a thin sputtered low Al-doped ZnO-layer (ZnO:Al) and a thin sputtered Al-layer followed by a thin NiV layer. The back contact structure has multiple electrical and optical functions as e.g. the extraction of the electric current from the p-i-n-structure, and the reflection of light which has not been absorbed in the p-i-n structure in the first pass. The industrially implemented back contact structure is a compromise among the cost of materials and fabrication, the deposition speed in production, and the desired physical properties of the layers which finally impact on the efficiency of the solar cell device. Apart from the materials which are implemented in the back contact structure also the deposition technology has an impact on the solar cell efficiency due to the physical properties of the layers and the layer interfaces.

In order to develop new materials and new deposition technologies for producing efficient back reflectors, systematic studies were carried out by UB and FZJ to develop back reflectors with the objective to produce higher efficiency in TS single junction a-Si:H solar cells. In this project, Ga-doped ZnO (ZnO:Ga) at UB and Al-doped ZnO (ZnO:Al) at FZJ, were considered for the back reflector stack. These materials have been deposited by two different techniques; rf magnetron sputtering at UB from planar target and DC magnetron sputtering from ceramic tube targets at FZJ. Furthermore, two different metal layers, aluminum (Al) and silver (Ag) have been used in the back reflector by UB and by FZJ to determine the difference in electrical and optical performance in solar cells and to evaluate the advantages or disadvantages of each layer for industrial application. The metal layers have been deposited by magnetron sputtering and thermal evaporation.

The first conclusion that can be drawn from these experiments is that packaging and shipment of the p-i-n coupons lead to a poorer electrical behavior of solar cells compared to those produced inline mainly due to native silicon oxide formation of the n layer of the p-i-n structure. Typically, lower FF and higher series resistance values have been found in solar cells prepared after transportation. Nevertheless, the use of a ZnO:Al layer DC sputtered from rotatable target presented comparable results to the planar targets presently used in TS, but with rotatable targets a better yield of the target material is achieved what makes this process interesting for industrial application. In the case of ZnO:Ga layers, although a slight increase in Jsc could be detected, results are also very close to those of ZnO:Al deposited by the same technique. The two main conclusions of the studies that can be drawn from this work package are:

1) The deposition of the back reflector TCO must be carried out inline to prevent any issue with contamination and the native silicon oxide formation on the p-i-n structure. Only under this condition, an exact value of the efficiency gain can be determined. The type of TCO layer (ZnO:Al or ZnO:Ga) and the deposition technique applied (planar or rotatable target) is of secondary importance for the efficiency gain and should be selected according to the process with lower overall implementation costs (target cost, yield, maintenance etc.).

2) The key issue in improving the back reflector performance is the metal layer used in the first 50-100 nm of the back reflector. The use of a very thin layer of silver in a stack TCO/Ag/Al/NiV as back reflector could improve about 5% the efficiency of the modules. However, reliability aspects have to be investigated in detail before implementing the Ag layer. The evolution of the Ag price and the overall module production cost has strong impact on the cost effectiveness of the implementation of the Ag layer. In Figure 13 the impact of the Ag price on the benefit is presented. In the graph it can be seen that increasing the silver price beyond 600 €/kg to about 850 €/kg reduces the benefit by about 1% when using an Ag layer in the back contact.

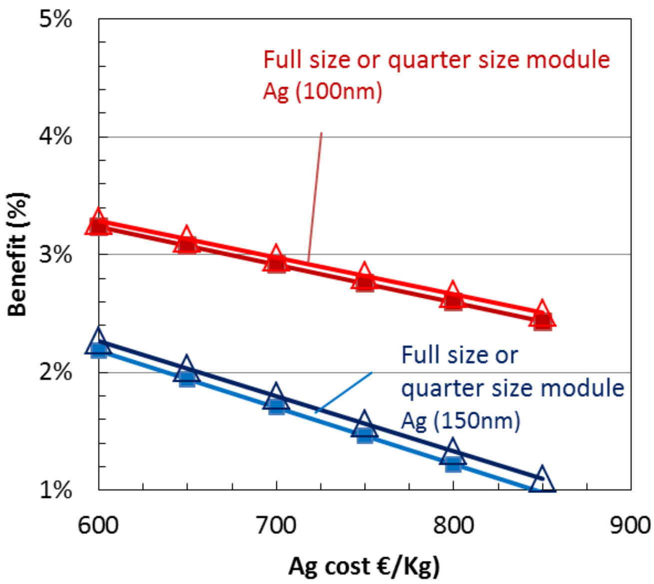

Figure 13: Increasing the silver cost beyond 600 €/W to 850 €/kg reduces the benefit of the incorporation of an Ag layer in the back contact by 1% (module production cost assumed to be 0.6 €/W, open triangles: full size module, closed squares: quarter size module).

Besides the impact of the Ag price, also the impact of the efficiency achieved in the module, the Ag layer thickness and the module production cost has been studied. Latter presented a further strong decrease in the benefit when reducing the overall module production cost. Since the evolution of the Ag price and the overall module production cost has strong impact on the cost effectiveness of the implementation of the Ag layer and due to the difficulty of obtaining a reliable long-term prevision of the evolution of these two factors, the implementation of the Ag layer presents an action of high risk and therefore the implementation was not considered by T-Solar. In addition, the two approaches, to change the ZnO-layer on the one hand by deposition of Ga-doped ZnO instead of Al-doped ZnO and on the other hand by sputtering from rotatable targets instead of sputtering from flat targets presented no significant increase of the efficiency, therefore was neither considered for an implementation.

