Special Workshop

Workshop Photovoltaics and nanotechnology: from innovation to industry

European Photovoltaic Projects "Cluster 2 - Thin film PV cells"

Organized during

EERA Workshop

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" Helmholtz-Zentrum Berlin für Materialien und Energie GmbH ",
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Organizers: *Dr Iver Lauermann, Dr. Bertrand Fillon,*

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European Photovoltaic Projects "Cluster 2 - Thin film PV cells"

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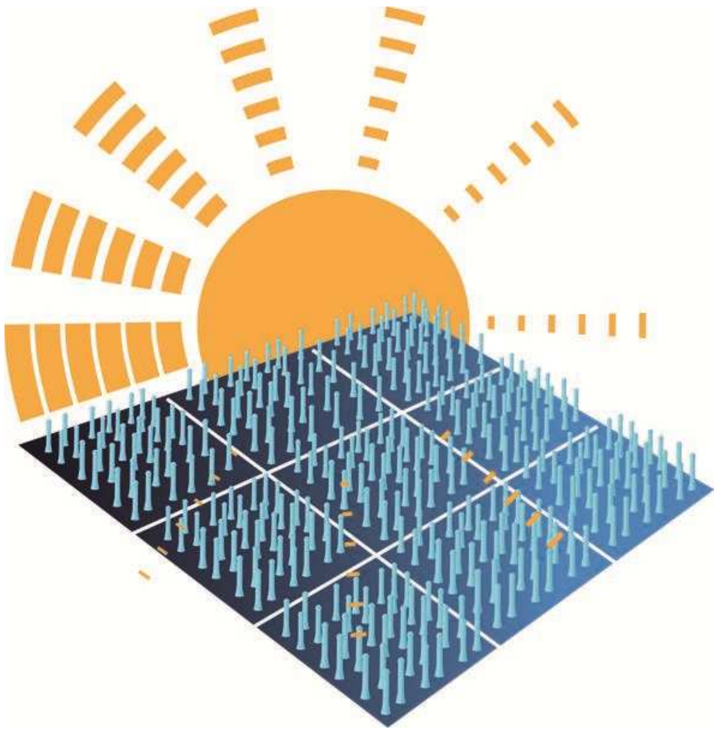

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Subcluster 2.1: Innovative or improved PV manufacturing processes

Chairman: Bertrand FILLON (CTO, CEA/LITEN, France)

HIGH-EF: Large grained, low stress multi-crystalline silicon thin film solar cells on glass by a novel combined diode laser and solid phase epitaxy process
Coord: Institute of Photonic Technology IPHT, Germany – **Silke Christiansen**

ALPINE : Advanced Lasers for Photovoltaic INdustrial processing Enhancement
Coord: University of Parma, Italy – **Stefano SELLERI (Veronica BERMUDEZ)**

INDUCIS: Development and Industrial implementation of cost effective advanced CIGS photovoltaic technologies
Coord: Nexcis, France - **Veronica BERMUDEZ**

ThinSi: Thin Si film based hybrid solar cells on low-cost Si substrates
Coord: STIFTELSEN SINTEF, Norway – **Alexander ULYASHIN**

NOVA-CI(G)S: Non vacuum
Coord: UMICORE NV, Belgium – **Fabrice STASSIN**

Large grained, low stress multi-crystalline silicon thin film solar cells on glass by a novel combined diode laser and solid phase epitaxy process

(Project **HIGH-EF,** Coord.: Institute of Photonic Technology IPHT, Germany)

Grant agreement n°: 213303
Start and end dates: 01/01/2008 to 31/12/2010

Co-ordinator: Institute of Photonic Technology, Jena, Germany / Dr. Silke Christiansen: silke.christiansen@mpl.mpg.de, tel: +491796894182

Consortium:

Partner	Beneficiary Name	Country	Role
1	Institute of Photonic Technology	Germany	Coordinator
2	CSG Solar AG	Germany	Testing of High-EF technology in production
3	Swiss Federal Laboratories for Materials Testing and Research	Switzerland	Structural and mechanical expertise
4	Hungarian Academy of Science; Research Institute for Technical Physics and Materials Science	Hungary	Photovoltaic materials structural analysis-TEM
5	Oclaro AG	Switzerland	Development of diode laser
6	Horiba Jobin Yvon	France	Development of powerful stress analysis tool
7	InESS-CNRS/ULP Strasbourg	France	Crystallization process simulation and optimization
8	ALMA Consulting Group	France	Project management

Title: **HIGH EF** Large grained, low stress multi-crystalline silicon thin film solar cells on glass by a novel combined diode laser and solid phase epitaxy process

Objectives:HIGH-EF will provide the silicon thin film photovoltaic (PV) industry with a unique process allowing for high solar cell efficiencies (potential for >10%) by large, low defective grains and low stress levels in the material at competitive production costs. This process is based on a combination of melt-mediated crystallization of an amorphous silicon (a-Si) seed layer (<500 nm thickness) and epitaxial thickening (to >2 µm) of the seed layer by a solid phase epitaxy (SPE) process. A low cost laser processing will be developed in HIGH-EF using highly efficient laser diodes, combined to form a line focus, that permits the crystallization of an entire module (e.g. 1.4 m x 1 m in the production line or 30 cm x 39 cm in the research line) within a single scan. Such a combined laser-SPE process represents a major break-through in silicon thin film photovoltaics on glass as it will substantially enhance the grain size and reduce the defect density and stress levels of multi-crystalline thin layers on glass compared e.g. to standard SPE processes on glass, which provide grains less than 10 µm in diameter with a high density of internal extended defects, which all hamper good solar cell efficiencies.

Description of the work:A diode laser crystallization process for a silicon seed layer on glass with large, low defective grains and low internal stresses will be developed based on a novel line-focus diode array with line focus; for that process, the laser-diode array will be developed in the course of HIGH-EF. A correct understanding is envisaged of when and how epitaxial re-growth on a laser crystallized seed starts and works. Also, understanding of how sharp doping profiles in the a-Si layer survive the solid phase epitaxy will be addressed. A stress analysis tool for large area testing needs to be developed where the Raman effect will be exploited for establishment of marketable stress characterizing tools. Materials optimization needs the combined structural and mechanical characterization by electron microscopy techniques e.g. electron backscatter diffraction (EBSD; to study grain size, grain boundary population, local stresses) and Raman spectroscopy (large area stress analysis, grain orientations) as well as reliability tests of the thin layers with respect to delamination and cracking.

Expected results: The unique manufacturing concept for thin film silicon based PV was developed. The optimized PV silicon parameters set for internally low defect and low stressed large grains in the seed layer and in the epitaxial SPC layer are found to be effective. Thirdly, the best materials obtained in the lab are tested in a ‘production environment, so that the path from innovation to mass production is very short. A new diode laser line and Raman spectrometer for the material testing was established and commercialized by Oclaro AG and Horiba Jobin Yvon.

