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Final report

CUSTCO

Cost efficient, upscalable and stable transparent conductive oxides for silicon solar cells based on passivated contacts.

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Research Programme Photovoltaics
CH-3003 Bern
www.bfe.admin.ch
energieforschung@bfe.admin.ch

Agent:
Indeotec SA
Puits-Godet 12a
2000 Neuchâtel
www.indeotec.com

Author:
Omid Shojaei, Indeotec SA, omid.shojaei@indeotec.com

SFOE head of domain: Stefan Oberholzer, OFEN, stefan.oberholzer@bfe.admin.ch
SFOE programme manager: Stefan Oberholzer, OFEN, stefan.oberholzer@bfe.admin.ch
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Summary

This project targets the development of industrially feasible transparent conductive oxides (TCO) to reduce the cost of high efficiency silicon solar cells using full-area passivated contacts, which have demonstrated efficiencies above 25% in cleanroom and pre-production environment. While research and industry currently focus on silicon thin films, either amorphous (a-Si) or silicon oxide (SiO_x)/polycrystalline silicon (pc-Si) fabricated in the range of 200°C to 900°C, respectively, the CUSTCO consortium will address the significant impact of the TCO on the cost and performance improvements of such devices and hence on the success for their industrialization. While the main focus will be on the TCOs, the silicon thin films will also be addressed since the overall contact properties and hence the performance and stability of the devices are defined by the tight interplay between both. TCO materials which are already widely used for thin film solar cells, displays or sensors will be tested for their applicability to such silicon wafer based solar cells and new materials will be explored or adapted. While the typical approach is to optimize the TCO for a given silicon contact system, we will first concentrate on a more holistic evaluation of the TCO and then choose the proper silicon-based contacts for device integration. The application of the developed a-Si or SiO_x/pc-Si based contacts will allow for a wide TCO process window to utilize so far unexplored potential of these materials. Material improvements by hydrogenation of the TCO will also be addressed with the final goal to demonstrate a cost efficient, upscalable and stable TCO for a highly efficient (>24%) silicon solar cell. An important aspect of the project will be the substitution or at least a drastic reduction of Indium, which is a rare element but currently the most widely used in TCO materials.

Zusammenfassung

Dieses Projekt zielt auf die Entwicklung industriell umsetzbarer transparenter leitfähiger Oxide (TCO) ab, um die Kosten für hocheffiziente Silizium-Solarzellen mit vollflächig passivierten Kontakten zu senken, die in Reinraum- und Vorproduktionsumgebungen Wirkungsgrade von über 25 % aufweisen. Während sich Forschung und Industrie derzeit auf dünne Siliziumschichten konzentrieren, die entweder aus amorphem (a-Si) oder aus Siliziumoxid (SiOx)/polykristallinem Silizium (pc-Si) bestehen und im Temperaturbereich von 200°C bis 900°C hergestellt werden, wird sich das CUSTCO-Konsortium mit den bedeutenden Auswirkungen der TCO auf die Kosten und die Leistungsverbesserung solcher Bauelemente und damit auf den Erfolg ihrer industriellen Nutzung befassen. Während der Schwerpunkt auf den TCOs liegt, werden auch die Silizium-Dünnschichten behandelt, da die gesamten Kontakteigenschaften und damit die Leistung und Stabilität der Geräte durch das enge Zusammenspiel zwischen beiden bestimmt werden. TCO-Materialien, die bereits in großem Umfang für Dünnschicht-Solarzellen, Displays oder Sensoren verwendet werden, werden auf ihre Anwendbarkeit für solche Solarzellen auf Silizium-Wafer-Basis getestet, und neue Materialien werden erforscht oder angepasst. Während der typische Ansatz darin besteht, die TCO für ein bestimmtes Siliziumkontaktsystem zu optimieren, werden wir uns zunächst auf eine ganzheitlichere Bewertung der TCO konzentrieren und dann die geeigneten siliziumbasierten Kontakte für die Bauelementintegration auswählen. Die Anwendung der entwickelten a-Si oder SiOx/pc-Si basierten Kontakte wird ein breites TCO-Prozessfenster ermöglichen, um das bisher unerforschte Potenzial dieser Materialien zu nutzen. Materialverbesserungen durch Hydrierung des TCO werden ebenfalls untersucht, mit dem Endziel, ein kosteneffizientes, hochskalierbares und stabiles TCO für eine hocheffiziente (>24%) Silizium-Solarzelle zu demonstrieren. Ein wichtiger Aspekt des Projekts ist der Ersatz oder zumindest die drastische Reduzierung von Indium, einem seltenen Element, das derzeit am häufigsten in TCO-Materialien verwendet wird.

Résumé

Ce projet vise le développement d'oxydes conducteurs transparents (TCO) industriellement réalisables pour réduire le coût des cellules solaires au silicium à haut rendement utilisant des contacts passivés sur toute la surface, qui ont démontré des rendements supérieurs à 25 % en salle blanche et en environnement de pré-production. Alors que la recherche et l'industrie se concentrent actuellement sur les couches minces de silicium, qu'il s'agisse de silicium amorphe (a-Si) ou d'oxyde de silicium (SiOx)/silicium polycristallin (pc-Si), fabriquées respectivement entre 200°C et 900°C, le consortium CUSTCO se penchera sur l'impact significatif du TCO sur le coût et l'amélioration des performances de ces dispositifs et donc sur le succès de leur industrialisation. Bien que l'accent soit mis sur les TCO, les films minces de silicium seront également abordés, car les propriétés de contact globales, et donc les performances et la stabilité des dispositifs, sont définies par l'interaction étroite entre les deux. Les matériaux TCO qui sont déjà largement utilisés pour les cellules solaires à couche mince, les écrans ou les capteurs seront testés pour leur applicabilité à ces cellules solaires à base de tranches de silicium et de nouveaux matériaux seront explorés ou adaptés. Alors que l'approche typique consiste à optimiser le TCO pour un système de contact en silicium donné, nous nous concentrerons d'abord sur une évaluation plus globale du TCO, puis nous choisirons les contacts en silicium appropriés pour l'intégration du dispositif. L'application des contacts développés à base d'a-Si ou de SiOx/pc-Si permettra une large fenêtre de traitement du TCO afin d'utiliser le potentiel jusqu'ici inexploré de ces matériaux. L'amélioration des matériaux par hydrogénation du TCO sera également abordée, l'objectif final étant de démontrer un TCO rentable, évolutif et stable pour une cellule solaire au silicium à haut rendement (>24 %). Un aspect important du projet sera la substitution ou du moins une réduction drastique de l'Indium, qui est un élément rare mais actuellement le plus utilisé dans les matériaux TCO.

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List of abbreviations

SFOE	Swiss Federal Office of Energy
TCO	Transparent Conductive Oxide
a-Si	Amorphous Silicon
SiOx	Silicon oxide
pc-Si	Polycristalline Silicon
ITO	Indium Tin Oxide
µ	Carrier mobility
HJT	Heterojunction

1 Introduction

For the emerging passivated contact technologies and especially the silicon heterojunction (HJT) cells tin doped indium oxide (ITO) is the current standard TCO material featuring only moderate carrier mobility (~40 cm²/Vs). However, for very high production volume (GW range) indium will be an issue, due to its limited supply and price fluctuation (http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en).

2 Context

2.1 Background / State of the art

Indium-based materials with better performance (higher µ) than ITO are currently explored [1, 2, 3]. While this can be considered as early stage investigations mainly to improve the understanding of material science related aspects, stability and industrial aspects are hardly explored, so far. As an example, several publications report on the very high mobility (µ > 120 cm²/s) of hydrogen doped indium oxide. However, these films are mainly produced by RF sputtering which is hardly applicable for large area depositions on industrial scale, compared to e.g. DC sputtering [4]. Furthermore, indium oxide is a rather brittle material which allows for the fabrication of the planar targets used in R&D environment but it is challenging to produce rotatable target which are preferred for industry due to the higher material yield. Finally, there is some evidence that some of these very high mobility materials can suffers from damp-heat degradation [5] (reduction of conductivity) which will reduce long-term performance of the system.

Therefore, finding a proper material for doping of indium oxide (metal elements like zirconium, hafnium, molybdenum, tungsten, cerium) to combine very high mobility (µ> 100 cm²/Vs) with industrial applicability and stability will be a main challenge of this project.

Aluminium doped zinc oxide is the most common indium-free TCO which is used for example in thin film solar cells. Challenges for this material are the relatively low mobility, strong thickness dependence of the mobility and damp heat degradation. Approaches to push the mobility of such indium-free TCO to the level of ITO are reported in literature and are based on e.g. hydrogenation [6] and process temperatures well above the 200°C [7] which are not applicable to a-Si based silicon HJT cells. To widen the process window for the TCO deposition we will increase the temperature stability by using O- or C-alloyed a-Si based contacts (undoped and doped a-SiOx:H, nc-SiOx:H as well as a-SiC:H films) and take advantage of the SiOx/pc-Si passivated contact technology with even higher process temperatures of up to 900°C.

2.2 Motivation of the project

While many lessons regarding the a-Si and pc-Si thin films have been learned from e.g. thin film solar cells and microelectronics, their combination with other TCOs than ITO is a rather novel field. Hence, besides finding a proper TCO material with good optoelectronic properties, the contact resistance between the TCO and the silicon thin films and damage to the silicon surface passivation also need to be considered for the final device integration.

2.3 Goals

Two basic strategies exist for Indium reduction:

> 1). Take full advantage of the intrinsically higher mobility of indium-based TCOs by using other dopants then tin to enable very high mobility’s (μ > 100 cm²/Vs). This allows for much thinner indium-based TCOs which will be capped by a dielectric (e.g. SiNx) or an indium-free TCO to function as anti-reflective coating
>
> 2). Improve indium-free TCOs with a current limitation to < 20 cm²/Vs to such an extent that highly efficient solar cells can be produced

In particular, the outcome of H2020 project INREP (http://www.inrep.eu/) will be considered in our initial screening of TCO materials. However, our goal is to go beyond the classical silicon HJT solar cell structure by looking at more robust and cost-efficient combinations of TCO and silicon thin film materials.

3 Appraoch and methodology

3.1 Global approach

The CUSTCO consortium brings together (i) academic experts in TCO and silicon thin film materials science to identify promising and industry-relevant materials, (ii) industrial partners to address upscaling aspects for deposition, material evaluation and synthesis, and (iii) the possibility to bring this together in a stable, highly efficient and cost competitive solar cell to finally ensure a short time to market. The role of Indeotec is to provide cost effective solution for the preparation of solar cell precursor that meet requirement for mass production of such device.

