Cofund 2

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

"CUSTCO"

Public Report

- The contribution from the partners in NL (UT, Solmates, now LAM Reasech) in this project was carried out with a **subsidy from the Ministerie voor Economische Zaken en Klimaat, Regeling nationale EZ-subsidies, subsidy scheme Top Sector Energie implemented by Rijksdienst voor Ondernemend Nederland**

- it is a SOLAR-ERA-NET energy project (ERA-NET energiecall)

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General Project Information

Project acronym: CUSTCO
Project title: "Cost efficient, upscalable and stable transparent conductive oxides for silicon solar cells based on passivated contacts."
Project number: SOLAR-ERA.NET Cofund 2 N° 060
Project website:

Start date of the project: 01.09.2019
End date of the project: 28.02.2023

Final Report
Report date: *31.03.2023*

Total project costs (EUR): 2.859.300
Requested funding budget (EUR): 1.974.300

Consortium Partners:

Short name of organisation	Fraunhofer ISE
Full name of organisation	Fraunhofer Institute for Solar Energy Systems
Department of organisation	Advanced Development of High-Efficiency Silicon Solar Cells
Type of organisation	Public research organisation
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Consortium Partner 2 contact details

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Department of organisation	Mesa + Institute for Nanotechnology
Type of organisation	Public research organisation
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Department of organisation	LPICM
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Observer

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Type of organisation	SME
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Publishable Project Summary

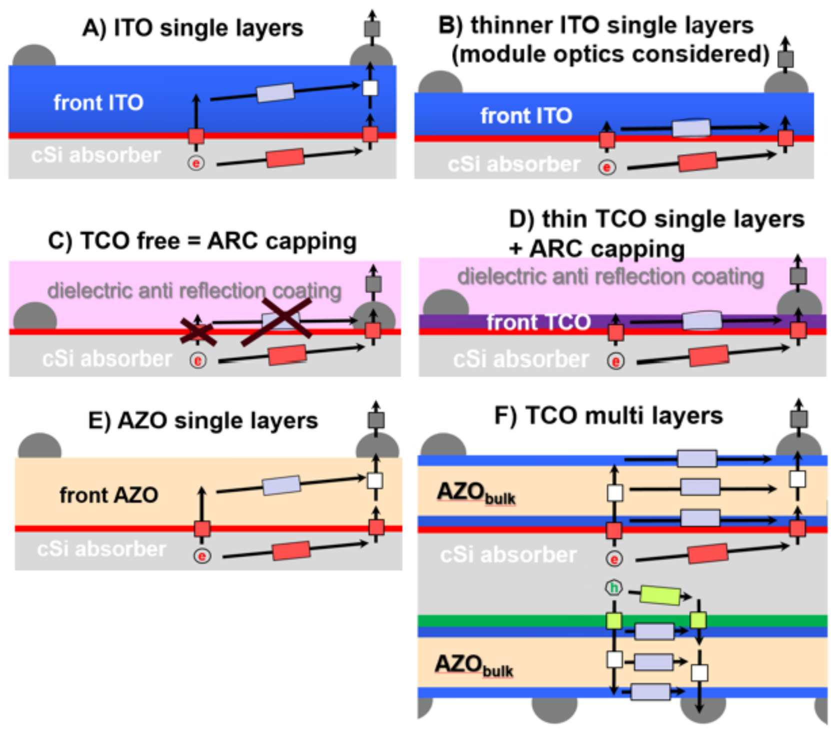
This project aimed to develop industrially feasible transparent and conductive oxides (TCOs) to lower the cost and market entry barriers for high-efficiency silicon solar cells with "Passivating Contacts".
For the emerging solar cell technology of "Passivating Contacts" and especially for Silicon Heterojunction (SHJ) solar cells, Tin Doped Indium Oxide (ITO) is the current standard TCO material. For the expected very high production volumes (multi GW range), the indium demand of the TCO electrodes will be a roadblock for the upscaling of this technology due to the limited indium supply, the lack of options for end-of-life recycling from the solar module, price fluctuations and the competition with other applications. This challenge is shared with other established and upcoming (thin film) solar cell technologies aiming for high volume production.

To tackles this challenge different strategies have been addressed in the framework of this project, targeting the device structures shown in Figure 1.
Some highlights are
#Structure C): Proof-of-principle for SHJ cells with TCO-free front side → **100% Indium reduction**
We evaluated processes routes with respect to their potential for upscaling and gained understanding how to efficiently utilize the lateral charge carrier transport provided by the Si absorber. While the absorber is the only lateral conductive layer in such a TCO-less device architecture, unlike other absorber materials used in thin film devices, the Si absorber can provide similar low sheet resistance as the typically additionally applied TCO films (e.g. structure A)). Ensuring a very low contact resistance at the direct contact between metal and doped silicon thin film for using an industrial metallization scheme was identified as one important building block to fully utilize the lateral transport provide by the Si absorber.