Further research needs: HIGH-EF officially ended in 2010, but the progress made within the project has paved the way for future research, which Christiansen is already planning. Her team managed to produce a solar cell with the potential for >15 percent efficiency, and this could be achieved (and possibly exceeded) by nanostructuring the High-EF multicrystalline silicon on glass, using silicon nanowires formed by wet chemical electroless etching of the starting layer. Proof of concept of this etching technique has already been demonstrated by Sivakov et al. in 2009, with power conversion efficiencies of around 5 percent. Additionally, a combination of hard and software developments (DuoScanTM andn SwiftTM) were carried out by Horiba Yobin Yvon that now permit Raman mappings of large areas at reduced measurement times, based on high speed detector stage coordination. Further success in this field may facilitate a new generation of high-performance electronic devices that are not reliant on the unsustainable power produced by fossil fuels.

Advanced Lasers for Photovoltaic INdustrial processing Enhancement

(Project **ALPINE**, Coord.: University of Parma)

Grant agreement n°: 229231
Start and end dates: 01/09/2009 to 31/08/2012

Co-ordinator: University of Parma (UNIPR) / Prof. Stefano Selleri: stefano.selleri@unipr.it

Consortium:

Partner	Beneficiary Name	Country	Role
1	**University of Parma**	Italy	
2	**Crystal Fibre A/S**	Denmark	
3	**Quanta System S.p.A.**	Italy	
4	**Bookham Switzerland AG**	Switzerland	
5	**EOLITE Systems**	France	
6	**Solar Systems & Equipment**	Italy	
7	**NEXCIS**	France	
8	**Zentrum für Sonnenenergie- und Wasserstoff-Forschung**	Germany	
9	**Würth Solar GmbH & Co.**	Germany	
10	**University of Verona**	Italy	
11	**European Commission - Joint Research Centre**	Belgium	
12	**Elettrosystem SAS**	Italy	
13	**LPKF Laser & Electronics AG**	Germany	
14	**University of Ljubljana**	Slovenia	
15	**MULTITEL**	Belgium	

Title: **ALPINE -** Advanced Lasers for Photovoltaic INdustrial processing Enhancement

Objectives: The main goals of the ALPINE project are:

- the realization of high quality beam, high power, short pulse, and high repetition rate fiber lasers in MOPA and Q-switched configurations;
- the demonstration that PCF platform allows high brilliance, high power laser systems and reliable and versatile frequency conversion;
- the development and manufacture of low cost and efficient thin film PV solar cells based on cadmium telluride and copper indium di-sulfoselenide;
- the improvement, in terms of precision and speed, of the existing scribing technology in PV modules through the usage of high quality beam fiber lasers;
- the development of a complete system for laser scribing which will completely replace mechanical scribing in all PV module production steps.

Description of the work: including if applicable benefits and barriers of nanotechnologies based approach.

Photovoltaic solar energy conversion is increasingly recognized as the key component of renewable energy source for the future. Developing cheap and efficient photovoltaic devices for very large scale applications is thus a mandatory challenge. Presently, silicon based technologies are highly dominant in supplying the growing PV demand, whilst new thin film technologies based on cadmium telluride (CdTe) and copper indium diselenide (CIS) or copper indium gallium diselenide (CIGS) materials are starting to deliver at the industrial level. With a potential conversion efficiency just below that of crystalline silicon PV, low-cost manufacturing strategies are needed to receive the level of market uptake required to have immediate economic or environment impact. From recent scientific developments, new production technologies can be anticipated to make more cost-effective devices and thus accelerate the uptake of PV. In this sense, a new generation of lasers, based on optical fibers, has recently appeared on the market bringing serious and deep advantages over previous technologies. Among these lasers, high power sources are mainly based on doped conventional silica or phosphate glass fibers, whose usage is still a limiting factor for building high energy, single-mode fiber lasers. In the meanwhile, medical, microelectronics, machining and micro-machining markets are driving research toward highly reliable, short wavelength, high repetition rate, narrow linewidth pulsed lasers with programmable parameters, such as pulse width, shape and energy.

These innovative laser systems will be developed in this project by using PCFs, a new class of optical fibers, also called microstructured optical fibers or holey fibers, in which the cladding is formed by a distribution of air-holes in a matrix of dielectric material, usually silica, running along the entire fiber length. These fibers are characterized by unusual and interesting light guiding properties, which are strongly related to the air-hole relative position, size and shape, and can be exploited in a wide range of applications, as in telecommunication systems, spectroscopy, microscopy, filtering, and sensing. PCF have also gained significant interest in the recent years due to their ability to deliver high power with excellent beam quality. In fact, PCFs can be made with high numerical aperture, large mode field diameter, all silica double cladding, which allows the fiber to be very robust towards high optical pump and high temperature, and present high threshold for nonlinearities. The laser design based on PCFs can thus bring important and crucial advantages with respect to standard fiber lasers in terms of brilliance of the source, ruggedness of the resonator, stability of the oscillating mode and efficiency. For these reasons, and for the unsurpassed design flexibility, PCF technology can be exploited in many fields and will be exploited by the ALPINE consortium for the laser development.

In addition, the ALPINE project will develop and test laser prototypes for an extremely exciting and constantly growing application, that is the scribing process used for the production of solar cells for PV energy production. In fact, the PV industry yearly growth rates over the last five years were more than 40% in average, which makes PV one of the fastest growing industries at present. Due to the fact that the price of the PV modules alone accounts for about 60% of the price of a PV installation, any improvement in the scribing process will allow to reduce the manufacturing costs and consequently help reducing the overall price of solar energy production, contributing to a further increase of the share of electricity produced by PV in the next years within the European Union. This result would be inline with the so called 20/20/20 target for 2020, for the promotion of the use of renewable energies, an important priority set by the European Commission.

Expected results: industrial applications and potential commercialisation

The aim of the ALPINE project is to develop advanced laser processing as a cost effective and high performance technique for the fabrication of novel solar cells, to stimulate the advance of laser industry and to enable growth in the high volume production of solar cells in the near future. In fact, laser processing is expected to be an important and growing production technique for this application. While laser micromachining is widely employed in the laboratory fabrication of some of the world’s highest efficiency silicon solar cells, in most instances the focus of the development is on cell performance with little regard to the manufacturing aspects in high volume. It is one of the objectives of this project to bring high efficiency laboratory cells closer to commercial reality by focusing on the manufacturing aspects with particular regard to high-speed laser processing. The availability of low-cost maintenance, reliable, robust and high efficiency laser sources will be a strong benefit for laser manufactures and integrators as well as for photovoltaic industry.

European countries have considerable expertise in laser technology and host a number of leading laser system manufacturers. With the rapid growth of the solar photovoltaic industry in Europe, Japan and the USA, continued support should be given to enable these manufacturers to develop their technology to compete in this growing international market. As a result of the expertise gained through participation in this project, industrial partners will have the possibility to sell innovative and advanced production tools based on the novel technology developed in the ALPINE project. Strong-added value will stem just from carrying out the work at a European level because of the leading position of the partners in several sub-fields at the core of the ALPINE concept. Continuous research and development is the key for superior products with high quality and cutting edge technologies. Europe is today leader in the world market for photonics, but innovation is necessary to defend this position.