Work Package 6: Advanced characterization methods

It was the aim of the project to increase the efficiency of thin film solar cells by improving the light trapping efficiency and by reducing parasitic losses. The improvement in the light trapping is achieved e.g. by antireflection coatings at the front glass surface, the optimization of the surface morphology of the front TCO layer, the implementation of intermediate reflectors (in the case of tandem solar cells) and the improvement of the back reflector. Standard methods for the characterization of solar cells are the measurement of current voltage curves and external quantum efficiency as reported in former work packages. However, also more advanced methods have been applied to determine the properties of materials and layers and to characterize the light trapping properties of TCO glasses.

Task 6.1 Characterization of surface morphology

Objective of this task was to support the development of new improved TCO layers by providing additional information about the morphology of the TCO layer. Knowledge about the TCO morphology and the correlation with its optical properties helps to interpret the electrical results of solar cells prepared on the TCO glasses. At the beginning of the project, basically 4 different glasses with TCO layers were available in the consortium: NSG/PKT (large volume industrially produced TCO glass provided by NSG/Pilkington, Japan), AN10 (large volume industrially produced TCO glass provided by AGC, Moustier, Belgium), Asahi U (commercially available TCO glass for laboratory purpose provided by AGC) and Asahi VU (experimental TCO glass provided by AGC). The morphology of these substrates was investigated at the beginning of the project. Figure 14 and Figure 15 show Scanning Electron Microscope (SEM) pictures of the surface of the four TCO glasses. In the images one sees the typical microcrystalline structure of SnO_2-type TCO layers grown at temperatures higher than 400ºC. In the top view the dimension of the crystal grains ranges from about hundred nanometers to about half of a micrometer. The images of the industrial TCO layers from NSG/PKT (Figure 14 left) and AGC AN10 (Figure 15 right) present similar distribution of the crystallites formed during the deposition, however the surfaces of the crystals of the NSG/PKT TCO layer appear rather plain while the crystal surfaces of the AN10 present a fine surface roughness.

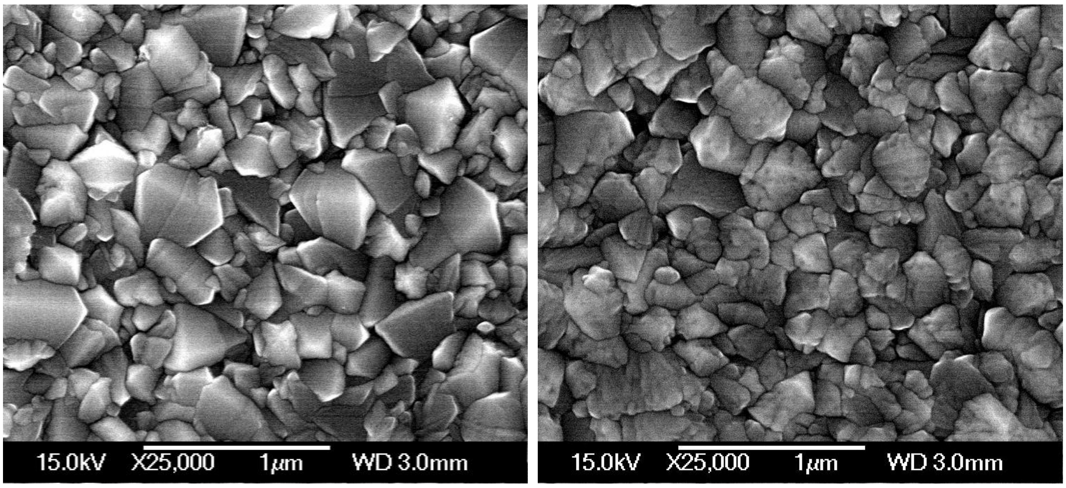

Figure 14: SEM picture of an industrial TCO sample from NSG/PKT (left) presenting a plain surface of the crystal grains and of AGC AN10 (right) showing fine surface roughness of the crystal grains.

Figure 15 presents SEM pictures of the Asahi TCO glasses used for laboratory solar cells. The comparison with the industrial TCO glasses shows that the crystallites here are grown in more ordered way, the surfaces appear plain as for the NSG/PKT TCO and the amount of big crystal grains is higher. In the top view, not much difference is found between the Asahi U and VU type TCO layer.

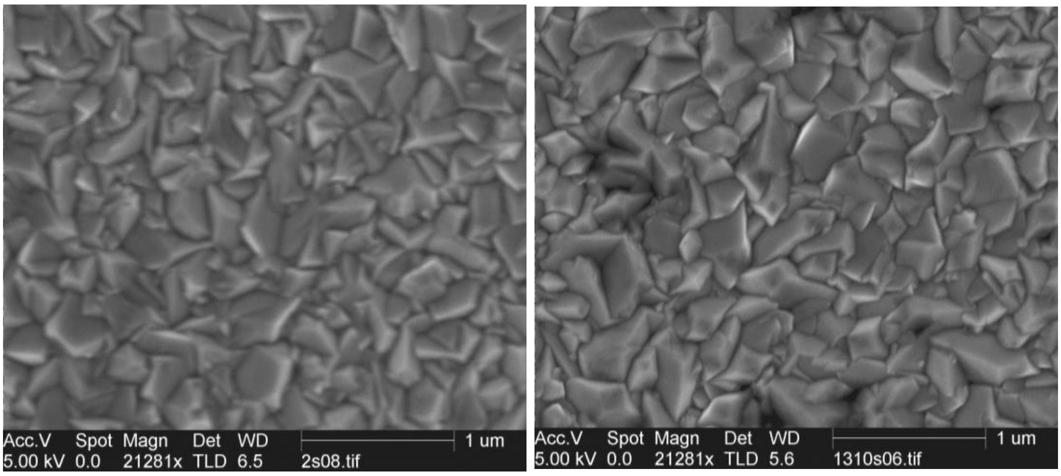

Figure 15: Scanning Electron Microscope picture of the surface of Asahi U TCO (left) presenting a more ordered crystal structure than the industrial TCOs and of Asahi VU TCO (right) showing a grain structure similar to the Asahi U-type TCO.