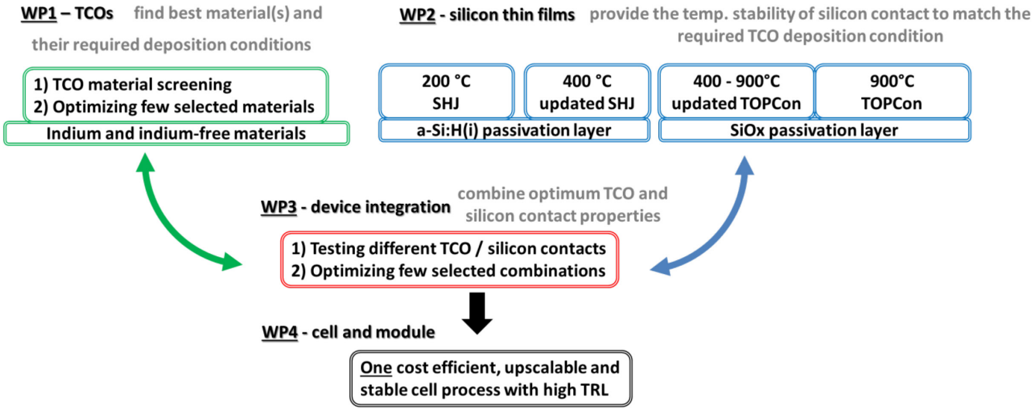

Figure 2 Overall view of all work packages within the projects

Especially, the main task will be to adapt PECVD layers (passivation, contact resistance) with the TCO chosen from other partners during first phase (WP2) of the project. This solution should be compatible with mass production integration, especially seen in the throughput of such a deposition system (i.e > 3’000 wph). Early results showed that the concept of the Indeotec Mirror technology fulfil the requirement of mass production compatibility. This simplified approach for manufacturing of silicon heterojunction needs to be further developed and adapted to TCO of choice resulting from this consortium.

This project targets the development of industrially feasible transparent conductive oxides (TCO) to reduce the cost of high efficiency silicon solar cells using full-area passivated contacts, which have demonstrated efficiencies above 25% in cleanroom and pre-production environment. While research and industry currently focus on silicon thin films, either amorphous (a-Si) or silicon oxide (SiO x)/polycrystalline silicon (pc-Si) fabricated in the range of 200°C to 900°C, respectively, the CUSTCO consortium will address the significant impact of the TCO on the cost and performance improvements of such devices and hence on the success for their industrialization. While the main focus will be on the TCOs, the silicon thin films will also be addressed since the overall contact properties and hence the performance and stability of the devices are defined by the tight interplay between both. TCO materials which are already widely used for thin film solar cells, displays or sensors will be tested for their applicability to such silicon wafer based solar cells and new materials will be explored or adapted. While the typical approach is to optimize the TCO for a given silicon contact system, we will first concentrate on a more holistic evaluation of the TCO and then choose the proper silicon-based contacts for device integration. The application of the developed a-Si or SiO x /pc-Si based contacts will allow for a wide TCO process window to utilize so far unexplored potential of these materials. Material improvements by hydrogenation of the TCO will also be addressed with the final goal to demonstrate a cost efficient, upscalable and stable TCO for a highly efficient (>24%) silicon solar cell. An important aspect of the project will be the substitution or at least a drastic reduction of Indium, which is a rare element but currently the most widely used in TCO materials.

4 Results

The corona pandemic strongly affected the project work during the reporting period (restricted laboratory access for all partners, a more than 6 months delay in the installation of the PLD tool at UT). Nevertheless, substantial progress was made (also due to adjustments in the schedule of the individual tasks) within all work packages.

it was extensively investigated how the reduction of the ITO layer thickness affects the cell and module performance and cost. For this, SHJ cells were fabricated with varying front-side ITO thickness. To ensure proper anti-reflection conditions, the cells were spray-coated with TiO_x layers afterward screen printing the Ag grid to yield a total (ITO + TiO_x) thickness of ≈75nm using a potentially cost-effective capping process. Electrical test structures were fabricated to understand how the vertical and lateral components of the cell’s series resistance evolve as a function of ITO thickness. Optical simulations were performed to compare the influence of ITO thickness on the front and back side on cell and module level. Finally, cost calculations revealed how the ITO thickness reduction translates into cost savings with and without the application of an additional capping layer on top.
Main outcomes here, in brief, are that due to the fact that a significant contribution of the lateral current transport can take place within the Si absorber itself when the electron contact is located at the front side, the requirement for the front-side-TCO sheet resistance is strongly relaxed. So far, we managed to thin down the ITO from 75 to 21 nm, while maintaining a similar efficiency level. We showcase that only the application of PVD metal (vs. printed Ag) would allow to omit the TCO completely, which would be compatible with the use of alternative metallization approaches, e.g. Cu plating. Regarding the optical performance, it was found that on module level the thickness requirements for the front- and rear side TCO are strongly relaxed compared to cell level. This is due to the encapsulation material and glass, both supporting the light incoupling by an improved refractive index gradient compared to the cell level. More precisely, the ITO thickness on the front side can be reduced by 10-20 nm, while the ITO on the

back side does not provide any optical advantage for bifacial cells, except in the atypical case of a very high albedo (> 0.2 suns). On the front side, TCO layers thinner than ≈50-60 nm require a transparent capping layer with refractive index similar to ITO. While this double layer approach reduces the In consumption, the decisive factor will be the costs for the additional capping layer. As cost calculations showed, the capping with PECVD-SiN_x is economically not necessarily attractive and either lower cost materials / processes should be used here.
Furthermore, for WP2.3, a rotary target with aluminium-doped zinc oxide was ordered serving as an indium-free reference material at ISE. For the "high mobility" process route the specifications for the production of a rotary target with cerium doped indium oxide was discussed and defined with the subcontractor Sindlhauser. For this purpose, Sindlhauser must carry out extensive preliminary work on target production since this is not a commercial product so far. Unfortunately, it has not yet been possible to place the order, as the boundary conditions under public procurement law between Sindlhauser and the ISE have still not been finalized. It is assumed that this target can be installed in an industrial sputtering system at ISE in Q4 2021.

The installation of the PLD tool from Solmates and the development of TCO processes: Because it is a new tool, the first developments were focused on Sn-doped In_2O_3, which is the reference TCO material also at Fraunhofer ISE. This allowed us to compare the performance of our developed PLD ITO processes in terms of materials and device performance with those of the Fraunhofer ISE. Several experiments were planned and performed in collaboration with Fraunhofer ISE, mainly solar cell fabrication and lifetime measurements to determine damage effects from the deposition. The results will be described in the WP2 section. In parallel to ITO, the development of Indium-free TCO, Ta-doped SnO_2, has started as well. Microstructural analysis of cells fabricated at Fraunhofer ISE and with TCO from UT, were furthermore performed at CNRS. Analysis of these data is in progress and will be described for the next reporting period.

The research has also focused on the development of thermally stable n-type and p-type µc-SiOx:H layers combined with a-Si:H and a-SiOx:H passivation stacks. While n-type µc-SiOx:H has been relatively easy to optimize (in particular thanks to *in situ* modulated photoluminescence) with symmetric structures reaching high lifetimes, the optimization of p-type µc-SiOx:H films has been much more challenging. Indeed, the crystalline fraction of the films has been found to rapidly decrease when the oxygen concentration is increased by adding more CO_2 to the SiH_4-H_2-TMB[1] gas mixture used to growth µc-Si:H films. Moreover, the conductivity of the films is rather low in the as-deposited state (~ 10^{-7} S/cm) and requires an annealing step at 250-300 °C to activate boron atoms and achieve a conductivity of 10^{-5} S/cm which is controlled by the amorphous phase of the nanostructured material. Nevertheless, these layers, when incorporated into solar cells, allow to keep a good passivation even after an annealing at 300 °C, which should broaden the process conditions for the TCO layer to be deposited on top.

More details about the individual work packages and its progress can be found in the next section.

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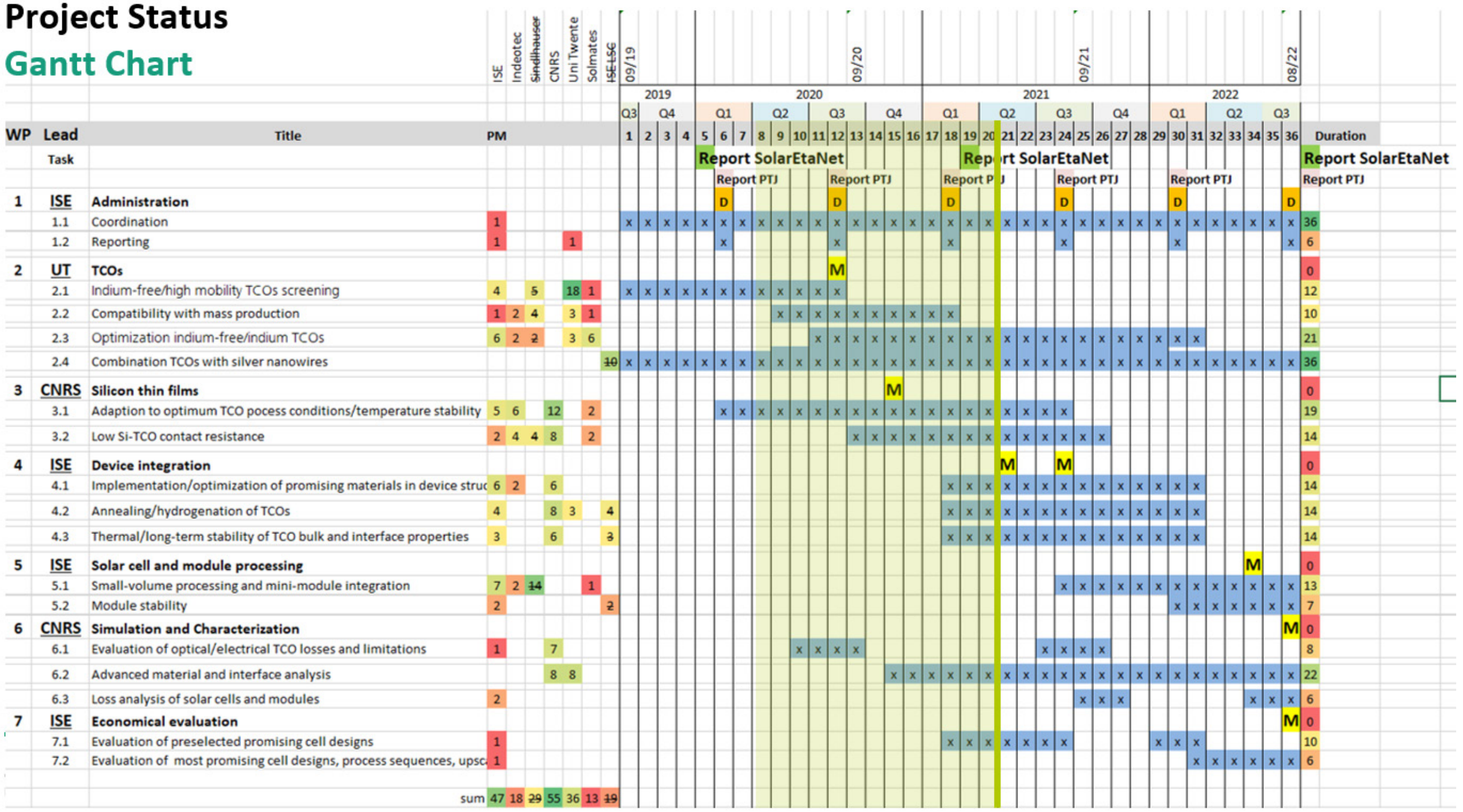
[1] TMB stands for trimethyl-boron

Figure 1 Gantt chart – Project progress between month 8 and 21.