The ALPINE project will potentially lead to the development of a new technology, where competition has not yet been established. The potential for innovation resulting from this research is thus considerable, being short term as well as long-term. In terms of a cost/performance ratio a significant advance on current technology is expected. In particular, by developing new concepts for laser scribing processes of photovoltaic thin films, the ALPINE project will allow to reduce the manufacturing costs of PV thin film solar modules. Due to the fact that the price of the PV modules alone accounts for about 60% of the price of a PV installation, this should consequently help reducing the overall price of PV energy production, contributing to a further increase of the share of electricity produced by PV in the next years within the European Union. This result would be inline with the so called 20/20/20 target for 2020 for the promotion of the use of renewable energies set by the European Commission. In January 2007 the European Commission put forward an integrated energy/climate change proposal that addressed the issues of energy supply, climate change and industrial development. Amongst other goals, the plan called for a 20% share of renewables within the EU by 2020. This should become a binding target all over EU and in each single Member State.

Basically, processing speed is the crucial factor for the necessary cost reduction in solar module production. Further advantages of laser application are the better availability in contrast to mechanical processes, reduced share of rejects and the potential for higher product quality. In addition, the amount of investment can be lowered by the use of fiber lasers instead of standard lasers. Details and numbers for any process are mentioned below.
Concerning P_2 and P_3, the mechanical scribing is still state of the art and has to be replaced by laser application for further improvements. Therefore the major technological challenge is to find appropriate laser parameters and settings. Subsequent to a successful development, a high processing speed is mandatory due to cost effectiveness. As thin film PV and especially the CIS technology is developing very fast in production capacities, the reduction of the number of machines is a crucial factor. Requirements like space, power supply, integration in production flow etc., are related to additional expenses for investments that are again essential for profitability. The positive consequences of a better cost effectiveness are therefore not limited on the running production but on plans for the future as well.

Currently the first patterning step P_1 is already done by laser application in case of substrate configuration (CIS technology) and co-evaporation procedures. The processing speed has to be increased but also the properties of the laser groove represent a very important factor for the overall module quality. Therefore, the Molybdenum has to be removed accurately without damaging the glass. Shunt behaviour could be caused and the process has to be improved by optimized laser parameters to achieve a better patterning quality. Currently reliability and reproducibility are high. Fibre lasers and processing speed of 5m/s could reduce costs at ca. 65%. In particular, in case of electrodeposited CIS, molybdenum can not be patterned before cell completion, which implies an improved beam control to avoid shunting and substrate damage.

Also the requirements for laser application for P_2 and P_3 are demanding. Apart from some tests, on the market there is no well-engineered laser process available to meet the needs of large scale production. Concerning quality and high throughput, it is an ambitious goal to qualify for all benefits, as for the P_1 step in the electrodeposite process. It is challenging but realistic to increase processing speed up to the range of 3-5 m/s. Costs for P_2 and P_3 could thus be reduced at roughly 60%. Since laser tools cannot be damaged and the processing is non-abrasive a very good availability is expected. For a higher yield the flexibility of lasers is also very advantageous and it should lower the percentage of rejects below 10-20%.
Moreover, the area between the scribing lines (P_1-P_3) needed for the interconnection is inactive and has no contribution to the module performance. The line width is in the range of 100 µm. If laser processing will succeed in reducing the line width and the distance between the lines themselves at ca. 50%, the module performance could be increased for more than 2.5%.

Development and Industrial implementation of cost effective advanced CIGS photovoltaic technologies

(Project **INDUCIS,** Coord: Nexcis, France)

Grant agreement n°: IAPP-285897
Start and end dates: 01/09/2011 to 30/08/2015

Co-ordinator: IREC- Catalonia Institute for Energy Research, Spain. Alejandro REREZ-RODRIGUEZ: aperezr@irec.cat

Consortium:

Partner	Beneficiary Name	Country	Role
IREC	CATALONIA INSTITUTE FRO ENERGY RESEARCH	Spain	Development of insitu/inline characterization tools to be installed in the production at NEXCIS. Research in new characterization methodologies. Transfer of knowledge to NEXCIS
NEXCIS	NEXCIS.	France	Fabrication at industrial scale of CIGS based modules and development of industrial methodologies. Transfer of knowledge in management to IREC

Title: **INDUCIS-** Development and industrial implementation of cost effective advanced CIGS photovoltaic technologies

Objectives: The main scientific objectives of the project are: a) to decrease the gap in the efficiency of ED-based solar cells in relation to that of devices fabricated with conventional higher cost PVD techniques and b) to improve the production yield and throughput by the implementation of quality control and process monitoring techniques

Description of the work: ED of a precursor layer followed by an annealing step is a high potential path to low cost manufacturing of high efficient thin film solar cells. ED is already a major technology for mass production of large-area metallic protective coatings in industry, with impressive figures as for instance in the case of zinc and cooper coating by roll-to-roll processes (several meters per minutes, deposition rates of tens of microns per hour, several meter large plates, etc.). Deposition baths can be stable for up to two years and have extremely high rate material utilization. Applying successfully such a technique for the mass production of CIGS solar modules is extremely well adapted for a large photovoltaic industry.
For this, a consortium formed by a research institute (IREC) and a company (NEXCIS) with strongly complementary competences and scientific background is defined. In this consortium, the strong experience of the group at the NEXCIS company on the development and industrial scale-up of ED based CIGS PV technologies is complemented by the solid background and maturity of IREC on the advanced characterization of heterostructures and processes in CIGS thin film technologies.

Expected results: The project will accelerate the market introduction of CIGS modules through novel manufacturing and real time characterization tools. A direct commercialisation of most results is possible via one of the project partner. INDUCIS includes also an intensive research and training program based on the development of intersectorial secondments of Early Stage and Experienced researchers between both institutions.

Thin Si film based hybrid solar cells on low-cost Si substrates

(Project **ThinSi,** Coord: STIFTELSEN SINTEF, Norway)

Grant agreement n°: 241281
Start and end dates: 01.01.2010 to 30.12.2013

Co-ordinator: SINTEF, Norway / Dr. Alexander Ulyashin, Tel.+47 93002224, alexander.g.ulyashin@sintef.no

Consortium:

Partner	Beneficiary Name	Country	Role
SINTEF	Stiftelsen SINTEF	Norway	Research organisation, development of low-cost Si powder based substrates
ISE	Fraunhofer Institute for Solar Energy Systems	Germany	Research organisation, deposition of epi-Si layers, solar cell processing
IMEC	Interuniversitair Micro-Electronica centrum VZW	Belgium	Research organisation, deposition of epi-Si layers, solar cell processing
ENEA	Ente per le Nuove tecnologie, l'Energia e l'Ambiente	Italy	Research organisation, optical characterisation of TCO layers
UNOT	University of Nottingham	UK	University, deposition of TCO layers and their characterisation
OIPT	Oxford Instruments Plasma Technology Ltd.	UK	Industrial company, advanced vacuum equipment developer
ELKS	Elkem Solar AS	Norway	Industrial company, silicon powder developer
PYRG	PyroGenesis S.A.	Greece	SME, substrate and solar cell structure producer
NTMD	NT-MDT Europe BV	Netherlands	SME, analytical equipment developer
IMPT	Innovative Materials processing Technologies Ltd.	UK	SME, non vacuum technology equipment developer
ISOF	Isofoton S.A.	Spain	Industrial partner, Solar cell and solar module producer

Title: **Thin Si film based hybrid solar cells on low-cost Si substrates**

Objectives: (i) to develop innovative methods for fabrication of low-cost Si based substrates ; (ii) to develop a process flow and advanced equipment for cost-effective fabrication of thin Si solar cells on low-cost Si based substrates, and assembly into modules ; (iii) To analyse the electronic properties of individual solar cell materials and their interfaces as well as the relationship between the deposition parameters and the device properties; (iv) to develop new methods for optical confinement; (v) to implement the "powder-to-substrate" concept based process flows to existing industrial lines.