Figure 16 compares the SEM pictures AN10 and new developed ANS10ME TCO glass in a tilted view. Despite that the TCO layer thickness of the ANS10ME is only 750 nm thick the surface morphology is the same as the one of the AN10 TCO layer.

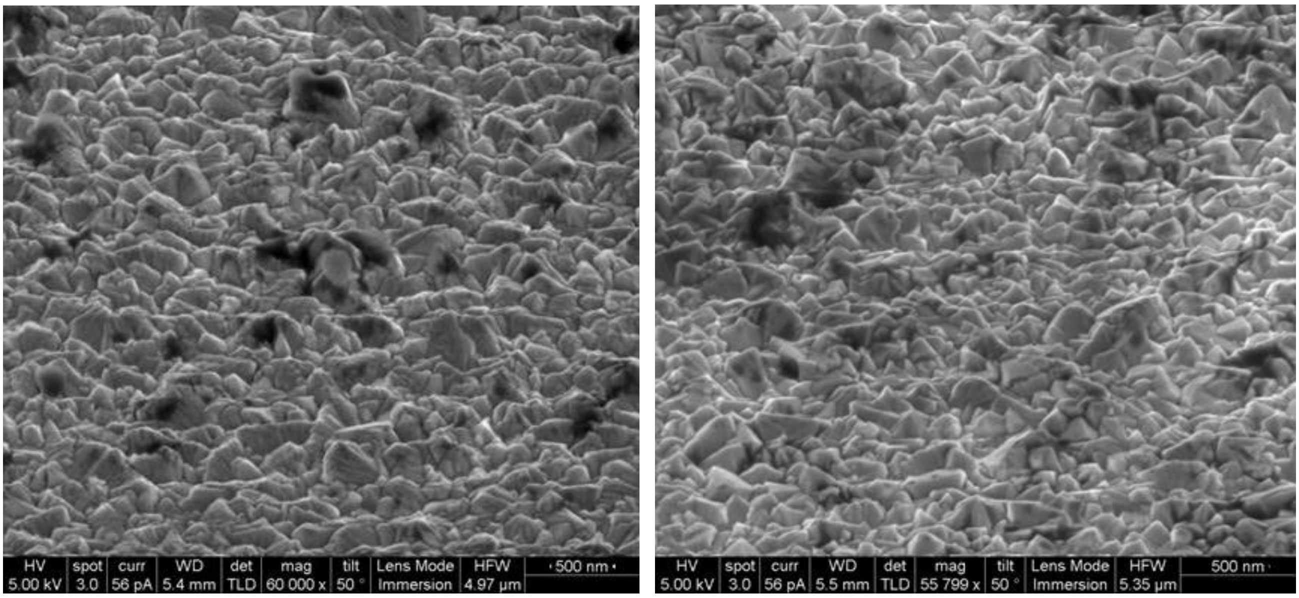

Figure 16: Tilted view on AN10 (left) and ANS10ME (right) present no difference in the surface topology.

Apart from SEM pictures, Atomic Force Microscopy (AFM) images were generated and analysed statistically. Table 13 summarizes average data characterizing the morphology of the TCO layers and optical properties of commercial TCO glasses from AGC. The total transmittance of ANS10ME is comparable to the commercial laboratory TCO glass of type Asahi U which is deposited on a thinner glass (1.1 mm). This high transparency is due to the low iron content of ANS10ME. The transparency of the TCO glass is an essential issue in the optimization of thin-film solar cells. ANS10ME TCO glass shows a higher diffuse transmission compared to Asahi U TCO glass. The transmission of the ANS10ME TCO glass is about 2% higher than AN10 TCO glass. Table 14 presents a resume of the electrical properties of commercial TCO glasses. ANS10ME TCO layer presents a carrier mobility which is improved by 17% compared to AN10. This led to similar sheet resistance but about 25% thinner TCO-layer.

Table 13: Statistical data characterizing the morphology and optical properties of the TCO layers.

Sample	RMS roughness (nm)	Total height (nm)	Diffuse Transmittance (400-800 nm, %)	Total Transmitance (400-800 nm, %)
AN10	47	363	10.2	83.8
ANS10ME	42	359	11.4	85.8
Asahi U	47	341	8.2	85.4

Furthermore, AFM measurements show a significant change in the surface texture of a given TCO layer by the deposition of an a-Si:H layer, e.g., the pyramid-like structure of an Asahi-U substrate is modified into a texture with round, nearly spherical features. In total, the deposition reduces the mean (rms) roughness of the interface and exhibits smaller surface angles. Modeling of the scattering properties of these interfaces showed more scattering into larger angles for the original TCO texture compared to the silicon covered surface texture. A detailed study of the impact of the non-conformal growth of the silicon on the absorption has to be performed by more advanced simulation tools, since the model used so far was successfully proven for single interfaces but might give insufficient information for the scattering into thin layers.

Table 14: Electrical properties of the TCOs.

TCO	**Rs (Ω/□)**	**d (nm)**	**ρ· (Ω·cm)**	**n(cm^{-3})**	**μ(cm^2/V·s)**
Asahi-U	9.5	≈800	7.6E-4	2.45E+20	33.6
AN10	8.7	≈1000	8.7E-4	2.73E+20	26.4
ANS10ME	8.3	≈750	6.2E-4	3.24E+20	31.0
Δ (ANS10ME-AN10)	**-4%**	**-25%**	**-28%**	**18.7%**	**17.%**

Task 6.2 Measurement of the properties of individual materials

Objective of this task was to obtain the optical properties (given as refractive index n and absorption coefficient α in function of the wavelength (or respective energy) of different amorphous and microcrystalline silicon layers manufactured by TS, UU and the FZJ. These optical properties are necessary for understanding the optical as well as the electrical characteristics of solar cells containing these materials. The optical data was obtained using a combination of photothermal deflection spectroscopy (PDS) and spectroscopic ellipsometry. While PDS measurements deliver a very precise absorption coefficient for values up to $10^5 cm^{-1}$, it is possible to obtain the refractive index n and the absorption coefficient for values above $10^5 cm^{-1}$ via ellipsometry. Figure 17 presents e.g. the comparison of refractive index (n) of p-doped amorphous silicon layers and Figure 18 the comparison of absorption coefficient of p-doped amorphous silicon layers.

