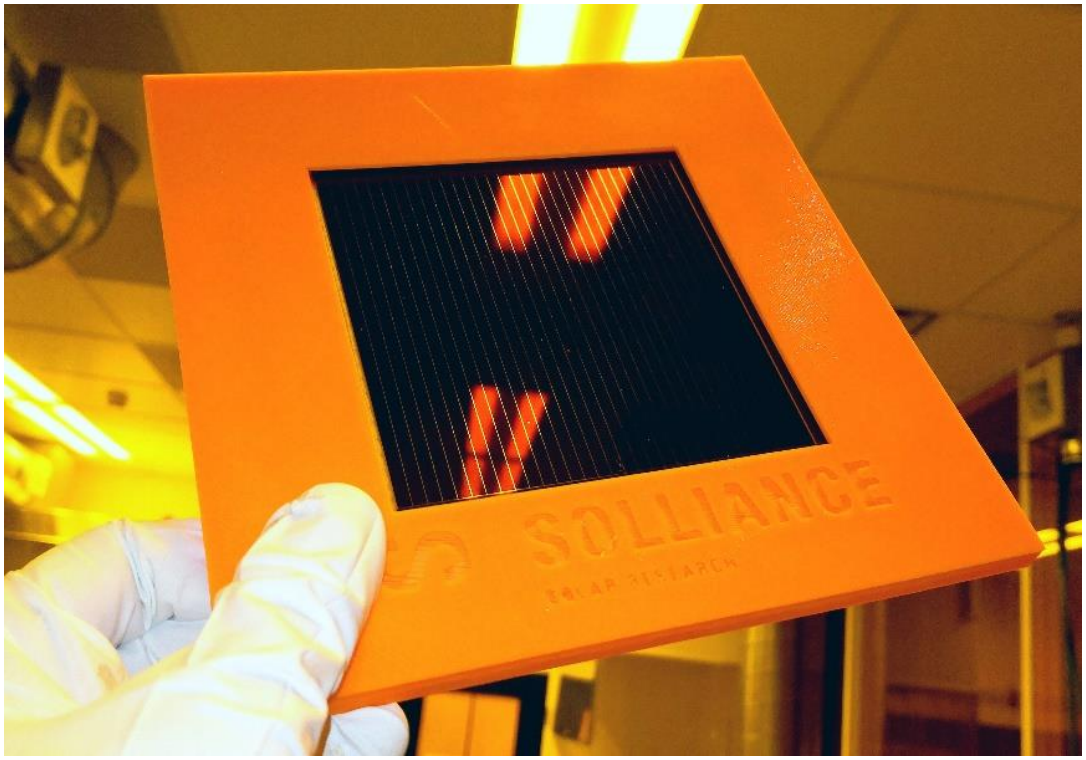
Openbare samenvatting

HIPER

High-efficiency SI PERovskite Tandem Solar Cells



June 2019

Contents

1 Data project

1.1 Project number

ES:
TR:
NL: TEUE116193

1.2 Project title

HIPER
High-efficiency S**I** **PER**ovskite Tandem Solar Cells

1.3 Consortium

Project coordinator:	TNO
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Partner :	Technische Universiteit Eindhoven (TUE)
	Tempress Systems B.V. (TPR)
	TNO
	iTechSolar (iTS)
	University of Valencia (UVEG)

1.4 Project period

January 1st, 2017 until June 30st, 2019.

Dit project is uitgevoerd met subsidie van het Ministerie van Economische Zaken, subsidieregeling Top Sector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland.

2. Executive and public Summary

2.1 Project aim

The overall project objective of the TKI Urban Energy project HIPER is to reach efficiencies which cannot be obtained by single junction cSi technology: 28% cell efficiency. Furthermore, the project aims to develop scalable process methods to fabricate 6x6 inch^2 modules, and to include such modules in 25% hybrid tandem modules.

Main objectives

The HIPER project ran for 30 months, with the following main objectives:

- Realize a 28% perovskite/cSi hybrid tandem solar cell.
- Realize a 25% perovskite/cSi hybrid tandem solar module on 6 x 6 inch2.
- Bring the technology readiness level (TRL) to 5 at end of project for the employed processing technologies.

Main Results

1. A record four terminal tandem device was realized by combining a 22.7% c-Si solar cell with a 18.0% semi-transparent perovskite solar cell**. The combination yields a hybrid tandem solar cell with 28.0%.**
   The 18.0% is measured on an aperture of 2 x 2 mm. The value corresponds to the current world record for perovskite/cSi hybrid tandems. The cell was measured with a AAA class solar simulator under 1 sun AM1.5 conditions (1000 W/m^2).

2. The 25% hybrid tandem was not obtained. The consortium reached 90% of the target with a 22.4% 6 inch hybrid tandem module consisting of a 22.5% cSi cell with a 13.5% semi-transparent perovskite module processed on 6 inch substrate.