Description of the work: The **main vision** of ThinSi is to develop a solar cell process chain for high throughput, cost-effective manufacturing of thin Si based solar cells on low-cost Si substrates. A set of innovative technological processes will be developed to realise this new concept and transfer the results it into production. ThinSi has the following R&D workpackages:

WP1: **Si powder synthesis and low-cost substrate processing**.

WP2: **Thin film processes**.

WP3: Analysis of properties of thin layers and solar cell structures

WP4: **Design, processing, characterization and testing of solar cells and modules**.
WP5: **Transfer to production lines**.

WORK PERFORMED AND MAIN RESULTS SO FAR

WP1: SPS Si powder based substrate surface without any voids and cracks, although consisting of large grains is shown in **Fig. 1**.

Figure 1: SEM images of SPS Si powder sintered wafer surface after chemical polishing

From **Fig. 1** it can be concluded that SPS process provides partial melting and recrystallization of Si at certain process conditions, providing formation of Si material similar to a conventional multi-Si. **Fig.2** shows an example of SPS Si powder based wafer with diameter of 200 mm.

Figure 2: Spark plasma sintered Si powder based wafer, disc with d = 200 mm.

Free standing ~300-500 µm thick 50x65 mm^2 as well as 156x156 mm^2 Si wafers have been produced from a low-cost and solar grade Si powders by the thermal spray method. These wafers exhibit all necessary properties (mechanically stable, ~0.01 Ωcm conductivity), which are required for the supporting substrates. An example of 156x156 cm^2 free standing substrate is shown in Erreur ! Source du renvoi introuvable.**.**

Figure 3: Si low cost substrate with dimension 156x156 mm^2

Main results of WP1 can be summarised as follows: (**i**) SPS as a method to produce dense and highly conductive silicon substrates has been identified; (**ii**) Thermal spraying of Si powder has been identified as a method to produce dense and highly conductive silicon substrates and thin layers; (**iii**) Silicon powder production, including B-doping process has been optimised and adjusted to obtain wafers and layers with the required electrical properties; (**iv**) Low cost wafers have been made from re-crystallisation of low purity silicon powder doped with B; (**v**) Bragg reflectors of PorSi have been etched into multi-Si wafers made from the ingot grown from low purity silicon powder doped with boron; (**vi**) Dense and conductive substrates have been produced by spark plasma sintering and thermal spraying of silicon powder doped with boron; (**vii**) Highly doped low-cost Si substrates have also been prepared via wafering of an ingot made of re-melted B-doped low purity silicon powder.

WP2: OIPT has developed PECVD (target temperature up to 700 °C) and magnetron systems (target temperature up to 600 °C), which can be used for the deposition of Si layers at elevated temperatures.

Moreover, an up-graded additional tool magnetron sputtering OIPT System 400 has been developed. Using the developed magnetron sputtering equipment OIPT has demonstrated the following: (i) High rate a-Si deposition up to ~200nm/min (H2 free), (ii) Time to grow 10µm ~ 1hr, (iii) magnetron process exceeds PECVD capability, (iv) 10µm a-Si deposited on prime silicon wafers and low cost ThinSi wafers at RT, 200°C and 300°C, (v) Excellent film adhesion – other technologies have tensile stress; (vi) Compressive film stress reduces with RF bias (<300MPa) and temperature (<250MPa).

Pyrogenesis has demonstrated that thin Si powder based layers can be deposited on any supporting substrate using thermal spray. Similar layers have been deposited on low-cost Si powder substrates using electronically grade Si powder. Properties of such layers are under the investigation currently.

Epitaxial processes for the deposition of thin Si layers at lower temperatures (< 1050°C) have been done on monocrystalline Si substrates in an Atmospheric Pressure Chemical Vapor Deposition system at ISE. Defect densities of the epitaxial layers have been measured. The goal of less than 10^5 defects per cm^2 was achieved for the temperature of 1050°C.

WP3: Since beginning of the project properties of Si powder based substrates have been analyzed by XRD, SEM, EDX, EBSD, Raman, conductivity measurements. Properties of ITO, AZO and FTO films have been investigated by AFM, XRD, transmittance, ellipsometry and conductivity measurements.

WP4: Reference solar cells on highly doped multicrystalline and monocrystalline Si substrates reached 13.3% and 15.3%, respectively. First solar cells on Si powder based substrates prepared via wafering of an ingot made of re-melted B-doped low purity silicon powder have been processed. The conversion efficiency for the best solar cell processed so far reached 11.9%.

WP5: A cost model for a standard technology of monocrystalline silicon cells has been developed to be used as reference for the ThinSi process chain (ISOFOTON). The breakdown of the model consists of wafer, solar cell and module steps. The wafer step implies polysilicon, ingot growing and wafering; the results of solar cell step show the following details: equipments (energy and depreciation), labour, material (materials and consumables), yield losses and fixed costs.

This estimation leads to the following graph (**Fig. 4**) in terms of cost (€/Wp) versus solar cell efficiency (%).

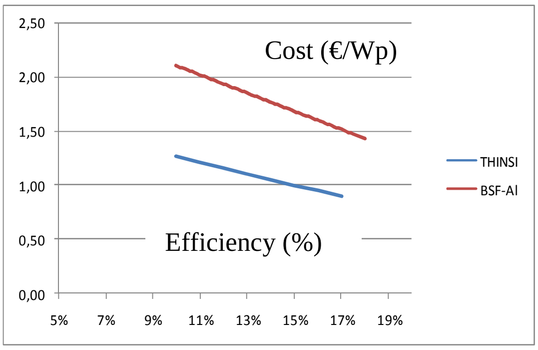

Figure 4: Cost of solar module versus solar cell efficiency for standard technology and ThinSi solar cells.

Expected results: A set of innovative technological processes will be developed to realise this new concept and transfer the results it into production. To realise a strategic Research Agenda developed in frame of the PV technology platform the cost effective manufacturing of thin Si based solar cells in frame of ThinSi project will target the cost of PV modules of about 1€/Wp.

Further research needs:

(i) Optimisation of fabrication of low-cost Si powder based substrates with the desired electrical and mechanical properties;

(ii) Cost effective processing of high quality thin Si layers deposited on top of low-cost substrates: CVD, magnetron sputtering, thermal spray.

(iii) Optimization of non-vacuum methods for the low-cost deposition of TCO layers.

(iv) Optimization of the solar cell processing chain for the Si wafer equivalent based solar cells.

(v) Implementation of a laboratory developed processing chain into industrial lines.