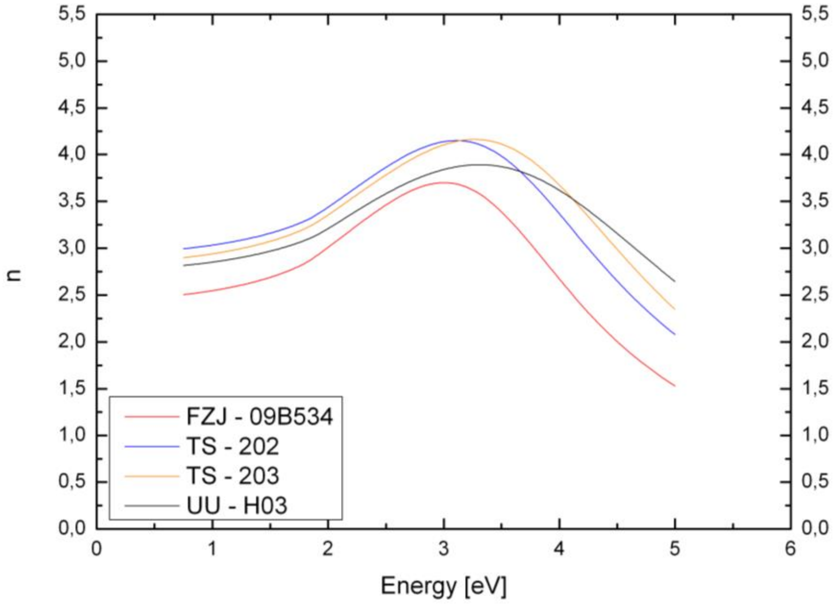

Figure 17: Comparison of refractive index (n) of p-doped amorphous silicon layers. The TS samples were deposited in two different chambers of the PECVD cluster, show slight differences in the refractive index.

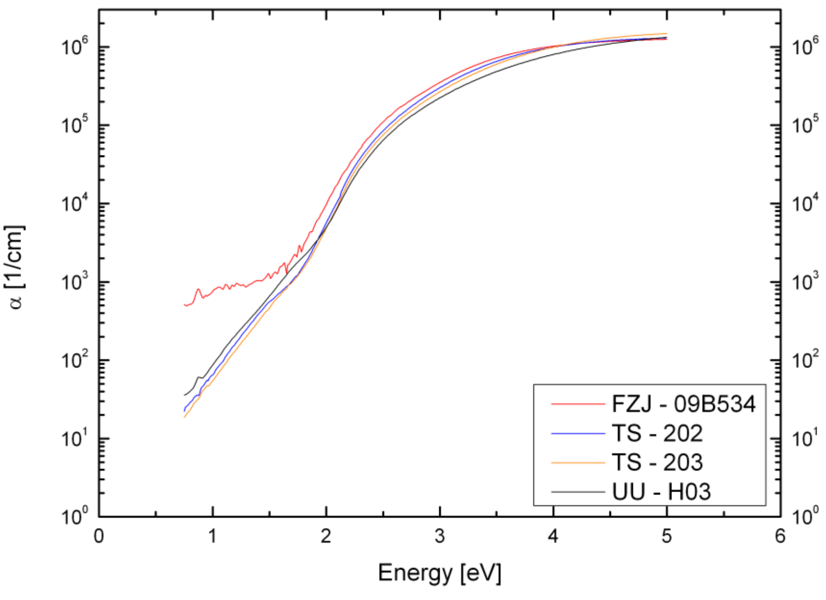

Figure 18: Comparison of absorption coefficient α of p-doped amorphous silicon layers. All samples show a very similar absorption coefficient, with the FZJ sample having a higher absorption in the sub-bandgap region.

Furthermore, the optical properties of microcrystalline silicon oxide layers from TS were investigated (see Figure 19). For the mc-SiOx:H layers, an inhomogeneity of optical properties in the direction of layer growth was introduced in the simulation model of FZJ to achieve satisfactory results when fitting the experimental (transmission and reflection) data for the determination of the refractive index and extinction (respectively absorption) coefficient in function of energy.