Project Status

Gantt Chart

			ISE	Indeotec	~~Sindlhauser~~	CNRS	Uni Twente	Solmates	~~ISE LSG~~	09/19												09/20												09/21											08/22	
										2019				2020												2021												2022								
										Q3	Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3		
WP	Lead	Title	PM							1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	Duration
	Task													Report SolarEtaNet														Report SolarEtaNet																		Report SolarEtaNet
															Report PTJ						Report PTJ						Report PTJ						Report PTJ						Report PTJ							Report PTJ
1	ISE	**Administration**													D						D						D						D						D						D	
	1.1	Coordination	1							x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	36
	1.2	Reporting	1				1								x						x						x						x						x						x	6
2	UT	**TCOs**																			M																									0
	2.1	Indium-free/high mobility TCOs screening	4		~~5~~		18	1		x	x	x	x	x	x	x	x	x	x	x	x																									12
	2.2	Compatibility with mass production	1	2	~~4~~		3	1										x	x	x	x	x	x	x	x	x	x																			10
	2.3	Optimization indium-free/indium TCOs	6	2	~~2~~		3	6												x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x						21
	2.4	Combination TCOs with silver nanowires							~~10~~	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	36
3	CNRS	**Silicon thin films**																						M																						0
	3.1	Adaption to optimum TCO pocess conditions/temperature stability	5	6		12		2							x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x													19
	3.2	Low Si-TCO contact resistance	2	4	~~4~~	8		2														x	x	x	x	x	x	x	x	x	x	x	x	x	x											14
4	ISE	**Device integration**																												M			M													0
	4.1	Implementation/optimization of promising materials in device struc	6	2		6																					x	x	x	x	x	x	x	x	x	x	x	x	x	x						14
	4.2	Annealing/hydrogenation of TCOs	4			8	3		~~4~~																		x	x	x	x	x	x	x	x	x	x	x	x	x	x						14
	4.3	Thermal/long-term stability of TCO bulk and interface properties	3			6			~~3~~																		x	x	x	x	x	x	x	x	x	x	x	x	x	x						14
5	ISE	**Solar cell and module processing**																																								M			0
	5.1	Small-volume processing and mini-module integration	7	2	~~14~~			1																									x	x	x	x	x	x	x	x	x	x	x	x	x	13
	5.2	Module stability	2						~~2~~																															x	x	x	x	x	x	x	7
6	CNRS	**Simulation and Characterization**																																										M	0
	6.1	Evaluation of optical/electrical TCO losses and limitations	1			7													x	x	x	x									x	x	x	x												8
	6.2	Advanced material and interface analysis				8	8																	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	22
	6.3	Loss analysis of solar cells and modules	2																															x	x	x							x	x	x	6
7	ISE	**Economical evaluation**																																										M	0
	7.1	Evaluation of preselected promising cell designs	1																								x	x	x	x	x	x	x					x	x	x						10
	7.2	Evaluation of most promising cell designs, process sequences, upsc	1																																					x	x	x	x	x	x	6
		sum	47	18	~~29~~	55	36	13	~~19~~																																					

Has there been any changes in the	No	Minor	Substantial	
Consortium composition?		X		
Work progress?		X		
Expenses (vs budget)?		X		

Comments on the changes in the project plan

Due to the bankruptcy of one of its customer in China (for Octopus 3 tool), Indeotec went through a difficult situation in 2021 and had to step down from the project in May 2021 (till the present report).

The Laboratory and Service Center (LSC) Gelsenkirchen has been closed and thus their activities in in the project have stopped. The exit of the original project partner LSC does not represent a risk for the whole project, as its part could be considered as a kind of additional benefit, the core activities should not be affected by this decision.

The order for TCO sputtering targets from the subcontractor Sindlhauser Materials has been delayed because the conditions under public procurement law could not yet be finally clarified between Sindlhauser and ISE. Therefore, the scheduled expenses needed to be postponed.

4.1 WP1 Administration

In-person project meetings with the entire consortium, which were scheduled to occur every 6 months, were not possible during the reporting period due to travel restrictions related to the Corona pandemic. These meetings were then replaced by productive conference calls (May 2020, November 2020, May 2021). In between, constant communication (by phone and mail) of the project partners, mostly bilateral, was continued to ensure close collaboration (joint experiments) and continuous exchange of information and results.

The partner Fraunhofer ISE LSC left the consortium. The final agreement with PTJ was made by LSC.

The request for a cost-neutral extension of the project duration by 6 months was decided at the last project meeting (May 2021).

4.2 WP2 TCOs

The electrical properties of ITO layers thinner than the standard (< 70 nm) were quantified. Here the growth and thus the electro-optical layer properties of TCOs can depend significantly on the substrate type. For this reason, characterization methods for the electrical TCO properties on device-relevant structures were developed. Deposited under the otherwise same conditions, thin ITO layers have a lower resistivity than thick layers due to a higher charge carrier concentration. This can be beneficial for the use of very thin ITO layers with the aim of reducing indium consumption.

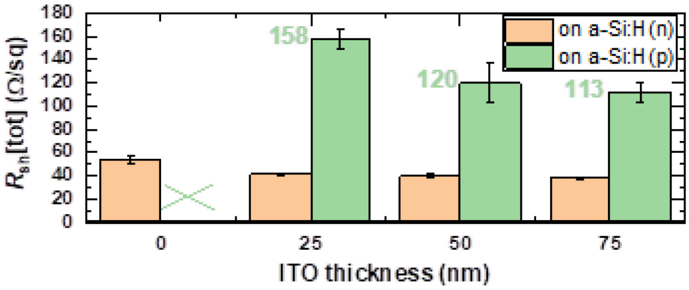


Figure 2: The sheet resistance (R_{sh}) measured for structures ITO films deposited with different thickness on SHJ substrates (textured wafer, a-Si:H(p) / a-Si:H(i) / c-Si(n) / a-Si:H(i) / a-Si:H(n) structure) was addressed via 4 point probe measurement in the Van der Pauw configuration. ITO was deposited on either the a-Si:H(n) or the a-Si:H(p) side. The measured R_{sh} strongly depends on whether the ITO deposited on the a-Si:H(n) side or on the a-Si:H(p) side is contacted. The low-resistance c-Si(n) / a-Si:H(i) / a-Si:H(n) contact leads to an effective parallel connection between ITO and wafer. For an ITO thickness of 0 nm, the R_{sh} of the wafer (~50 Ω/sq) was measured. Then, with increasing ITO thickness, R_{sh} decreased slightly. The R_{sh} values obtained on the a-Si:H(p) side correspond to the ITO layer alone, which is electrically decoupled from the substrate due to the effective electrical barrier of the a-Si:H(p) / a-Si:H(i) / c-Si(n) junction. With reduction of the ITO thickness, the R_{sh} increased only moderately, clearly deviating from a linear relationship between sheet resistance and layer thickness.

UT: Taking advantage of the low damage deposition capabilities of the PLD reactor manufactured by Solmates, different ITO PLD-deposition recipes were developed. The reactor included different modules to reduce the amount of particles in the films and to mitigate deposition damage. Overall, it seems that the most impactful parameters during the deposition to mitigate damage is the working pressure. Based on this assumption, three PLD recipes were developed at three different pressures: the “low” pressure ITO deposition performed at 0,005 mbar, the ”intermediate” pressure ITO deposition performed at 0,02 mbar and the “bilayer” recipe consisting of a very thin ITO layer (about 1-2 nm thick) deposited at much higher pressure, i.e. 0.1 mbar on top of which is another ITO layer deposited according to the low pressure recipe done at 0,005 mbar.

The three deposition processes were independently optimized to reach similar electronic and optical ITO properties in the as-deposited state as close as possible to a sputtered ITO reference (Sheet resistance (Rs) < 100 Ω/sq; Carrier concentration (Ne) about $1{,}5.10^{20}$ cm^{-3} , Hall mobility (µ) > 30 $cm^2(V.s)^{-1}$) optimized to meet the requirements of a front electrode of Silicon Hetero-Junction Solar cells. More specifically the films were optimized to meet comparable sheet resistance (about 60 Ω/sq as deposited) which takes a key role in lateral transport. The PLD deposition parameters were designed to reach about 100 nm thick ITO films (on a planar substrate) for all three recipes while keeping optical absorptance as low as possible (< 10% in the spectral range of interest).

The ITO films were co-deposited on SHJ precursors and pieces of glass following the three recipes, the ITO films properties were measured on the pieces of glass:

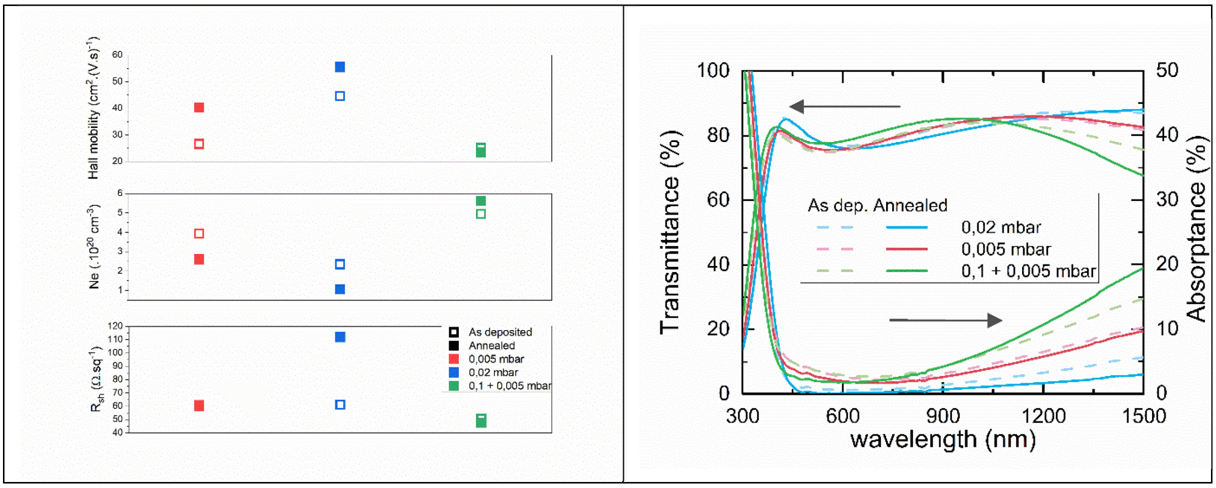


Figure 3: optoelectronic properties of PLD-deposited ITO on flat glass at three different working pressures. Left: Electrical properties before and after annealing process including sheet resistance (R_{sh}); Carrier concentration (Ne), and Hall mobility (µHall). Right: Optical properties of the films before (dashed lines) and after annealing (solid lines)

Figure 3 shows the sheet resistance (R_{sh}) of the three ITO films as deposited and after annealing. The three films are showing similar R_{sh} about 60 Ω/sq as deposited. “0,005 mbar” and “0,1 + 0,005 mbar” ITO also display similar R_{sh} about 60 Ω/sq after annealing but “0,02 mbar” ITO has a higher sheet resistance of 100 Ω/sq. The cause of this difference will be discussed in the next section about structural properties.