Non vacuum processes for deposition of CI(G)S active layer in PV cells

(Project : **NOVA-CI(G)S** Coord: UMICORE NV, Belgium
Fabrice STASSIN)

Grant agreement n°: 228743
Start and end dates: 01/01/2010 to 01/06/2013 (42 months)

Co-ordinator: Umicore, Belgium / Fabrice Stassin: fabrice.stassin@umicore.com

Consortium:

Partner	Beneficiary Name	Country	Role
1	Umicore SA	Belgium	Development of precursors materials
2	Zentrum für Sonnenenergieund Wasserstoff-Forschung (ZSW)	Germany	CI(G)S layer deposition & activation
3	EMPA Materials Science and Technology (EMPA)	Switzerland	CI(G)S layer deposition & activation
4	Technische Universität Chemnitz (TUC)	Germany	Large area deposition & annealing of CI(G)S layer (rigid, flexible substrates)
5	Xennia Technology Ltd	United Kingdom	Formulation of inks based on developed precursors
6	Wuerth Elektronik Rsearch GmbH	Germany	Exploitation & Dissemination Evaluation of developed technologies
7	Flisom Ltd	Switzerland	Evaluation of developed technologies Large scale deposition on flexible substrates
8	Valtion Teknillinen tutkimuskeskus (VTT)	Finland	Formulation of inks based on developed precursors

Title: **NOVA-CI(G)S -** Non-vacuum processes for deposition of CI(G)S active layer in PV cells

Objectives: Current production methods for thin film photovoltaics typically rely on costly, difficult to control (over large surfaces) vacuum-based deposition processes that are known for low material utilisation of 30-50%. NOVA-CI(G)S proposes alternative, non-vacuum ink-based simple and safe deposition processes for thin film CI(G)S photovoltaic cells. The low capital intensive, high throughput, high material yield processes will deliver large area uniformity and optimum composition of cells. The project objectives are to achieve competitive about 14% small area cell efficiency and to demonstrate the processes at high speed on rigid and flexible substrates while maintaining acceptably high efficiencies. The processes reduce cost of the CI(G)S layer by 75-80% in comparison to the evaporated CI(G)S, which translates into a 20-25% reduction of total module cost. Major scientific breakthroughs of the project include improved materials control in novel precursor materials by using nano-sized particles of specific chemical and structural characteristics and innovative ink formulation, to enable coating by simple processes while avoiding the use of toxic gases in subsequent process steps. This industry-led project constitutes the first essential step for a fully non-vacuum, roll-to-roll process aimed to achieve the solar module production cost below 0,8 €/Wp that will make photovoltaic directly competitive to traditional energy generation.

Description of the work: including if applicable benefits and barriers of nanotechnologies based approach.

- WP1 (Umicore as leader): Precursor materials and ink formulation
- WP2 (ZSW as leader): CI(G)S layer deposition and activation
- WP3 (TUC as leader): Large area deposition and annealing of CI(G)S layer
- WP4 (WERes as leader): Exploitation & Dissemination
- WP5 (Umicore as leader): Management

Developped technology will rely upon the use of inks prepared from particles, considering the following requirements and benefits:

- Typical particles we consider are partly based on metal oxygen-bearing derivatives
- Particles prepared using Umicore’s competences on wet-phase chemistry
- Inks prepared according to end-application specifications
- 2 materials systems selected for further optimization
- Move away from resort to H_2Se or harsh selenization conditions

Expected results: industrial applications and potential commercialisation

- Non-vacuum deposition of the CI(G)S layer while maintaining acceptably high efficiency
- Non-vacuum deposition of CI(G)S layers realized at high speed on rigid & flexible substrates whilst maintaining acceptably high efficiency on assembled cells
- Significant impact on reducing the cost (€/Wp) of the CI(G)S layer and pave the way to addressing the device’s adjoining layers ultimately achieving a CI(G)S TF module cost of below 0,8 €/Wp
- Fastened market development of CIGS technology as an alternative to non-thin film based PV

Further research needs:

- Control of composition and features of particles for development of inks
- Development of formulations without the use of too much of C-based stabilizer
- Control of deposition parameters and reliability of deposition technology
- Annealing / conversion of deposited layers into performant CIGS absorber layer (phase formation, morphology of layer, cracks, impurities, stoechiometry control)
- Avoid use of hazardous chemicals
- Printing of adjacent layers

Subcluster 2.2: Innovative PV materials

Chairman: Friedrich Kessler, (Group leader "Flexible CIGS solar cells" (ZSW), Germany)

PolySiMode: Improved polycrystalline-silicon modules on glass substrates
Coord.: Interuniversitair Micro-Electronica Centrum, IMEC, Belgium
Ivan GORDON

SILICON-Light: Improved material quality and light trapping in thin film silicon solar cells
Coord: Energieonderzoek Centrum Nederland, ECN, The Netherlands)
Wim SOPPE

HELATHIS: High efficient very large area thin film Silicon photovoltaic modules
Coord: : T-SOLAR GLOBAL S.A, Spain - **Mickaël VETTER**

hipoCIGS: New concepts for high efficiency and low cost in-line manufactured flexible CIGS solar cells
Zentrum für Sonnenenergie und Wasserstoff-Forchung, Baden-Wuertemberg, ZSW, Germany – **Friedrich KESSLER**

Improved polycrystalline-silicon modules on glass substrates

(Project **PolySiMode**, Coord.: Interuniversitair Micro-Electronica Centrum, IMEC, Belgium)

Grant agreement n°: 240826
Start and end dates: 01/12/2009 – 30/11/2012

Co-ordinator: imec, Belgium / Dr. Ivan Gordon: gordoni@imec.be, Tel: +32 16 28 82 49)

Consortium:

Partner	Beneficiary Name	Country	Role
1	Imec	Belgium	Coordinator
2	CSG Solar AG	Germany	Participant
3	Fraunhofer ISE	Germany	Participant
4	Fyzikalni Ustav Av	Czech Republic	Participant
5	Helmholtz Zentrum Berlin	Germany	Participant
6	CNRS-InESS	France	Participant

Title: **PolySiMode** - Improved Polycrystalline Silicon Modules on Glass Substrates

Objectives: Thin-film polysilicon solar cells have recently emerged as a promising thin-film alternative to bulk crystalline Si. With Solid Phase Crystallization (SPC) of amorphous Si, CSG Solar AG has achieved mini-modules (10x10 cm^2) with an efficiency of more than 10%, matching the efficiencies of the best European micromorph mini-modules. In this project, for the first time, the leading European institutes in the field of thin-film crystalline-silicon solar cells (CSG, FZU, IMEC, InESS, ISE, and HZB) will join forces to accelerate the further development and improvement of cost-effective large-area polysilicon modules. Indeed, simulations point out that with the proper crystallographic quality of the polysilicon material and with advanced device processing, single-junction polysilicon solar cells with efficiencies as high as 15% are feasible.
The aim of this project is to increase the efficiency of large-area polysilicon modules to more than 12% and thus to improve their cost-effectiveness. While projections for CSG Module Cost of Goods Sold per Watt Peak (COGS/Wp) are currently around 1€/W for 2012, this project aims to reduce that value to 0.7 €/Wp by the end of the project (i.e. in the same time frame). This will be achieved by the improvement of the crystallographic and electronic quality of the active polysilicon material and by the implementation of new, advanced methods for light confinement. The present device structure and material of the CSG modules will be taken as the starting point. By advanced characterization of the polysilicon material and related interfaces, a better understanding of the relationship between the growth parameters, the electrical and optical properties of the material and the resulting device properties will be obtained. This information will be used to enhance the material quality by the development of more effective post-deposition treatments (defect annealing and hydrogen passivation) for polysilicon and by the development of improved material growth processes leading to a much lower number of defects in the material. Besides by an improved material quality, the efficiency of polysilicon modules will also be increased by the development of advanced methods for light confinement. The active participation of CSG within this project will allow the consortium to produce in-line module demonstrators (39 x 30 cm2) by application of the developed process steps in the pilot line of CSG and also to accurately determine the influence of the developed technologies on the cost-effectiveness of polysilicon modules.