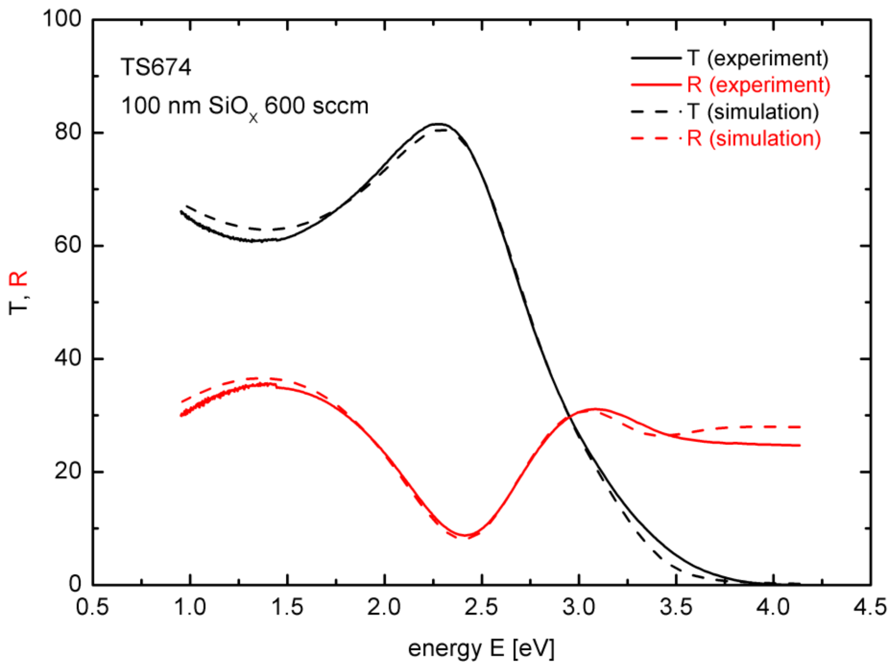

Figure 19: Transmission and reflection measurements of the 100 nm thick mc-SiO_X:H layer. Solid lines show the experimental results, dashed lines are determined by optical simulations.

In addition, the temperature dependent conductivity of microcrystalline silicon and microcrystalline silicon oxide layers from TS was determined (see Figure 20).

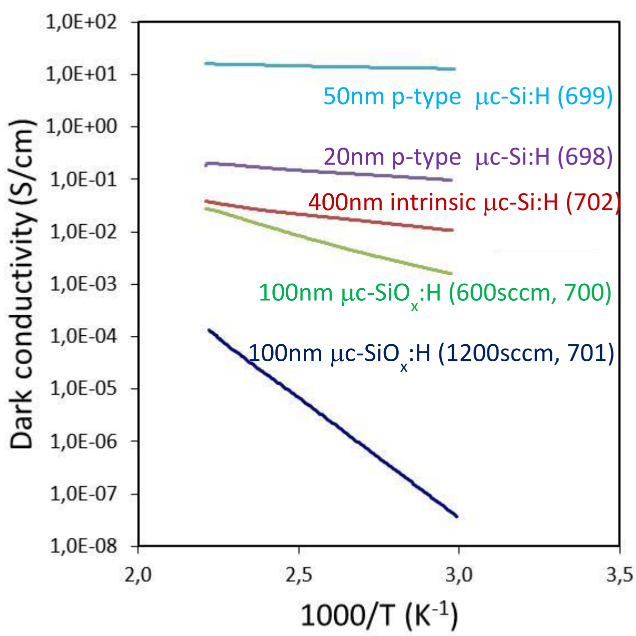

Figure 20: Arrhenius plot showing the dark conductivity of two p-type mc-Si:H layers (TS698 and TS699), an intrinsic mc-Si:H layer (TS700) and two mc-SiOx:H layers (TS701 and TS702) from TS as a function of the inverse temperature measured at UB.

<u>Task 6.3 Correlation of local light trapping behaviour and solar cell performance by experiment</u>
Textured surfaces are used to improve the light absorption in solar cells. The improvement is attributed to light scattering at the rough interfaces (e.g. at the TCO/silicon interface for transmission and at the silicon/back reflector interface for the reflection). A further optimization of the light

scattering needs a detailed knowledge about the scattering properties of individual surface features of the statistically rough interfaces (roughness in the nm to μm scale). To provide this knowledge, an optical near-field analysis was done in this task. The analysis is done by near-field scanning optical microscopy (NSOM) experiments in combination with optical simulations based on finite-difference time-domain (FDTD) method. From this, the evanescent part of light as well as the local light absorption in the silicon is extracted. Light that is totally internally reflected shows an exponential decrease in intensity in the surrounding medium. These are the evanescent modes that reflect the intensity of the guided optical modes inside the layer. Therefore, these modes are taken as a benchmark for the light trapping in the solar cell, since NSOM experiment is only possible in the outer medium air and not inside the silicon. In contrast, the optical simulations allow also studying the local absorption inside the silicon. Therefore, the combination of both methods provides important knowledge about the light trapping properties of individual surface features. Figure 21 shows an example of topography of an a-Si:H p-i-n layer stack on top of the AN10 substrate measured by AFM and NSOM (not at the same position as AFM picture) and measured local light intensity distribution in air close to the surface at a wavelength of 705 nm.

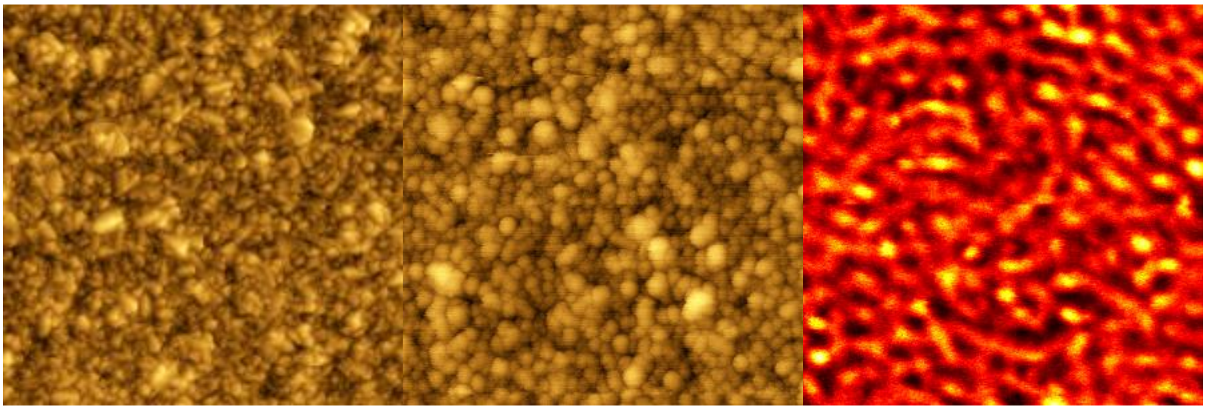

Figure 21: Topography of an a-Si:H p-i-n layer stack on top of the AN10 substrate measured by AFM (left) and NSOM (middle, not at the same position as AFM picture). Measured local light intensity distribution in air close to the surface at a wavelength of 705 nm (right). The scanning area is 10 µm x 10 µm.