Figure 3 shows the carrier concentration increasing with the working pressure from $2{,}5.10^{20}$ cm^{-3} for “0,02 mbar” to 5.10^{20} cm^{-3} for the “0,1 + 0,005 mbar” as deposited. For the “0,02 mbar” and “0,005 mbar” ITO, the carrier concentration drops after annealing to 1.10^{20} and $2{,}25.10^{20}$ cm^{-3} respectively. Note that for the “0,1+0,005 mbar”, carrier concentration increases very slightly after annealing to $5{,}5.E^{20}$ cm^{-3}. Interestingly, the “0,1+0,005 mbar” is displaying the highest carrier concentration of the three samples. The 0,1 mbar buffer layer (sublayer of the “0,1+0,005 mbar” film) is so thin, it actually is difficult to characterize. Clearly the 0,1 mbar buffer layers influences the film properties but so far, the state of the interface between the two sublayers is unknown and so forth how the two sub-layers synergize together remain unclear.

Mobility displayed on figure 3 is about 25 $cm^2(V.s)^{-1}$ for “0,005 mbar” and “0,1+0,005 mbar” ITO and 46 $cm^2(V.s)^{-1}$ for “0,02 mbar” as deposited. After annealing mobility increases to 55 $cm^2(V.s)^{-1}$ for “0,02 mbar” and 41 $cm^2(V.s)^{-1}$ for “0,005 mbar”. Similarly to Ne, the “0,1+0,005 mbar” mobility remain virtually unchanged with a value of 23 $cm^2(V.s)^{-1}$.Here, the “0,005 mbar” and “0,02 mbar” deposited films follow the trend of mobility increase with annealing, but same as for the carrier concentration, the “0,1+0,005 mbar” ITO does not follow the trend. One hypothesis is that the “0,1 mbar” sub-buffer-layer is deposited at so high pressure that it is not as dense as the other films and thus may lead to a lower mobility (rougher/poorly designed grain - interface due to nano porosity making electronic motion more difficult in other words there probably is a higher energetic barrier to overcome ta with an accurately designed film).

The optical properties, absorptance and transmittance of the three ITO films before and after annealing are displayed on the right panel of Figure 3.
All three films present a low absorptance (< 20 %) over the whole spectral range of silicon heterojunction solar cells (300 – 1200 nm). In the UV-Vis range (300 – 400 nm), we also observe a very slight Burstein-

Moss shift with the increasing working deposition pressure in accordance with the carrier density reported.
The optical absorptance of the films in the near-infrared region increase with the carrier density as expected, showing the highest free carrier absorption (FCA) for the bilayer film and the lowest FCA for the films deposited at “0,02 mbar”, for which the absorptance remains below 10% over the whole spectra range.

Quantification of these parameters is clearly showing the relationship between the carrier density and the optical performances. Overall, the intermediate pressure ITO displays better performances: lower absorptance especially in the NIR range because of its lower free carrier absorption thanks to its lower carrier concentration, the film also displays higher mobility (still un-explained) but a higher sheet resistance after annealing. It seems that the “0,02 mbar” ITO lays in some “deposition pressure soft spot”, displaying different but interesting properties.
In order to investigate the causes of for the films properties, structural properties were studied.

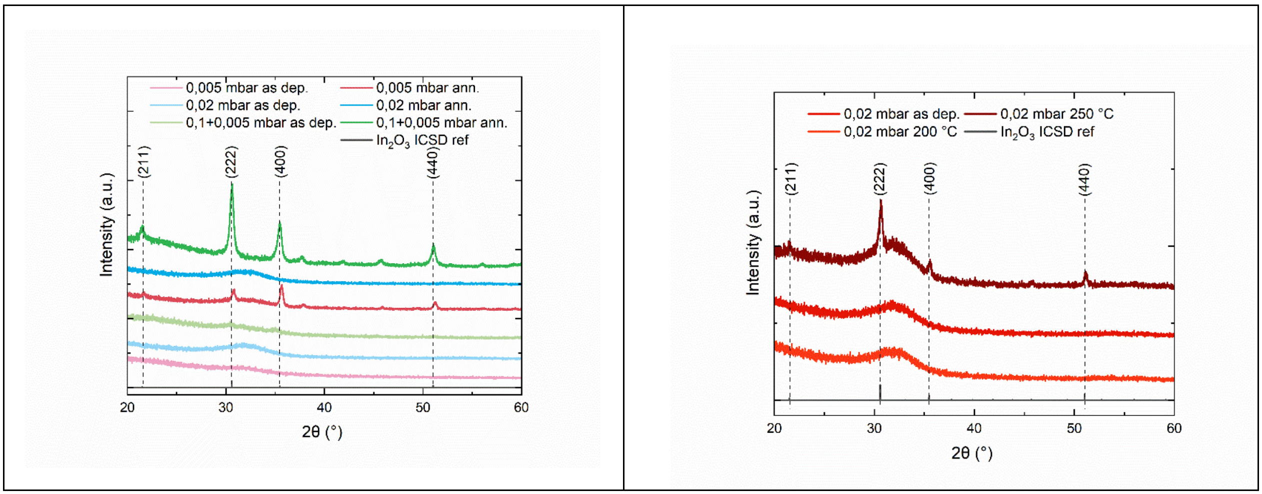


Figure 4: XRD spectra of ITO deposited at three different working pressures on pieces of flat glass before and after annealing at 200 °C. b) ITO spectra deposited at intermediate pressure on pieces of flat glass as deposited, after annealing at 200 °C and after annealing at 250 °C. Data were vertically translated for clarity but relatives intensities of the different spectra were kept unchanged for fair comparison.

Investigation of structural properties of the three ITO before and after annealing were done using Grazing-Incidence XRD. Results are presented on figure 4: before annealing only the classic halo (around 2θ = 33°) from glass is present for all three films, describing the amorphous nature of the as deposited films. After 200 °C annealing, “0,005 mbar” and “0,1 + 0,005 mbar” ITO display (211), (222), (400) and (440) as main reflections corresponding to the In_2O_3 bixbyite reference pattern. The presence of these multi-reflections highlights the polycrystalline nature of the films. Interestingly “0,05 mbar” and “0,1 + 0,005 mbar” ITO show different preferential orientations, (111) and (100) respectively. This may be due to the different deposition working pressures as previously suggested by other studies.

The case of 0,02 mbar ITO is different because after 200 °C, the film still does not show any reflections and remains amorphous. Figure 4 shows the GI-XRD of ITO films annealed at different temperatures, study conducted to investigate the amorphous/polycrystalline transition temperature of this film.

The diffractogram of 0,02 mbar ITO, recorded after 250 °C ex-situ annealing, exhibits the same reflections as the two other polycrystalline ITO. The film follows the (111) preferential orientation, same as the “0,1 + 0,005 mbar” ITO. This highlights the relationship between working deposition pressure, kinetic energy of the landing species during PLD process and the crystallization energy. It seems that high working deposition pressures induce (111) orientation whereas lower pressures give rise to (100) preferential orientations. Note that the orientation of the 0,1 + 0,005 mbar ITO may be induced by the first very thin (1-2 nm) ITO layer deposited at high pressure, e.g., 0,1 mbar.

Interestingly, the ITO with highest mobility is the one that seems amorphous even after annealing, but the effect of microstructure and carrier density on the mobility of the films needs to be further investigated. For the 0.02 and 0.005 mbar deposited films, the amorphous or polycrystalline nature could explain the increase of mobility after deposition.

UT: Indium Free TCO

As detailed in the last project report, development of indium free TCO are based on Ta:SnO_2 compositions. More specifically at this early stage, the starting material composition is 14 weight % Ta_2O_5 in SnO_2, the PLD-depositions and subsequent characterizations have been performed. For these preliminary results, oxygen content in the PLD-deposition atmosphere was investigated.

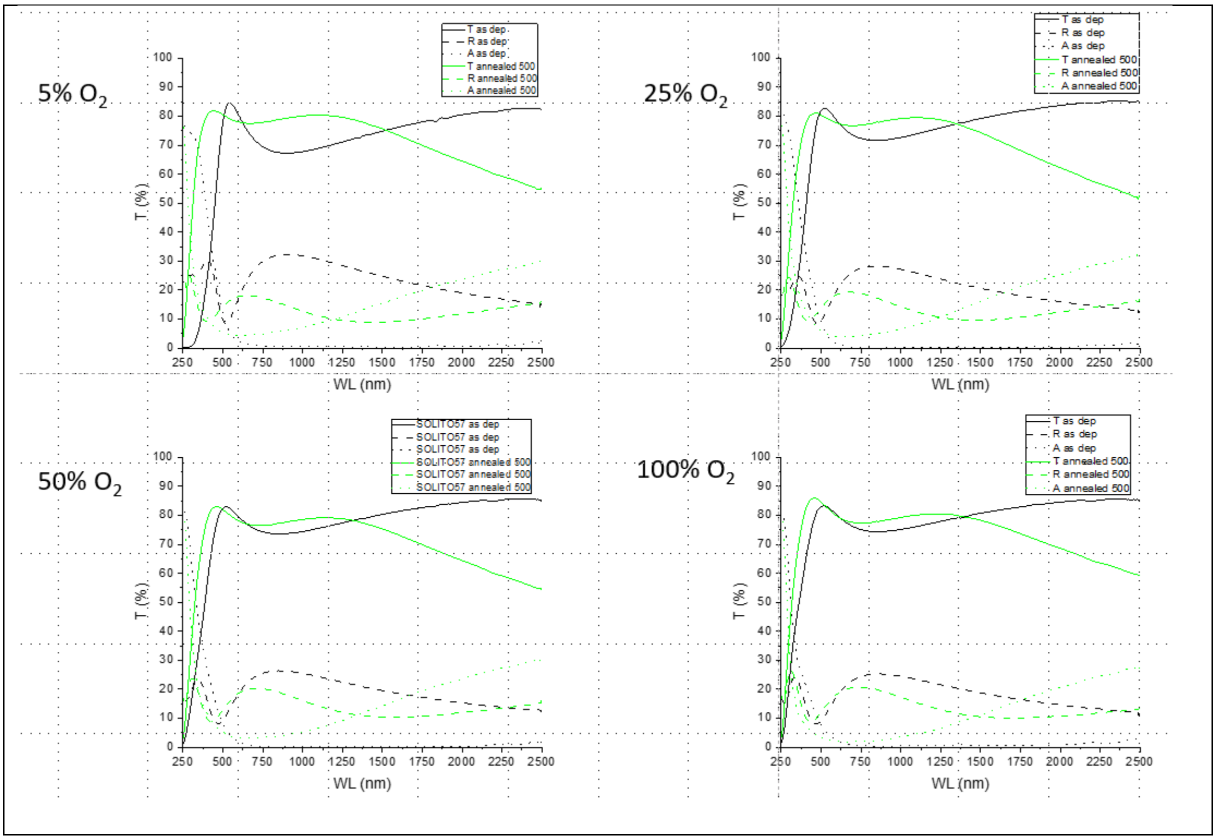


Figure 5: Optical properties of Ta:SnO_2 films, deposited by PLD at 5 / 25 /50 and 100 % O_2/Ar content.