Description of the work: This project would build on the knowledge of the best partners in the field (the major institutes working on thin-film polysilicon PV in Europe are present in this consortium) but would go beyond what has been done so far. We will aim to improve the polysilicon material quality by developing novel deposition methods to reduce the defect density in the material (WP1), and by developing post-deposition treatments to anneal and passivate the remaining defects more effectively and by investigating the use of a-Si for surface passivation and heterojunction emitters (WP2). Moreover, the light confinement for polysilicon modules in superstrate configuration will be enhanced by further developing the abrasion-etch texture method and by introducing advanced new concepts like plasma texturing and multi-layer anti-reflection coatings (WP3). A detailed characterization of the samples will lead to a comprehensive understanding of the relation between material properties, interface properties and processing methods and will therefore open up new strategies for further improvement (WP4). We will also focus on identifying characterization methods that are best suited for in-line characterization in a production environment and we will try to develop for the very first time a standardized measurement procedure for c-Si thin-film modules (WP5). Process steps developed within the project will be integrated and tested at module (30 x 39 cm^2) level, while the cost-effectiveness of these new process steps when implemented in production will be determined (WP5).

Expected results: The main concrete scientific and technological expected results of the project are:
- Development of alternative Si deposition methods, having increased growth rates and/or leading to higher material quality
- Optimized in-line post-deposition treatments (defect annealing and hydrogen passivation) leading to improved polysilicon material quality
- Improved light trapping schemes that enhance the efficiency of polysilicon modules
- Improved understanding of the relationship between silicon growth parameters, post-deposition treatments and material quality
- Thin-film polysilicon modules (39 x 30 cm2) produced in-line with efficiencies above 12%
- A Cost of Goods Sold per Watt Peak value for polysilicon modules below 0.7 €/Wp at the end of the project

The main channel for exploitation of the project results is through commercialization of the products by the industrial partners in the consortium.

Improved material quality and light trapping in thin film silicon solar cells

(Project **SILICON-Light,** Coord: Energieonderzoek Centrum Nederland, ECN, The Netherlands)

Grant agreement n°: 241277
Start and end dates: 01/01/2010 to 31/12/2012

Co-ordinator: ECN, the Netherlands / Dr. Wim J. Soppe, soppe@ecn.nl, +31 224 564087

Consortium:

Partner	Beneficiary Name	Country	Role
1	Energy research Centre of the Netherlands	Netherlands	Coordinator and the lead participant for WP1 and WP3.ECN will bring in their expertise on PECVD of silicon layers for solar cells and light trapping.
2	Ecole Polytechniqe Federale de Lausanne	Switzerland	PVLab will be leading WP5 (high efficiency solar cells) and contribute its experience to the other work packages, WP2 (light trapping) and WP3 (silicon layers) in particular.
3	VHF Technologies	Switzerland	Development of improved efficiency a-Si solar cell processes on nano-textured substrates; Demonstration of roll-to-roll processing of nano-textured substrates in pilot-line and improvement of efficiencies for a-Si :H and uc-Si modules; Reliability testing of demonstration PV modules produced in roll-to-roll processes; Final user of project technology
4	Technical University of Denmark	Denmark	Providing high spatial resolution information about silicon layers and solar cells that are fabricated, characterized and tested by the other partners using transmission, scanning and focused ion beam electron microscopy.
5	Nanoptics	Germany	Manufacturing of nano-textured masters. Manufacturing of shim families and production shims (clean room development and production), Improved pilot production of beam-cured micro- and nano-structured films
6	University of Ljubjana	Slovenia	Modeling and simulation of thin-film photovoltaic devices, optimization of surface texture for efficient light trapping, optical and electrical characterization of materials and devices.
7	Universidad Politécnica de Valencia	Spain	UPVLC will develop processes such UV in combination with e-beam lithography using special resists and polymers, to achieve very-high aspect ratio features, and will fabricate samples and masters of a variety of shapes and designs that will be used as substrates for the deposition of the subsequent layers needed to complete a thin-film device.
8	Umicore Materials AG	Liechtenstein	Umicore will be the lead participant for WP4. Umicore will bring its expertise in TCO sputtering target development
9	Shanghai Jiaotong University	China	SJTU will bring in their expertise on research and fabrication of nanostructure for solar cells and light trapping and fabricate new back-reflector structure for testing by partners.

Title: **SILICON-LIGHT –** Improved material quality and light trapping in thin film silicon solar cells

Objectives: The general technological objectives of SILICON-Light are the development of better materials for single junction amorphous, microcrystalline and tandem micromorph (amorphous/microcrystalline) silicon solar cells and to transfer the processing of these materials to an industrial production line of these solar cells.
In more detail, the most important technology objectives are:

1) Development and industrial implementation of textured back contacts in flexible thin film silicon solar cells,
2) Thin film silicon solar cells on flexible substrates with higher efficiencies (> 11%) than present state of the art, through implementation of optimized interfaces, improved silicon absorber material and novel light trapping methods.
3) Graded or tandem TCO layers which minimize the work function barrier between the p-layer and the TCO layer, while retaining the present quality of conductivity and transmission of the TCO layers.
4) Development of new ceramic target materials suitable for the PV industry, combining low costs of AZO with the high conductivity and transparency of the more expensive ITO.

Description of the work: In Silicon-Light methods are being investigated and improved to fabricate thin silicon layers with thickness of about 1/1000 of a millimetre out of a gas phase on foil by means of Plasma Enhanced Chemical Vapour Deposition (PECVD). The purpose is to make high quality amorphous and micro-crystalline silicon at relatively low process temperatures (typically below 200 ºC), allowing the usage of cheap plastics as substrate foil. To collect all sunlight into only one micrometer of silicon, special structures need to be incorporated in the solar cells which trap the light. In Silicon-Light we investigate methods to create light-scattering textures at the rear side of the cell. For the fabrication of these textures, with structures on nanometre scale, methods from the semiconductor industry like e-beam lithography will be applied. To demonstrate that these textures can be manufactured on large scale, these methods will be combined with large scale production methods which are used in the holographic industry. Another aim of the project is to develop new TCO layers for thin film silicon solar cells. TCO (Transparent Conductive Oxide) layers are needed to collect the generated current at the front side of the solar cell. Indium Tin Oxide (ITO) is technically a good candidate but the scarceness of Indium requires to investigate alternative materials. Zinc-Oxide is a possible alternative but has certain disadvantages related to its stability in humid environments. In Silicon-Light new TCO materials will be developed that should combine the advantages of ITO with that of ZnO.