In this way, the local transmitted light intensity distribution on a-Si:H p-i-n layer stacks on top of a textured SnO_2 substrate (AN10) was obtained experimentally by near-field scanning optical microscopy and theoretically by rigorous solution of Maxwell's equations using the finite-difference time-domain method. It was carried out that due to the shape and size of the NSOM tip, on the one hand the surface features of the AN10 substrate cannot be resolved and that on the other hand the distance between the tip and the surface is larger for most of the locations on the surface than the adjusted 20 nm (approximately). Therefore, the analysis of the NSOM images does not provide reliable data concerning the local light trapping. However, the results from the optical simulations overcome these experimental limitations and allow additional insights into the layer stack of the solar cell. From both experiment and simulation, it was concluded that both ZnO:Al and mc-SiO_X:H intermediate reflector are able to transfer light from the bottom to the top cell. However, both intermediate reflectors reduce overall EQE, with the ZnO:Al layer showing a strong decrease in bottom cell performance for wavelengths around 700 nm. The mc-SiO_X:H layer has only little impact on the total response. This can be attributed to the optical properties of the ZnO:Al. It has a less pronounced increase in refractive index in the long wavelength region, meaning a strong refractive index jump over the whole spectrum, resulting in a strong reflection into the top cell regardless of wavelength.

Task 6.4 Durability test of ARC

In the framework of WP2, two different approaches for anti-reflecting coatings (ARC) deposited on the front glass of the superstrate (TCO-covered glass) of a-Si(:H) thin film modules were investigated. The first approach consisted in the deposition by high temperature sol-gel based processes carried out by an in line process performed during or after the manufacturing of the TCO-covered front glass (TCO-glass). The second approach consisted in low temperature spraying and curing of sol-gel solutions. In addition, the development of the SiO_x coatings and their texturing by hot-embossing lithography by this second approach was performed. The first approach, on the one hand, has the advantage of being an established method that produces a clear increase in optical transmission of the superstrate, e.g. the cover glass of crystalline silicon modules. On the other hand, since it is a high temperature process, the ARC has to be deposited before p-i-n silicon layers deposition, and the ARC must be compatible with the vacuum deposition process and eventual contamination of silicon layers has to be checked. The second approach presents the advantage of being applicable after finishing module fabrication process. To study the durability of ARCs, two representative samples of each technology (AGC-ARC and UB-ARC) were submitted to the thermal cycling test (10.11 in IEC norm 61646) and the humidity-freeze test (10.12 in IEC norm 61646). Since AGC-ARC layers are only available on TCO-covered glass, and to discard or evaluate any effect of these treatments on the TCO layer, TCO-covered glass and laminated samples to protect the TCO side were also subjected to the same tests. Table 15 presents e.g. the integrated transmittance (Ti, wavelength range 400-800nm) before and after thermal cycling and humidity freeze tests and corresponding variations dT, calculated at different positions (T1-T4) of AGC-ARC/Glass/TCO samples.

Table 15: Integrated transmittance (T_i) before and after thermal cycling and humidity freeze tests and corresponding variations dT, calculated at different positions of AGC-ARC/Glass/TCO samples.

Positions	Thermal cycling test			Humidity-freeze test		
	$T_{i\ Before}$ (%)	$T_{i\ After}$ (%)	ΔT_{TC} (%)	$T_{i\ Before}$ (%)	$T_{i\ After}$ (%)	ΔT_{HF} (%)
T1	79.8	79.9	+0.1	79.7	79.6	-0.03
T2	79.5	79.7	+0.2	79.6	79.5	-0.1
T3	79.7	79.6	-0.1	79.4	79.4	-0.1
T4	79.5	79.6	+0.2	79.0	79.4	+0.4

Apart from performing transmission measurements of TCO glass samples, surface morphology was obtained by interferometer microscopy. In general, from both methods the results showed a very small degradation effect, in the range of 0.4 % in optical transmittance for UB and AGC ARCs after thermal cycling and humidity freeze tests. ARCs were found to be very stable in the durability tests presenting no considerable degradation in optical transmission and morphological properties.