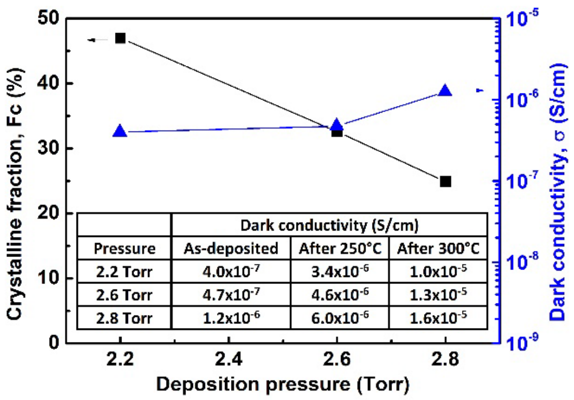
Sample	5% O_2	25% O_2	50% O_2	100% O_2
R_{sh} ($\Omega.sq^{-1}$)	3080	1025	2015	1915
Ne (10^{20} cm^{-3})	1,9	1,8	2,6	0,33
μ ($cm^2.(V.s)^{-1}$)	1,5	6,6	1	10,5

Table 1: Electronic properties of Ta:SnO_2 films, deposited by PLD at 5 / 25 /50 and 100 % O_2/Ar content

These data show that higher oxygen content leads to better films properties. Both in terms of optical properties such as low absorptance and higher electronic conductivity. For the annealing of these films, the annealing atmosphere was changed to 5%H_2/Ar and the temperature was increased to 500 °C. Indeed, films annealed in air were showing poor or no conductivity. In order to increase films properties, usage of TiO_2 anatase as a deposition substrate is considered based on the following paper: High Mobility Exceeding 80 cm2 V-1 s-1 in Polycrystalline Ta-Doped SnO_2 Thin Films on Glass Using Anatase TiO_2 Seed Layers, Shoichiro Nakao *et al* 2010 Appl. Phys. Express 3 031102.
Two other targets of the Ta:SnO2 containing 7 wt.% Ta_2O_5 and 2wt.% Ta_2O_5 are also ready to start material development and determine the optimum dopant concentration. Note that the next steps of the CUSTCO project will focus on Indium free TCO development.

4.3 WP3 Silicon thin films

Microcrystalline silicon oxide thin films are currently being studied by various groups which have implemented them in solar cells. The main advantages of this material is a reduced optical absorption, a better thermal stability and hopefully a high enough conductivity. However, the fine optimization of these materials, in particular when p-type doped, turns out to be very much challenging, with unexpected effects such as an improvement in the conductivity of the films upon annealing at 250 °C and 300 °C (Figure 3), while their crystalline fraction decreases (Figure 4).



	Dark conductivity (S/cm)		
Pressure	As-deposited	After 250°C	After 300°C
2.2 Torr	4.0×10^{-7}	3.4×10^{-6}	1.0×10^{-5}
2.6 Torr	4.7×10^{-7}	4.6×10^{-6}	1.3×10^{-5}
2.8 Torr	1.2×10^{-6}	6.0×10^{-6}	1.6×10^{-5}

Figure 3. Crystalline fraction (Fc) and dark conductivity of as deposited p-type μc-SiOx:H films as a function of deposition pressure. The lines are provided as guides to the eye.

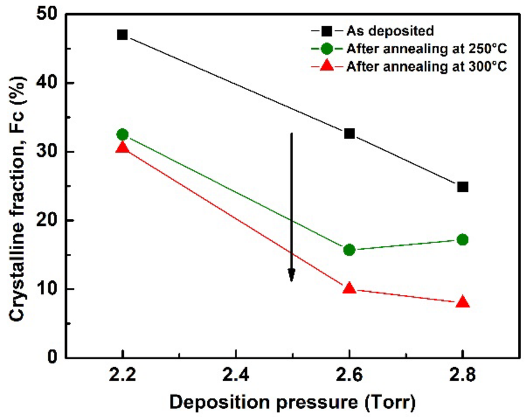


Figure 4. Crystalline fraction (Fc) of p-type μc-SiOx:H films as-deposited (black squares), after annealing at 250° C (green circles) and 300° C (red triangles) for the sample of the deposition pressure series. The lines are provided as guides to the eye.

These results have been presented at the last EUPVSEV conference. The optimized p-type and n-type μc-SiOx:H layers are currently being implemented on solar cells.

4.4 WP4 Device integration

In addition to the electrical bulk properties of the ITO layers (WP2), the contact resistance (ρ_c) of the c-Si / a-Si:H / ITO / metal system, which is decisive for cell integration, was investigated as a function of ITO thickness. With respect to metallization, two methods were compared: screen printing of a silver-containing paste (SP-Ag), which is considered the industry standard, and vapor deposition of a metal layer stack (PVD metal). The results show that the ITO layer not only affects lateral transport and light coupling, but in the case of SP-Ag is also crucial to enable low contact resistance to the a-Si:H layer. It can be concluded that TCO-free SHJ cells are not feasible with conventional screen-printed metallization and can only be realized with PVD metal contacting. This approach, in turn, is compatible with an electroplating-based metallization sequence (industrially scalable), where contacting takes place through PVD metal seed layers. Besides the significant TCO savings, such a metallization approach (Cu plating) also allows the significant reduction of Ag consumption.

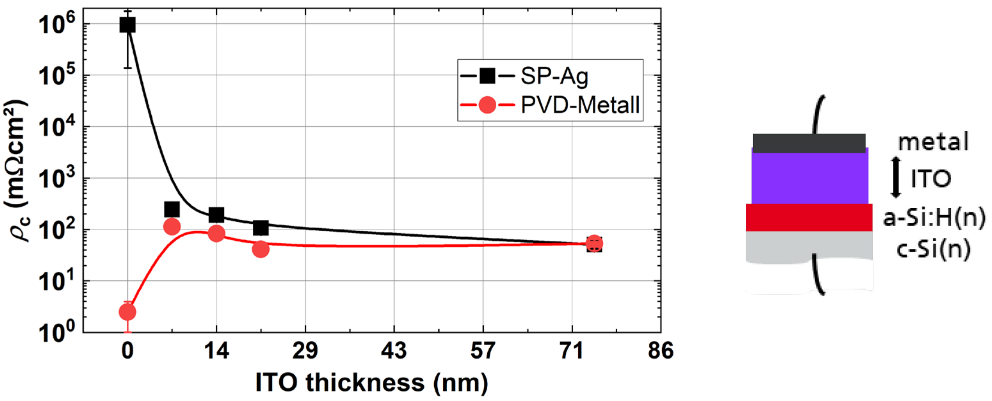


Figure 6: Electrical test structures to determine contact resistance (ρ_c) as a function of ITO layer thickness were fabricated to further understand how the vertical component of series resistance of SHJ cells behaves as a function of (front side) ITO thickness. Two metallization methods were compared. Here, a fundamental difference between metallization via screen-printed silver paste (SP-Ag) and a vapor-deposited metal (titanium, PVD metal) is revealed when the ITO layer is omitted (0 nm ITO, direct metal - a-Si:H(n) contact). While the a-Si:H(n) layer cannot be contacted electrically by SP-Ag, the PVD metal allows very good contact (ρ_c < 5 mΩcm²) without an ITO interlayer. For the conventional ITO layer thickness of 75 nm, both metallization processes are at a very similar ρ_c level (difference less than the resolution limit of the using these test structures). The reason why the contact resistance increases for ITO thicknesses in the range between 21 and 8 nm for thinner ITO (for both metallization methods) is currently still under investigation.

4.5 WP5 Solar cells and modules processing

Complementing the preliminary investigations on the influence of ITO thickness on lateral (R_{sh}) and vertical (ρ_c) current transport, a batch of monofacial SHJ cells (with rear side p/n junction) was prepared at ISE, where the front side ITO thickness was varied between 0 and 75 nm. Here, ITO deposition was performed in an inline sputtering system. To optically compensate for the missing ITO to ensure anti-reflection conditions, a TiO_x capping layer (refractive index very similar to ITO) was deposited after the screen-print metallization using the vacuum-free and scalable spray-coating method. While the efficiency level can be maintained up to an ITO thickness > 20 nm, the series resistance increases significantly for even thinner front-side ITO layers, with a corresponding negative impact on cell fill factor and efficiency. If the front-side ITO layer is omitted entirely, the very high ρ_c at the SP-Ag / a-Si:H(n) interface (see WP4) leads to non-functional solar cells, although lateral current transport would still be provided by the Si wafer.

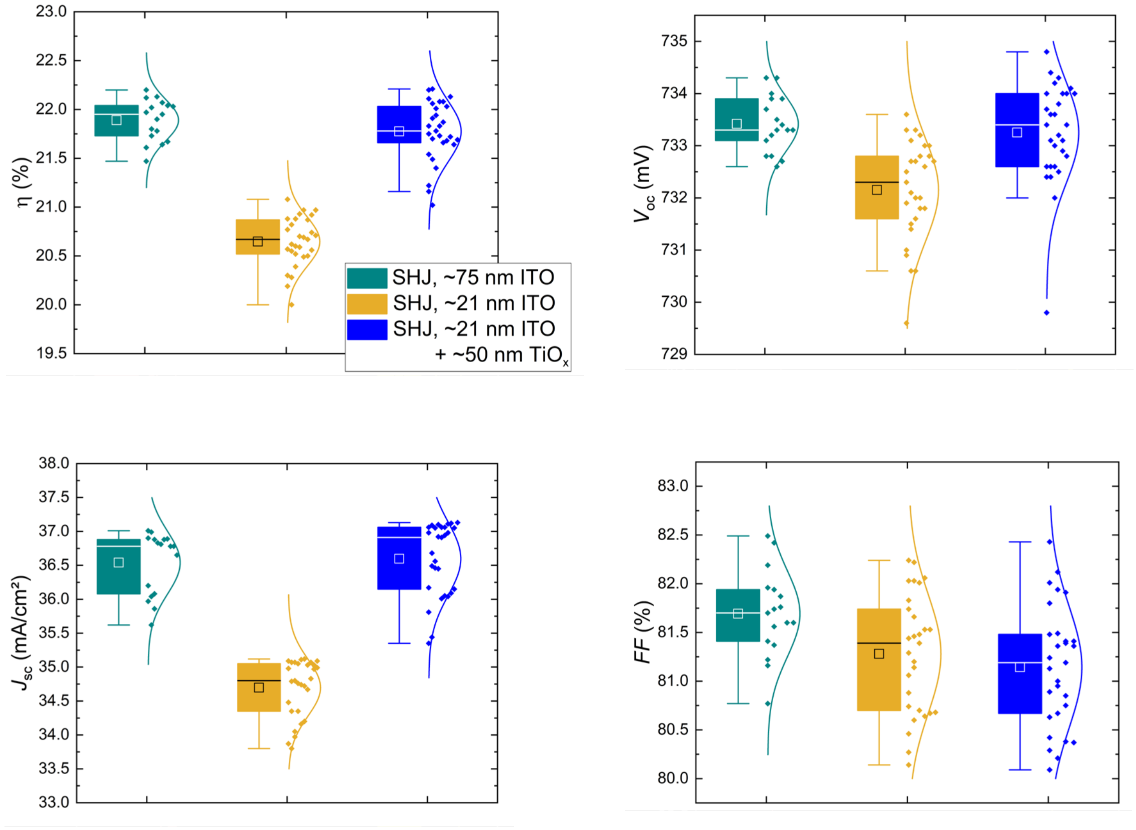


Figure 7: I-V parameters of monofacial SHJ solar cells with p/n junction on the rear side and different design of the front electrode. The short-circuit current (J_{sc}) is lower when the ITO layer thickness on the front side is reduced (36.5 mA/cm² for the standard 75 nm thick ITO layer and 34.7 mA/cm² for 21 nm ITO), due to nonideal antireflection conditions. The fill factor (FF), on the other hand, suffers only moderately from the thickness reduction (81.7% →81.3%). After supplementing the 21 nm thin ITO layer with ~50 nm of sprayed-coated TiO_x, the antireflection properties improve significantly, leading to a J_{sc} (36.6 mA/cm²) even slightly higher than that of the 75 nm ITO single layer. The average efficiency of the cells with 75 nm ITO (21.9 %) is comparable to that of the cells with the ITO / TiO_x double layer (21.8 %).