Expected results: The project should lead to improved fabrication processes for thin film silicon solar cells on foil, leading to higher module efficiencies at the same or lower costs per module area, than for the present available production technologies.

Further research needs: More academic research on the growth of silicon layers in PECVD processes.

High efficient very large area thin film Silicon photovoltaic modules

(Project **HELATHIS** Coord: : T-SOLAR GLOBAL S.A, Spain)

Grant agreement no: 241378
Start and end dates: 01/01/2010 to 31/12/2012
Co-ordinator: T-Solar Global S.A., Spain / Dr.-Ing. Michael VETTER: michael.vetter@tsolar.eu, tel: +34 988 540 253

Consortium:

Partner	Beneficiary Name	Country	Role
1	T-Solar Global S.A.	Spain	Project coordination, Implementation of new TCOs and solar cell structures into industrial production line.
2	AGC Glass Europe	Belgium	Development of TCO and ARC for mass production.
3	Research Centre Juelich	Germany	Development of TCO, a-Si single and micromorph tandem junction. Solar cell and material characterisation.
4	Utrecht University	The Netherlands	Development of a-Si single and micromorph tandem junction. Solar cell and material characterisation and modelling.
5	University of Barcelona	Spain	Development of TCO and back reflector. Development of a-Si single junction. Solar cell and material characterisation and modelling.

Title: HELATIS - High efficient very large area thin film Silicon photovoltaic modules (www.tsolar.com/helathis)

Objectives: T-Solar Global S.A. (T-Solar) manufactures amorphous silicon (a-Si) thin film modules, producing modules in a 50MW facility, using Applied Materials SUNFAB technology. AGC Glass Europe is the European branch of AGC, the world biggest producer of flat glass with several facilities worldwide to produce glass covered with transparent conductive oxide (TCO), which is the substrate for producing thin film silicon modules. The Institute for Energy and Climate Research-5 (IEK-5) at the Research Centre Juelich (FZJ) is a publicly funded research centre that has concentrated its work on thin film silicon solar cells and related materials for several decades. The Debye Institute for Nanomaterials Science at the Utrecht University (UU) has a strategic and detailed know-how on thin film deposition processes, interfaces, and manufacturing of complete thin film multi-junction solar cells. The Utrecht Solar Energy Laboratory has been developing solar cells for many years. The Solar Energy Group at the Department of Applied Physics and Optics of the University of Barcelona (UB) started activities in thin film silicon solar cells in 1984 and actually is focusing their activity on the deposition of thin film silicon solar cells at low temperatures and on new strategies for light confinement based on hot-embossing technology.
This project identifies optical light confinement as a key point to increase module efficiency in thin film silicon solar modules. The optimisation of the properties of TCO-layers at the front contact and the back reflector has to be achieved for large area deposition. Additionally, methods for the reduction of reflection losses at the front glass are developed. This optimisation has to be done for both single a-Si cell modules and for modules with a-Si/micro-crystalline (□c)-Si tandem structure, where, in the latter case, an intermediate reflector (IR) has also to be considered.
The objective of the project is to drive the implementation of optical layers as part of adapted thin film silicon solar cells into large scale production facilities.

Description of Work: This project develops innovative schemes for silicon thin film solar modules for application in large area industrial production. This includes most of the optical confinement strategies that are presently state-of-the-art in the highest efficiency amorphous silicon laboratory solar cells. The experimental work of the Work Plan is structured in relation to the interfaces of the a-Si thin film module: Work Package (WP) 2 -Glass front surface - is dedicated to the development of anti-reflection coatings for very large area glass surfaces. WP3 –Glass/TCO interface- deals with the development of improved front TCO layers. Fabrication and optimisation of the glass/TCO structure is performed in AGC production facilities on large scale. WP4 –Intermediate reflector (tandem structure) – is devoted to the development of Intermediate Reflectors (IR) based e.g. on PECVD SiOx-layers for the light management in modules with a-Si/□c-Si tandem solar cells. Furthermore, new photonic structures will be developed on a laboratory scale. WP5 –Back reflector- is dedicated to the optimisation of the back reflector structure and consists, for example, of the development of optimised sputtering target materials for flat targets as well as for rotating targets and the development of optimised film properties of TCO layers. Finally, WP6 – Advanced characterisation methods - contains various tasks related to in-depth investigation and characterisation of material properties and structures used in the solar module, including new materials and new structures developed on a laboratory scale. Nanotechnology is under consideration in the development of textured structures for TCO-layers, anti-reflection coatings and IR-layers. The optimisation of textured surfaces for perfect light confinement has to be simultaneously performed on the nanometre as well as the micrometre scale and interaction with the thin films of the solar cell structure has to be considered. The film thickness of the basic layers of the thin film solar cell are in the nanometre scale, so the p-type layers and n-type layers are in the range of 10-20nm and amorphous intrinsic silicon layers and layers in the back reflector are in the range of a few 100 nm. The exact control of the film properties to achieve good film uniformity on very large area is a challenge and respective in-situ and in-line measurement technologies have to be applied to maintain process stability. For IR layers photonic structures in the nanometre scale are under development, implementing e.g. multiple nanometre layer structures, quantum dots and nanoparticles. The challenge for the implementation of these structures is the demonstration of feasibility on a laboratory scale.

Expected Results: The main objective to fabricate large area (5.7 m^2) modules with 7% stabilized efficiency after one year of project execution has been achieved and a stabilised module efficiency of 8% for single junction modules is scheduled within 2 years and for very large area tandem modules efficiency of 11% is projected at the end of the project. On a laboratory scale single junction solar cells with stabilised efficiency of 10% and tandem solar cells with stabilised efficiency of 13% is scheduled. Optimised TCO glass will be developed and TCO glass production capacity will be made available for GW-scale module fabrication. Including the expected reduction in material costs, module production costs of T-Solar are expected to be in the range 0.70 €/Wp at the end of the project.

Further Research Needs: At the end of this project the gap between highest efficiency laboratory solar cells and large area modules is estimated to be about 2% absolute, respectively 25% relative. To reduce this efficiency gap it will be necessary to up-scale new advanced laboratory or pilot processes which have demonstrated improved material properties to achieve cost effective large area processes. In addition existing large area process machines must be adapted (e.g. the reactor geometry or utilising new process materials) to obtain process conditions to produce improved material properties in a specified process window. Furthermore, laboratory solar cells must be improved beyond the existing limits by new and advanced process methods including e.g. triple junction designs to approach to theoretical limits - this will also open the way for further improvement of industrial modules.
Apart from increasing the efficiency of thin film modules, the cost reduction of the different materials included in the module has to be significantly advanced. The reliability and warranty of all module components and of the module itself must be increased beyond the 25 year level actually standard in the market to improve the economical performance of photovoltaic installations. An intensive cooperation between module component and module manufacturers has to be achieved to develop optimised components and to increase the variety of equivalent and interchangeable components in the market. This will improve and secure the material supply and it will create more competition in the supply market. The certification process for new module components must be made faster and less cost intensive.
The development of in-situ and large area in-line control metrology must be advanced, including the integration of metrology tools into the factory automation systems (FAS) and material handling systems (MHS). This will permit improved quality control and advanced statistical process control (SPC). Control metrology must be developed on a wider base to cover the whole process chain and to reduce the respective metrology installation costs. Standardisation of interfaces between metrology tools and FAS/MHS must be realised to facilitate easier and faster implementation.