Task 6.5 Infrared inspection of very large area modules

In the solar module production process of T-Solar efficiency losses due to resistive losses can appear at different places in a solar module, e.g. resistive heating under current flow can occur in electrical contact areas due to incomplete soldering of the buss bars, in small shunts in the pin structure or due to failures in the laser scribing process. The here applied method is to inject an electrical current into a module and to detect the electrical power losses of the defects in form of radiation with a camera. The radiation can result from resistive heating e.g. produced in shunts or from electroluminescence radiation emitted from the solar cell operating in so-call “forward conditions”. The radiation is typically in the infrared wavelength range. These investigations were carried out first on a laboratory level with quarter size modules (1.1 m x 1.3 m). Several experimental studies were performed in order to correlate the appearance of defect structures in the images of modules with variations in the production process. So, several defects resulting from errors in the production process causing shunts have been identified and were related e.g. to the laser scribe processes, to dust particles etc., in addition the electroluminescence radiation from modules could be photographed. It was demonstrated that infrared imaging can contribute significantly to the quality assessment of the module production process. Then, the implementation of an in-line camera inspection system for full size (2.6 m x 2.2 m) modules was demonstrated. Two camera systems, one applying CCD chip technology , (Hamamatsu, silicon technology), sensible in the NIR wavelength range, and another camera system applying lock-in thermography (Thermosensorik, LIT), using an InSb chip sensible in the MIR wavelength range, were evaluated for module quality assessment. The experimental set-up of LIT is much more complicated and about a factor of five more expensive than the CCD camera set-up, however, both methods are complementary and in principle able to detect the same defects in modules. Since the CCD technology presents before mentioned cost advantage experimental work was concentrated on this technology. After the determination of the optimum range of current and exposure time for the acquisition of images and other experimental details off-line in the laboratory, a Hamamatsu Orcaflash 4.0 camera was installed in the solar simulator of the T-Solar production line. The solar simulator is an excellent place for this kind of camera inspection, since it is a completely enclosed dark space and the module is connected electrically to measure the current voltage (IV) curve under standard test conditions. So, for the acquisition of the images only a switch has been to be introduced in the electric measurement system to disconnect the IV curve measurement system and to connect a current source to inject the current into the module. Figure 22 (left) shows the image of a standard module where all production processes were well adjusted and which presents not any defect. One sees only the electroluminescence radiation homogeneously distributed and eleven dark horizontal lines are visible resulting from so-call hot-spat laser scribes to protect the module for high current flow under partially shadowing conditions. The laser scribe design results in 12 parallel blocks of 216 one cm wide solar cells connected in series. Other marks and lines on the module seen in the photo are artifacts resulting from parasitic light entering the solar simulator box. On the right side one sees a photo of a module from a test series of prototype TCO glass with TiO_2 interface layer (IFL) performed in WP3. With the IFL layer the process parameters of all laser scribe process needed to be newly adjusted which was not done successfully for the here shown module and is nearly impossible to detect in this detail with any other method. It seems that due to the slightly thicker layers of the p-i-n structure in the middle of the module the P2 and P3 laser scribe are not processed with adequate energy resulting in shunted cells indicated by the black lines (or black cells). In this way, high resolution images where every 1 cm wide solar cell can be identified in a 5.7 sqm module can be generated in the solar simulator. By injecting forward currents into the module in the range of about 1-3 A and applying exposure times from a few seconds to one minute, data acquisition times are achieved well below the production tact time of 3 minutes per module in the solar simulator. The implementation of such a CCD camera system is very easy to perform in the solar simulator box and presents a very low cost solution providing an excellent assessment of the electrical quality of each module at the end of the production process. It presents an excellent method especially to control the laser scribe processes performed in each module.

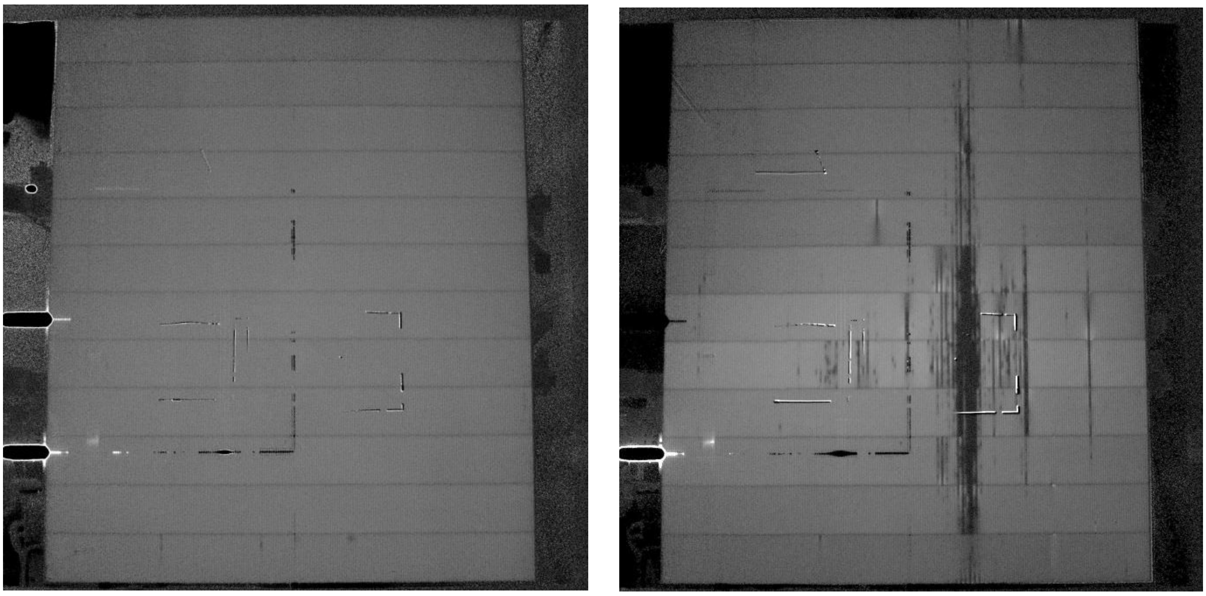

Figure 22: Left) Photo of a module without any defects as usually fabricated with all production processes well adjusted. Marks visible on the module are artifacts due to parasitic light entering the solar simulator box. Right) Photo of a module of a test series with prototype TCO glasses with interface layer between TCO layer and p-layer, where the laser scribe process parameters were not well adjusted for the whole module area.