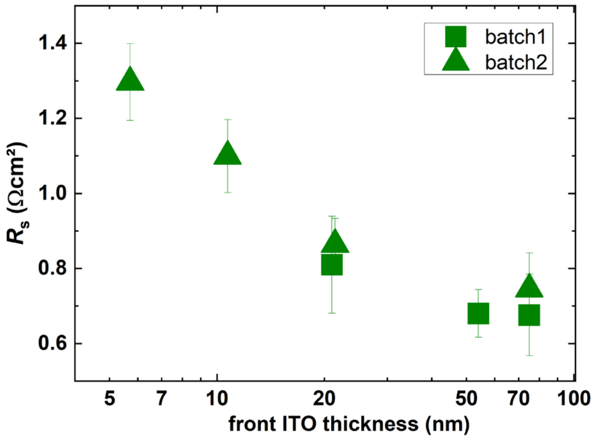


Figure 8: This figure shows the R_s extracted from the I-V curve of the cells partially shown in Figure (batch1). In another experiment (batch2) the ITO thickness on the front side was now further reduced. For front side ITO thicknesses < 20 nm, the R_s increased now noticeably, which accordingly also led to a reduced cell efficiency (not shown). The ρ_c studies (Figure) indicate that in addition to the thickness-dependent ITO sheet resistance, the increased contact resistance also contributes to this R_s increase. Cells where the ITO layer was omitted completely showed no functionality in combination with screen-printed contacts, which can be attributed to the contact barrier between SP-Ag and a-Si:H(n) (WP4).

UT: PLD deposited ITO at the three different pressures described in WP2 were applied as front and back contacts in SHJ solar cells and solar cells performances were evaluated.

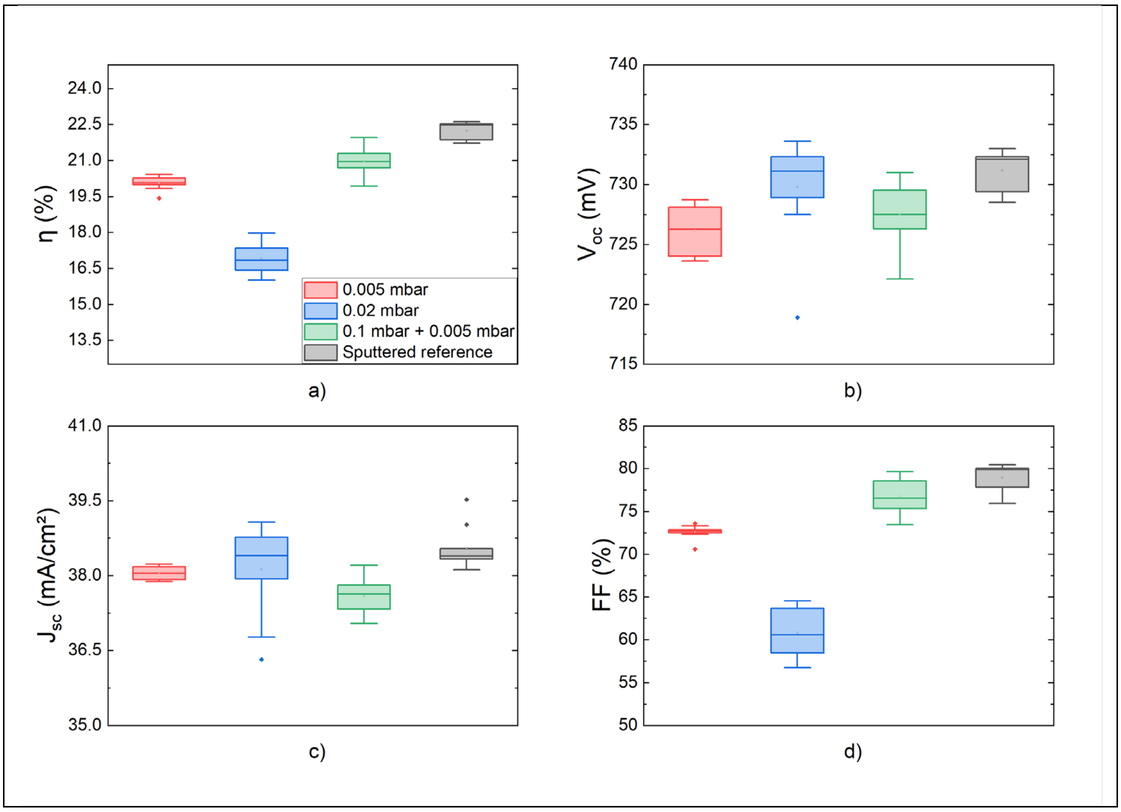


Figure 9: Integration of PLD-grown ITO at three different working pressures as TCO for SHJ solar cells. a) efficiency, b) V_{oc}, c) J_{sc} and d) Fill factor of the batch of cells.

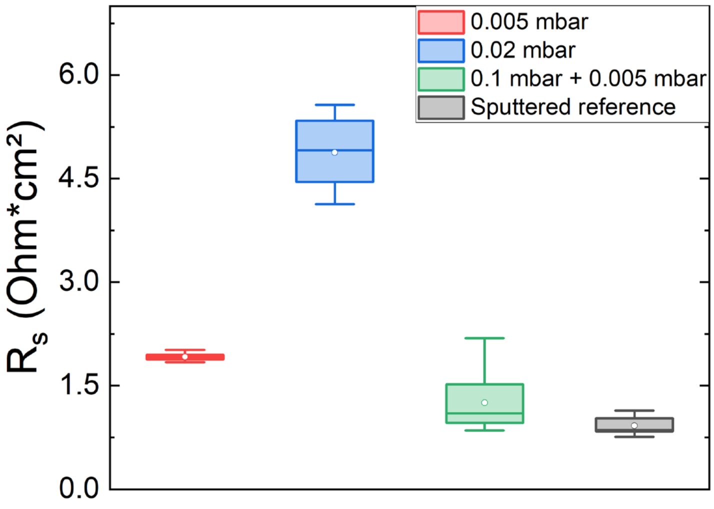


Figure 10: Integration of PLD-made ITO at three different working pressures as TCO for SHJ solar cells: series resistance of the batch of cells

J_{sc} measured on the cells for the three types of ITO follow the overall trend of the ITO films properties measured on pieces of glass: “0,005 mbar” < 0,1 + “0,005 mbar” < “0,02 mbar”. There were no impactful differences among the cells measured in terms of V_{oc}. The series resistance of the cells match the sheet resistance trend observed for the ITO films. Cells with the “0,02 mbar” ITO show the highest series resistance similarly to the “0,02 mbar” ITO films displaying the highest sheet resistance. Sheet resistance of the ITO film may have an impact on the series resistance observed at the cell level. Another hypothesis to explain the high series resistance is the formation of a native SiO_2 very thin layer at the TCO/a-Si:H interface. Indeed, the higher pressure (therefore higher oxygen content- stoichiometry wise) used for this “0,02 mbar” deposition may lead to the formation of a very thin native oxide layer. Moreover, the lower kinetic energy of the ions in the plasma (also linked to the higher pressure e.g. 0,02 mbar) may not be high enough to punch through that native oxide layer if that layer is present (compared to the higher kinetic energy of the “0,005 mbar” and “0,1 + 0,005 mbar” deposition processes that may be high enough to punch through). TEM and EDX with partner CNRS, and ToF-SIMS investigations are ongoing to unravel the possible presence of the native oxide layer and the status of the TCO/a-Si:H interface. As a result, the efficiencies reported for these cells follow the series resistance trend. The higher series resistance of the cells containing “0,02 mbar” ITO leads to about 19,3% efficiency compared to about 20,6% for the cells containing the two other kinds of ITO. These parameters were also compared with the ITO-SHJ baseline from Fraunhofer ISE reporting about 22% efficiency.

High efficiency SHJ with thinner TCO:

In this section we show a proof of the performances that can be reached with a thinner ITO. To meet the best anti-reflective coating (ARC) conditions, the ITO layer shall be around 75 nm on textured wafers. Following the same cell structure as previously described, and only for the cells made with 0,1 + 0,005 mbar ITO, cells with thinner front electrode (ITO) were manufactured. On top of these cells, the ITO layer was compensated with Spay-casted TiO_x to meet the ARC conditions. The cells were characterized, and a drop of series resistance was observed, probably due to the main thermal processes. In addition to this, a significant gain in generated current (about 1 mA/cm^2) is observed.

Figure 11 shows the efficiency of the cells before and after TiOx compensation, accounting for an overall 0.7 % improvement.