New concepts for high efficiency and low cost in-line manufactured flexible CIGS solar cells

(Project **hipoCIGS** Coord: Zentrum für Sonnenenergie und Wasserstoff-Forchung, Baden-Wuertemberg, ZSW, Germany)

Grant agreement n°: 241384
Start and end dates: 01/01/10 to 31/12/12
Co-ordinator: ZSW, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg / Friedrich KESSLER: friedrich.kessler@zsw-bw.de, +49 (0)711 7870 201.

Consortium:

Partner	Beneficiary Name	Country	Role
ZSW	Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW)	Germany	Project coordination, substrate evaluation, back contact and Na supply, CIGS deposition, thin absorbers, inline vacuum buffer on large area, series interconnection, TCO testing
FLISOM	FLISOM AG	Switzer-land	Substrate evaluation, back contact and Na supply, CIGS deposition, thin absorbers, vacuum buffer, series interconnection, test of novel TCO
TATA	TATA STEEL TECHNOLOGY B.V.	The Nether-lands	Development and supply of mild steel foils, low carbon steel for enamelling
PEMCO	PEMCO BRUGGE BVBA	Belgium	Substrate development and substrate supply, Na doping
WS	WÜRTH SOLAR GmbH & CO KG	Germany	Substrate evaluation large area, evaluation CIGS results, series interconnection, test of novel TCO
EMPA	EIDGENÖSSISCHE MATERIALPRÜFUNGS- UND FORSCHUNGSANSTALT	Switzer-land	Substrate evaluation, back contact and Na supply, CIGS deposition, thin absorbers, inline vacuum buffer, series interconnection, test of novel TCO
TNO	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPEL IJK ONDERZOEK	The Nether-lands	Substrate texturing, series interconnection, development and supply of novel TCO layers, barrier layer on top
WUT	POLITECHNIKA WARSZAWSKA	Poland	Correlation of Na doping / CIGS quality and of PV performance with CIGS doping and defect concentration, metastabilities and long-term-stability

Title: **hipoCIGS -** New concepts for high efficiency and low cost in-line manufactured flexible CIGS solar cells

Objectives: Main project goal is to investigate, test and develop innovative flexible substrate materials and deposition processes applicable for a future inline and roll-to-roll production of highly efficient flexible solar cells and modules using thinner CIGS absorber layers and with potential for low production costs below 0.6 €/Wp.

Description of the work: Novel concepts in growth of "high quality" layers and interfaces for efficiency improvement will be developed, aiming at new world record efficiencies on polyimide and cost-effective metal substrates. New enamel formulations are investigated to be applied especially on low carbon steel for electrical insulation and as Na-supply source. Additionally, an evaporated In_2S_3 based buffer layer, an atmospheric pressure PECVD window layer and suitable interconnect technologies are developed. To reduce the absorber thickness and thus materials consumption and manufacturing costs substrate and TCO texturing is investigated. Neither roll-to-roll production nor encapsulation is an issue of this project, but all developed processes and materials are compatible to a future R2R-manufacturing.

Expected results: The project will accelerate the market introduction of CIGS modules through novel manufacturing processes for high efficiency, low cost and light weight CIGS modules. The polyimide, mild steel or aluminium substrates enable integration of CIGS modules in low cost and light weight building components and transport applications. A direct commercialisation of most results is possible via the project partners.

Further research needs: Further research may be necessary regarding: i) textured and highly efficient devices with thin CIGS absorbers and ii) long-term stability of flexible devices.

Round table session summary

Cluster 2 Workshop

Round table session:

Nanotechnology for PV thin film: research needs and recommendations

Since few years, manufacturing capacity of PV thin film has increased strongly and there have been significant efficiency advances. Along this Cluster 2 Workshop we have identified some priority topics: material development, transparent electrodes, high productivity deposition techniques, encapsulation processes and quality control.
Reducing absorber layer thickness is a strong driver for decreasing the cost. Firstly it enables faster deposition processes (lower Capex) and reduces material usage, therefore mitigating the effect of rising cost of elements such as indium and tellurium. Secondly, this will also help to increase V_{oc} and FF of solar cells, hence, increase the efficiency. This has proved to be challenging in current devices based e.g. on CIGS or CdTe. Simultaneously we need to increase the efficiency of devices with thinner absorber by employing advanced light management and 3-dimensional design
The low cost technologies are being developed for thin film technologies, the described bottlenecks need to be overcome before market launch of such processes. In fact, tape casting, wet coating or printing technologies are some of the low cost approaches that can be realized at high speed, but they need to provide a better reliability, enhanced control of the deposition parameters and of the morphology of produced layers, lower cracks and lower impurities formation. Qualitative and quantitative understanding of defects, impurities, metastabilities, layer structures are required in order to pursue the progress of the thin film technologies. Also the understanding of electronic band structure in relation to buffer layer chemistry is requested.
Today, flexible photovoltaic (e.g. thin film PV, OPV, …) is lacking a suitable high barrier and low cost encapsulant material. Several manufacturers of flexible $Cu(In,Ga)(Se,S)_2$ (CIS) based solar modules are still forced to package their devices by glass plates and thus losing the immanent advantage of low weight and flexibility. Apart of the physical requirements a main challenge so far is to produce these high barrier films at reasonable costs. Better understanding of barrier phenomena at nanoscale are required in order to reach value below 10^{-5}. Its long-term stability should be comparable to glass encapsulants and survive respective aging tests. The availability of stable, flexible and cost effective transparent encapsulation would substantially contribute to leverage the flexible and lightweight CIS or OPV technology and the exchange of the cover glass by a cheaper plastic foil would be of interest for producers of rigid photovoltaic modules as well.

Additional topics have been highlighted like modelling heterostructures (including substrates and encapsulation), finding alternatives to critical materials. Important criteria for PV materials are abundance, non-toxicity and manufacturability with respect to thin film production either by replacing rare elements in current materials or by screening and developing new possible semiconductor materials.
Within the first route replacing In and Ga in high efficiency $Cu(In,Ga)Se_2$ solar cells by Zn and Sn has spurred considerable research efforts in photovoltaics based on kesterite $Cu_2ZnSn(S,Se)_4$.(CZTSSe). This approach could be readily introduced in present production lines using a vacuum process a non vacuum process could be used which has already shown very promising results (IBM:10% efficiency). However, further substantial efforts are necessary to reach completive efficiencies beyond 15%.
Regarding the second route, binary/ternary systems of cheap, abundant and non-toxic materials (such as FeS_2 Cu_2S, CuO, Cu_2O or hydrogen based alloys) may be considered if supported by sound first principles considerations and calculations or by preliminary experimental investigations which clearly show their photovoltaic potential. Quantitative understanding of all interface and light trapping and development of improved selected cell layers (nanocrystals, nanodots,..) at the nanoscale will be useful.

Participants

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