The potential impact

In the frame of the dissemination activities, three articles presenting work performed within the HELATHIS project are published by the project partners in peer-reviewed journals (J. App. Phys., J. Non-Cryst. Sol., Mat. Sci. Eng. B) so far and eight contributions were presented in conferences and are published in the respective conference proceedings (EU-PVSEC, ICANS, E-MRS, CDE), three of them were oral presentations. Another two contributions were presented in February 2013 in the Spanish Conference of Electronic Devices (CDE) 2013 and will be published in the next weeks. TS published several press releases during the last years e.g. when the project started or about the publications on conferences. To promote the distribution of the publications of the HELATHIS project the respective data have been introduced on the OpenAIRE portal created in the frame of the FP7 project "Open Access Infrastructure for Research in Europe" (FP7 Infrastructures, GA 246686). Apart from this, the HELATHIS project was presented in four workshops by the coordinator, reporting on the progress of the scheduled work (1st EU PV-Cluster Workshop "Photovoltaics and Nanotechnology, Sept. 2010, Aix-les-Bains, France; Spanish Workshop "Energía en el Programa Marca de IDT", organized June 2011 within the EU-Project ER-INNOVA, Ferrol, Spain; European Energy Research Alliance (EERA) Workshop, Oct. 2011, Berlin and 4th International Workshop on Thin-Film Silicon Solar Cells (IWTFSSC-4), March 2012, Neuchatel, Switzerland).

Exploitation of the project results has been made in very large volume production on industrial level of TCO glass by AGC and silicon thin film modules by TS. On the one hand, development of ANS10ME TCO glass for large volume production has been a great success since, apart from the increase in module efficiency in the T-Solar production to nearly 8%, during the operation of the project the whole module production of Applied Materials SUNFABs in Europe (T-Solar Global 40MW corresponding to approx. 700.000 sqm TCO glass per year, Signet Solar 25 MW, Masdar PV 40MW, SUNFILM 60MW, Malibu 40MW, Moncada Energy 40MW) had changed from formerly in Japan produced NSG/Pilkington TCO glass to TCO glass produced in Moustier, Belgium, which has resulted in a big impact on the European economy.
On the other hand, T-Solar was able to export a large number of modules to different countries, as given for example by one of the two 22 MW PV plant installed in Peru (Arequipa) shown in Figure 23.

Figure 23: Approx. 50 000 T-Solar modules are installed in one of the two 22 MW PV plants in Peru. Here is shown the Repartición site near Arequipa in the south of Peru (marked by the letter A in the left side map).

Comparing large PV plants in different technologies (e.g. crystalline silicon modules or other thin film technologies) with TS a-Si:H module technology, the experience in the last years has shown that TS installations with a-Si:H modules work very efficiently in very hot climates with a big part of the irradiation near AM1 conditions (e.g. near the equator). This is due to the small power temperature coefficient of a-Si:H modules (e.g. about half of that of crystalline Si modules) and the high blue wavelength range ratio of the spectral response. In some installations where different PV technologies were compared, the PV plants with TS a-Si:H modules achieved up to 20% more electric energy as PV plants with other technologies with the same nominal electric power capacity of the PV plant. This suggest, on the one hand, that basic parameters and standard methods (e.g. at standard test conditions, STC, Normal Operating Cell Temperature, NOCT, etc.) used to calculate the dimension and power output of PV plants have to be reviewed to correctly calculate the levelized cost of energy (LCOE) for project planning. Since viable models and respective software considering all the metastable effects of a-Si:H modules to calculate correctly LCOE for big a-Si:H PV plants are not available, a-Si:H technology was handicapped in the past and often was considered less “bankable”. This could also have an impact on propagation of a-Si:H/mc-Si:H tandem technology. It suggests that both technologies present economic advantages in certain regions of the world which are not well noticed so far.

In the last 5 years, PV technology as implemented by T-Solar suffered several strong backstrokes. For T-Solar, Spanish energy policy cutting all subsidies for photovoltaic energy generation since 2009 resulted in the loss of the Spanish home market. Reorientation to European and international markets was extremely difficult in the following years due to the financial crisis triggered in 2008. Later in 2010 and 2011 the world wide PV market was determined by creating enormous production

over capacity, especially in Asia, and was followed in 2012 by worldwide module oversupply resulting in an artificial strong decay of module prices below the long–term experienced industry learning curve, with many companies selling modules under production costs and accumulating enormous losses on the balance sheets. In this environment T-Solar's technology partner Applied Material decided in middle of 2010 to retire from the turn-key concept of the SUNFAB technology and in consequence the necessary grouping of the SUNFAB technology clients and the necessary growth to be competitive in a long term on a worldwide level was stopped. In contrary nearly all SUNFAB factories in Europe (e.g. Signet Solar, Sunfilm AG later Schüco KG and Malibu also later Schüco KG, and other players in silicon thin film technology) had to shut down factories since they could not compete with the extremely low module prices of the market. The biggest competitor of Applied Materials in the field of silicon thin film technology, Oerlikon, has sold its silicon thin film department in early 2012 to the Japanese company Tokyo Electric which most probably will result in further drawbacks for silicon thin film technology in Europe in the future by shifting more PV manufacturing technologies to Asia. Recently, the European Community has started procedures to protect the European manufacturing market from low price subsidized Chinese modules, similar as United States is protecting its market since about half a year ago, but these activities, most probably will be too late to keep European PV module manufacturing industry on a significant capacity level. In the long-term, the breaking down of the PV manufacturing industry in Europe will also negatively affect the R&D in this sector, which could also result in negative impact on the PV equipment manufacturing industry, also a big sector for employment in Europe. So, if there will be no strong political intention and intervention in Europe to keep the PV manufacturing industry alive, then also many decades of intensive, leading European R&D will find its application outside of Europe.
In this environment, T-Solar, nevertheless having undercut its module production cost continuously under the scheduled values in the last years, thanks to an enormous effort of the whole production team and thanks to the support of the R&D performed in the HELATHIS project to increase module efficiency, recently could not follow alone anymore the artificial strong module price decay of the last year's PV market. T-Solar had not the financial background to operate for a long time with financial losses and therefore, was forced to stop manufacturing about half a year ago with the perspective to definitely shut down the factory soon if no support will appear from any political side. This will result in a big negative impact on the labour market of the Galician community and will contribute to further drive the Spanish labour market into the abyss.

Address of the project public website:

www.tsolar.com/helathis