#Structure D): Thin ITO films combined with non-vacuum based dielectric capping layer → **70% indium reduction**
In this configuration a thin TCO remains which can be beneficial with respect to good contact between metal and the doped silicon thin film and lateral transport. However, the need of having a second thin film layer deposited on top of the finished solar cell at the end of the cell process adds complexity, e.g. with respect to the process flow which needs to be considered for the techno-economical evaluation of such an approach. We showed that used of spray coated TiOx could be an interesting alternative to the established vacuum based deposition of dielectrics.

#Structure F): While further research is needed for the aforementioned approaches towards higher TRL, we successfully establish TCO multilayers as an effective means to balance the trade-off between indium-lean devices and process complexity and resulting techno-economical aspects. For sandwich structures using an indium-free TCO bulk layer (AZO) with thin ITO layers at the interface we managed → **75% indium reduction**
We gained a thorough understanding on the role of each layer, e.g. that for a zinc oxide (ZnO) based TCO bulk layer an ITO capping is vital for (chemical) long term stability and that further research is needed for the explored tin oxide (SnO) based indium-free TCOs and more disruptive material alternatives.

#Structure B): We also highlighted that a straightforward approach, actually the first step that should take towards indium reduction, is to focus optimization on the final use case of the solar cell, the solar module. Mainly due to relaxed requirements on the anti-reflection properties if the TCO, depending on the targeted module design this opens up some design freedom to thin down the front and rear side TCO (ITO) layers.
→ ~**25% indium reduction at the front**
→ >>**25% indium reduction at the rear**

	Figure 1: Schematic representation of the approaches for indium reduction pursued in the project. For simplicity only the front side is shown. Red layer: ETL at front side of SHJ cell. Possible carrier transport path is indicated.

Dissemination and Communication Activities

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, Pere Roca I Cabarrocas, M.Bivour, M.Morales-Masis*	*Wafer-scale pulsed laser deposition of ITO for solar cells: reduced damage vs. interfacial resistance*	*Materials Advances*	*Open access Pages: 3469-3478*	*na*	*Volume 3, Feb 2022*
Article	*Y. Smirnov P-A. Repecaud M. Morales-Masis*	*Three-dimensional in situ imaging of single-grain growth in polycrystalline In2O3:Zr films*	*Communication Materials*	*Open access*	*Na*	*3:38 ,Feb 2022*
Article	*P-A. Repecaud*	*Correlated Metals Transparent Conductors with High UV to Visible*	*Advanced Materials Interfaces*	*Open acces s,*	*na*	*Volume10, Issue1 Oct. 2022*

	M. Morales-Masis	*Transparency on Amorphous Substrates*		*Page 2201 335*		

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 Hydro-gen 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*	*Pulsed 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*
10th Metallization and Interconnection Workshop 2021	*Martin Bivour, et al.*	*2021*	*Challenges and Perspectives for the TCO and Metal Electrodes in Perovskite-Silicon Tandem Solar Cells: Performance and Scalability*
Poster presentation at WCPEC-8 2022	*Antonio J. Olivares and Pere Roca i Cabarrocas*	*2022*	*Influence of the Growth Temperature and RF Power in p-Type nc-SiOx:H Films on the Performance of Silicon Heterojunction (SHJ) Solar Cells*
TCM-TOEO 2022 (invited)	*Martin Bivour, et al.*	*2022*	*Metal Oxides for Silicon and Perovskite Solar Cells: Material Requirements and Sustainability*

			Aspects for Large Scale Deployment of TCOs
TCM-TOEO 2022 (invited)	*M. Morales-Masis*	*2022*	*Transparent Electrodes for high efficiency Solar cells*
MRS Fall 2022 (invited)	*M. Morales-Masis*	*2022*	*Physical Vapor Deposition of Transparent Electrodes for Solar cells*
Oral presentation at WCPEC-8 2022	Martin Bivour et al.	*2022*	*Indium Reduction by 75% Using TCO Multilayers:* *An Industry Ready Approach for Indium Lean SHJ Cell?*

List of other dissemination activities (media coverage, events organized by project, presentations and panel debates, participation in third-party events)

Type (media coverage, events organized by project, presentations and panel debates, participation in third-party events)	Description	Year
Choose type	*Description of activities*	*Year in which activity was conducted*
Panel debate	*10th Metallization and Interconnection WS (Martin Bivour)*	*2021*
Panel debate	*Tandem PV conference (Monica Morales Masis)*	*2022*

List of patents

Patent Application Number / License	Title of the patent application / license	Name of the applicant	Name of the inventor
n.a.	*n.a.*	*n.a.*	*n.a.*

Comments related to the SOLAR-ERA.NET Cofund call management and administrative procedures:
none