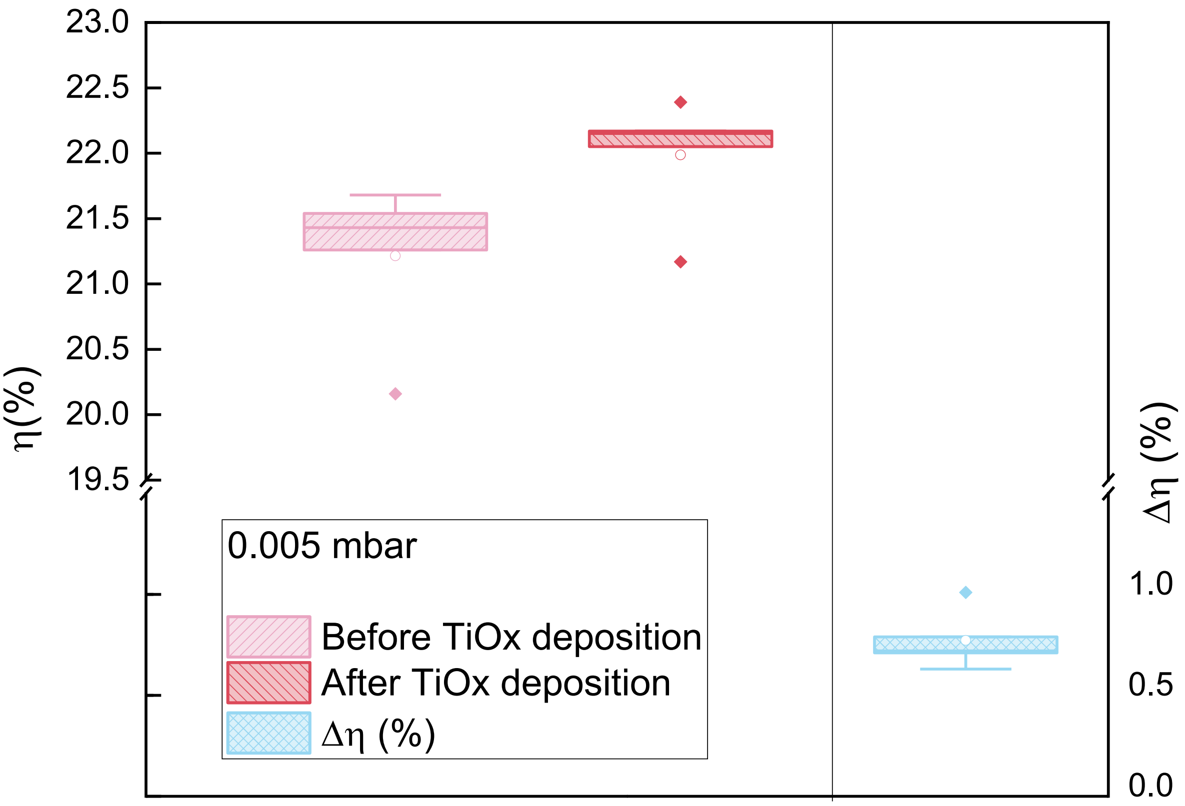


Figure 11: Efficiencies of SHJ cells with ITO (0,1 + 0,005 mbar) before and after TiO_x compensation

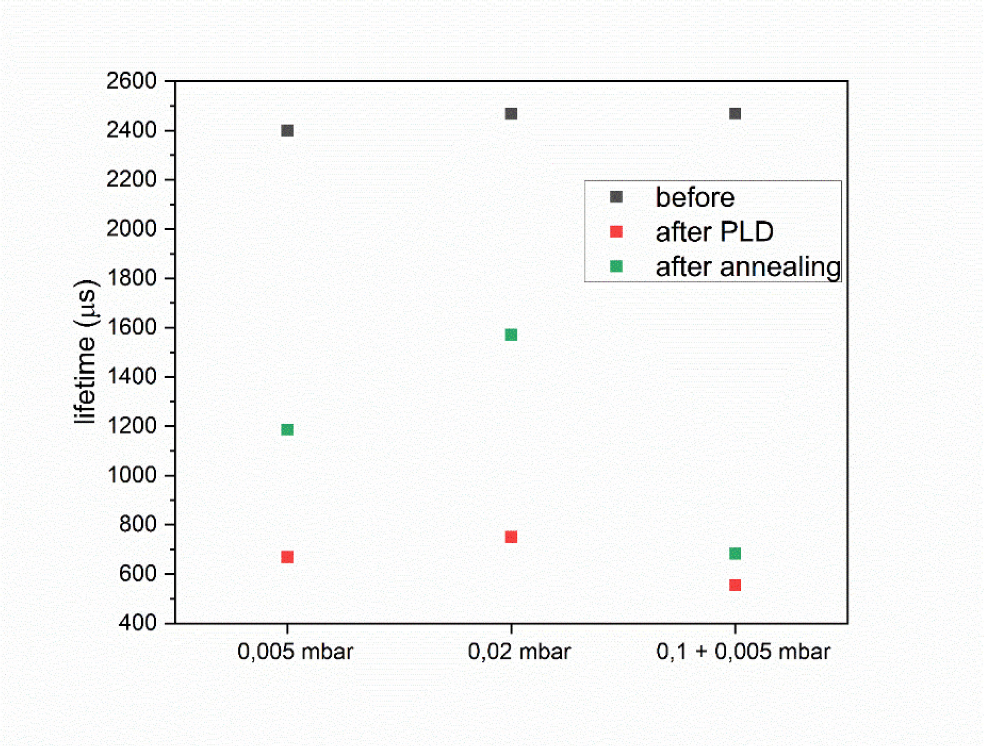


Figure 12: Integration of PLD-made ITO at three different working pressures as TCO for SHJ solar cells: carrier lifetime measured before PLD ITO deposition processes, after PLD depositions processes and after annealing process of the whole cells.

As previously mentioned, working deposition pressure is a possible way to mitigate deposition damage and improve the cells performances. In order to measure the impact of the TCO deposition on the charge carrier lifetime, carrier lifetime was measured at three stages of the precursor fabrication. At first on the cells precursor without TCO, after the PLD ITO depositions following the three pressure recipes and lastly after thermal treatment of the whole stack. The carrier lifetime drastically drops after the ITO depositions for all three deposition pressures, note the drop is about the same for all three samples (from about 2450 µs to about 600 µs). After annealing there is a partial recovery of the lifetime for the 0,005 and 0,02 mbar deposited ITO, but no recovery for the bilayer. Further investigations are ongoing to understand these observations, including a second set of samples, to discard other effects such as transport and sample manipulation.

4.6 WP6 Simulation and Characterization

In the starting report, electrical simulations addressing the resistive losses as a function of contact resistance and sheet resistance of the front TCO were shown.
Now, using optical simulations, the influence of the TCO thickness on the front and back side of the cell on the light management at cell and module level was investigated. The results show that the TCO thickness requirements at the module level are strongly relaxed compared to the cell level. This can be attributed to the encapsulation of the cell by the EVA/glass combination, which supports light incoupling by a more gradual refractive index gradient compared to the cell level. More specifically, the TCO thickness on the front side can be reduced by 10-20 nm without increasing the optical losses. Moreover, the simulations show that from an optical point of view, the TCO layer on the rear side of bifacial cells may even be arbitrarily thin, except in the atypical case of very high rear side illumination (albedo > 0.2 x

front side illumination). On the front side, TCO layers thinner than ≈ 50-60 nm require a transparent capping layer with a refractive index spectrum similar to that of the TCO to minimize reflection losses (antireflection condition).

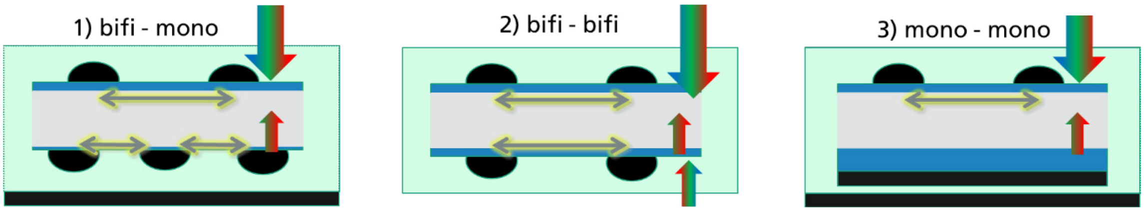


Figure 3: The intrinsic bifaciality of the SHJ technology allows the fabrication of both bifacial (1 and 2) or monofacial cells (3). For monofacial cells the rear TCO serves as an optical spacer to prevent surface plasmon absorption in the rear metal. For this purpose, layers of considerable thickness (> 100 nm) are used ideally. However, since no lateral conductivity is required and the TCO is completely covered by the metal, indium-free materials are well suited here, which are otherwise often avoided due to lower electron mobility or stability issues.

Bifacial cells can be integrated in monofacial (1) or bifacial modules (2), with the latter being advantageous when a significant illumination entering from the rear side of the module (e.g. large albedo) is expected. In both cases the local metal contacts require lateral conduction in the wafer/rear TCO system. In Figure 4 it is shown how the light management behaves as a function of front and back TCO thickness for the two different module designs (1) and (2).

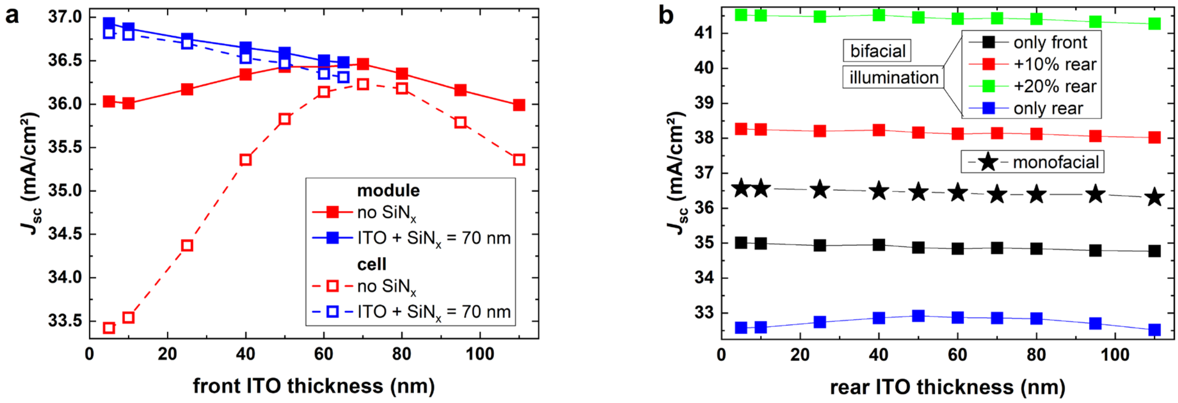


Figure 4: To investigate in more detail how the TCO thickness on the front (a) and rear side (b) affects the light management at the cell and module level (expressed by the J_{sc}), optical simulations were performed using SunSolve from PV Lighthouse. For the fs-ITO of a bare cell, a pronounced thickness optimum around 70 nm is obtained, which minimizes the reflection losses in case of the direct air / TCO interface. However, the insertion of the encapsulating EVA and the glass leads to a more gradual increase in refractive index ($n_{air} < n_{glass} < n_{EVA} < n_{ITO}$), improving the overall anti-reflection conditions and significantly broadening the J_{sc} trend around the ITO thickness optimum. Hence, on module level, a fs-ITO thickness reduction of 10-20 nm is easily acceptable (ΔJ_{sc} (70 → 50 nm) = 0.03 mA/cm²). For further reduction, a capping layer of suitable refractive index is required to compensate for the lack of thickness. Here SiN_x was used, since $n_{SiNx} \approx n_{ITO}$. Being more transparent than ITO (for the simulations already a relatively transparent ITO layer was used with moderate doping density of $1\text{x}10^{20}$ cm^{-3}), the bilayer approach increases J_{sc} on cell and on module level.

Regarding the rear TCO of bifacial cells, a distinction must be made between monofacial and bifacial module designs. For monofacial modules, the good rear reflection due to the rear EVA / backsheet combination renders the rear TCO unnecessary regarding optical performance. The parasitic absorption of the near-infrared (NIR) light in the rear-side ITO then gradually decreases for thinner layers, which increases J_{sc} (black stars (b)). Similar results are obtained for bifacial modules with front-incident illumination (black squares) with efficient NIR rear-reflection at the rear EVA / glass / air stack. For illumination from the rear side, a flat ITO thickness optimum around 60 nm is again observed (blue squares), which is due to the anti-reflection properties. However, this has little impact for the combination of front- and rear illumination at the albedo fractions typically present below 20%. In summary, at the rear side, the TCO is not needed for optical reasons and the required thickness can be optimized exclusively for electrical transport.

4.7 WP7 Economical evaluation

Cost of ownership calculations were performed to quantify the cost benefit for reducing ITO thickness. While significant savings can be achieved here, the process for any required capping layer should be thoroughly selected to benefit from the reduced indium-consumption. Here, capping with PECVD-SiN_x may not be economically attractive and lower cost materials/processes should be used, such as has been done experimentally with spray-coated TiO_x.

Current work is focused on evaluating the process route using indium-free TCOs (e.g. AZO). Preliminary results show that there is a clear cost advantage at the cell level when ITO is replaced by AZO. However, it is expected that the stability issues of AZO can lead to higher module costs compared to ITO.

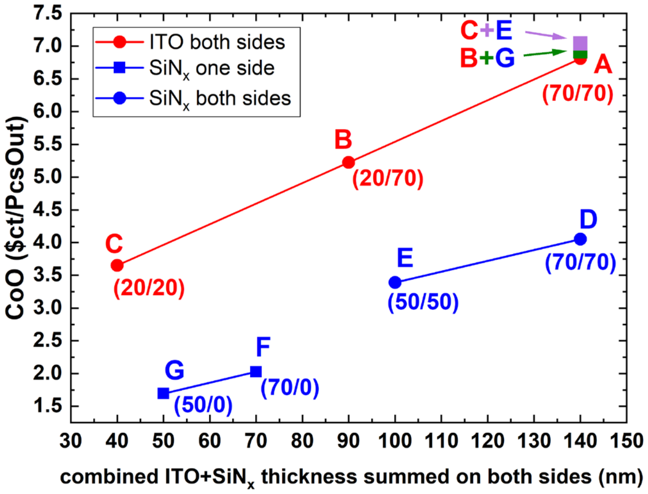


Figure 5: Cost of ownership (CoO) calculations were performed for the process steps of the ITO sputter-deposition (red line), the PECVD-SiN_x (blue lines) and the combination of both (violet and greed dots), as a function of the applied layer thicknesses on front and rear side. The cost analysis was performed using the SCost modelling approach, which is aligned with the SEMI standards E35 and E10. The cost model input parameters are based on latest data provided by industrial manufacturing equipment suppliers. For ITO, inline coating can typically be performed for both sides within the same sputter tool. Since this is not the standard for PECVD-SiN_x (e.g. in PERC production lines), an additional tool is assumed for each cell side coated with SiN_x. Compared to the standard with 70 nm ITO on both sides (A: 6.81 \$ct/wafer) significant cost savings can be achieved by reducing the ITO thickness to 20 nm on one side (B: 5.22 \$ct/wafer) or on both sides (C: 3.65 \$ct/wafer). However, if 50 nm of SiN_x (G: 1.69 \$ct/coating) is added to compensate for the optical thickness, the additional cost of the PECVD system cancels out the savings in indium consumption.

5 Discussion of results

it was extensively investigated how the reduction of the ITO layer thickness affects the cell and module performance and cost. For this, SHJ cells were fabricated with varying front-side ITO thickness. To ensure proper anti-reflection conditions, the cells were spray-coated with TiO_x layers afterward screen printing the Ag grid to yield a total (ITO + TiO_x) thickness of ≈75nm using a potentially cost-effective capping process. Electrical test structures were fabricated to understand how the vertical and lateral components of the cell's series resistance evolve as a function of ITO thickness. Optical simulations were performed to compare the influence of ITO thickness on the front and back side on cell and module level. Finally, cost calculations revealed how the ITO thickness reduction translates into cost savings with and without the application of an additional capping layer on top.

Main outcomes here, in brief, are that due to the fact that a significant contribution of the lateral current transport can take place within the Si absorber itself when the electron contact is located at the front side, the requirement for the front-side-TCO sheet resistance is strongly relaxed. So far, we managed to thin down the ITO from 75 to 21 nm, while maintaining a similar efficiency level. We showcase that only the application of PVD metal (vs. printed Ag) would allow to omit the TCO completely, which would be compatible with the use of alternative metallization approaches, e.g. Cu plating. Regarding the optical performance, it was found that on module level the thickness requirements for the front- and rear side TCO are strongly relaxed compared to cell level. This is due to the encapsulation material and glass, both supporting the light incoupling by an improved refractive index gradient compared to the cell level. More precisely, the ITO thickness on the front side can be reduced by 10-20 nm, while the ITO on the back side does not provide any optical advantage for bifacial cells, except in the atypical case of a very high albedo (> 0.2 suns). On the front side, TCO layers thinner than ≈50-60 nm require a transparent capping layer with refractive index similar to ITO. While this double layer approach reduces the In consumption, the decisive factor will be the costs for the additional capping layer. As cost calculations showed, the capping with PECVD-SiN_x is economically not necessarily attractive and either lower cost materials / processes should be used here.

Furthermore, for WP2.3, a rotary target with aluminium-doped zinc oxide was ordered serving as an indium-free reference material at ISE. For the "high mobility" process route the specifications for the production of a rotary target with cerium doped indium oxide was discussed and defined with the subcontractor Sindlhauser. For this purpose, Sindlhauser must carry out extensive preliminary work on target production since this is not a commercial product so far. Unfortunately, it has not yet been possible to place the order, as the boundary conditions under public procurement law between Sindlhauser and the ISE have still not been finalized. It is assumed that this target can be installed in an industrial sputtering system at ISE in Q4 2021.

The installation of the PLD tool from Solmates and the development of TCO processes: Because it is a new tool, the first developments were focused on Sn-doped In_2O_3, which is the reference TCO material also at Fraunhofer ISE. This allowed us to compare the performance of our developed PLD ITO processes in terms of materials and device performance with those of the Fraunhofer ISE. Several experiments were planned and performed in collaboration with Fraunhofer ISE, mainly solar cell fabrication and lifetime measurements to determine damage effects from the deposition. The results will be described in the WP2 section. In parallel to ITO, the development of Indium-free TCO, Ta-doped SnO_2, has started as well. Microstructural analysis of cells fabricated at Fraunhofer ISE and with TCO from UT, were furthermore performed at CNRS. Analysis of these data is in progress and will be described for the next reporting period.

The research has also focused on the development of thermally stable n-type and p-type µc-SiOx:H layers combined with a-Si:H and a-SiOx:H passivation stacks. While n-type µc-SiOx:H has been relatively easy to optimize (in particular thanks to *in situ* modulated photoluminescence) with symmetric structures reaching high lifetimes, the optimization of p-type µc-SiOx:H films has been much more challenging. Indeed, the crystalline fraction of the films has been found to rapidly decrease when the oxygen concentration is increased by adding more CO_2 to the SiH_4-H_2-TMB[2] gas mixture used to growth µc-Si:H films. Moreover, the conductivity of the films is rather low in the as-deposited state (~ 10^{-7} S/cm) and requires an annealing step at 250-300 °C to activate boron atoms and achieve a conductivity of 10^{-5} S/cm which is controlled by the amorphous phase of the nanostructured material. Nevertheless, these layers, when incorporated into solar cells, allow to keep a good passivation even after an annealing at 300 °C, which should broaden the process conditions for the TCO layer to be deposited on top.

6 Conclusions and outlook

Meaningful demonstration of a cost efficient, up-scalable and stable TCO for highly efficient (>24%) silicon solar cell will show the potential for the industrialization of the next generation silicon solar cell concepts and how this can be leveraged by TCO improvements, along with optimization of the silicon contacts and module integration. The results of this project will enable the European industry partners to increase their participation in expected future investments in this market, to maintain their leading position and preserve technological leadership.

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[2] TMB stands for trimethyl-boron

7 Publications [within the project]

List of peer reviewed articles, books, book chapters etc. published with or submitted to academic publishers

Type (article, report, book, compendium, journal)	Author(s) *Name(s)*	Title	Published in (*Name of publication medium)*	Page no.	ISSN/ ISBN	Issued/ volume/ year
journal	*L. Tutsch, H. Sai, T. Matsui, M. Bivour, M. Hermle, T. Koida*	*The sputter deposition of broadband transparent and highly conductive cerium and hydrogen co‐doped indium oxide and its transfer to silicon heterojunction solar cells*	*Prog Photovolt Res Appl.*	*1-11*	*n.a.*	*https://doi.org/10.1002/pip.3388* *(2021)*
journal	*C. Luderer, L. Tutsch, C. Messmer, M. Hermle and M. Bivour*	*Influence of TCO and a-Si:H Doping on SHJ Contact Resistivity*	*IEEE Journal of Photovoltaics*	*329-336*	*n.a.*	*vol. 11, no. 2 (2021)*
Article	*Y.Smirnov, L.Schmengler, R.Kuik, P-A.Repecaud, M.Najafi, D.Zhang, M.Theelen, E.Aydin, S.Veenstra, S.De Wolf, M.Morales-Masis*	*Scalable Pulsed Laser Deposition of Transparent Rear Electrode for Perovskite Solar Cells*	*Advanced Materials technologies*	*Open-acces 2000856, 9 pages*	*n.a.*	*Volume 6, Issue 2, February 2021*
Article	*Y.Smirnov, P-A.Repecaud, L.Tutsch, M.Bivour, M.Morales-Masis*	*The critical role of TCO deposition pressure on series resistance, fill factor and final solar cell performance*	*In preparation*			*In preparation*

List of non-peer reviewed publications (reports, briefs, books, articles targeting policy-makers, industry or other end users)

Type (report, brief, book, article etc.)	Author(s)	Year / publication	Title
Choose type	*Name of author*	*Year of publication*	*Title of publication*
Oral presentation at 37th EUPVSEC 2020	*L. Tutsch, T. Koida, H. Sai, M. Bivour, M. Hermle and T. Matsui*	*2020*	*The Sputter Deposition of Low Resistive and Broadband Transparent Cerium and Hydrogen Co-Doped Indium Oxide and Its Transfer to Silicon Heterojunction Solar Cells*
Poster presentation at 1st International Tandem PV workshop	*Y. Smirnov, P-A Repecaud, M Morales-Masis*	*2021*	*Pulse Laser Deposition of Transparent Rear Electrode for Buffer Layer Free Perovskite Solar Cells*
Solliance Day 2021 (invited)	*Y. Smirnov, P-A Repecaud, M Morales-Masis*	*2021*	*Physical Vapor Deposition of Halide Perovskites and Transparent Contacts for Solar Cells*
EMRS fall 2021 (invited)	*Y. Smirnov, P-A Repecaud, M Morales-Masis*	*2021*	*Transparent Contact Materials for Solar Cells: Interfaces and Device Performance.*
MRS Fall 2021 (invited)	*Y. Smirnov, P-A Repecaud, M Morales-Masis*	*2021*	*The critical role of TCO deposition in solar cell performance*
Oral presentation at 38th EUPVSEC 2021	*Antonio J. Olivares, Gurleen Kaur, Mateusz Poplawski, Anatole Desthieux and Pere Roca i Cabarrocas*	*2021*	*Optimization of the conductivity and crystalline fraction of p-type μc-SiO_x:H films for silicon heterojunction solar cells*

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