3. As industrially scalable processes were deployed to manufacture both the semi-transparent perovskite mini-modules and the c-Si cell, we evaluate that with **the 21.4% 6 inch hybrid tandem module, a TRLof 5 has been reached**.

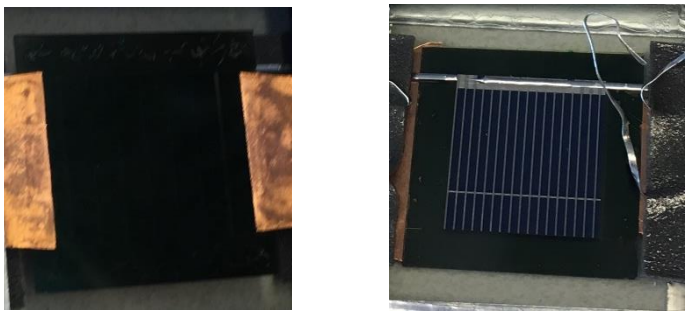

Figure 2.1 **Front (perovskite) and backside (c-Si) of a (bifacial) hybrid tandem mini-module (~3x3 cm^2)**

2.2 Exploitation

The promising results of the HIPER project and the continuing commitment of the partners to further support and invest in the development of this emerging PV technology, a follow-up project proposal was submitted (HIPER XL), although without success. Even without this support, the consortium members aim to continue the research as it allows to enter a new efficiency regime not attainable with affordable single junction PV technologies today.
UVEG has strong ties with Oxford PV, generally recognized as the most successful start-up company developing hybrid tandem devices. TNO and Tempress develop a low cost cSi cell specifically suitable as bottom cell in a hybrid perovskite/cSi tandem device. TNO negotiates with commercial partners to further develop hybrid tandem technology. Technology developed by TUE and TNO (e.g. the soft deposition of a compact metal oxide layer on top of a perovskite solar cells stack) is shown to be particular use full in perovskite top cells, and generates economic activity within NL.
For iTS, the project resulted in more insight in the environmental aspects of solar cells. HIPER led to a first baseline process for efficient perovskite solar cells in Turkey. Currently, scale up of the technology is considered in the framework of a new institute, together with regional solar cell manufacturers.

2.3 Project management

The project structure is described by 5 work packages as indicated below. The HIPER contains three technical workpackages (WPs). WP1 focuses on the cSi design and development; WP2 on the perovskite layer and subcell development; and WP3 on the tandem cells and modules, comprising tasks on highly transparent conductors, and 2T and 4T tandem designs. Section 3 of this final report follows the WP structure to report on the results of the project.

WP1:	cSi Bottom cell technology	(**TNO**)
WP2:	Perovskite top cell technology	(**TNO**)
WP3:	Tandem cells and modules	(**TUE**)
WP4:	Performance evaluation	(**TNO**)
WP5:	Project management	(**TNO**)

The interdependencies between the work packages is schematically presented in figure 2.2.

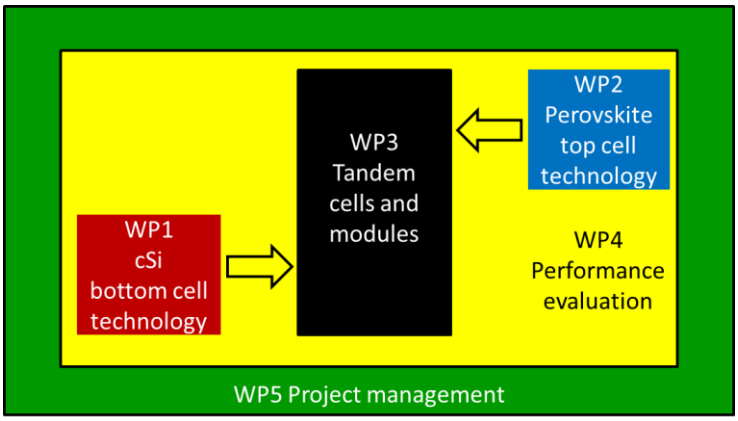

Figure 2-2. Project structure of HIPER

3. Conclusions and recommendations

The project was a success which overachieved the expectations. The following results have been obtained:

- State-of-the-art perovskite solar cells based on vacuum and ambient processes
- 28% perovskite / cSi 4T tandem efficiency (world record for a 4T tandem cell on cell)
- Semi-transparent perovskite cells with 17 – 18%.
- Detailed study of ALD passivation layers for perovskite solar cells
- Cost calculations for hybrid tandems
- Industrially relevant processes developed for processing semi-transparent perovskite cell stacks
- Interconnection process developed for monolithic semi-transparent modules using laser scribing
- 21.4% perovskite / cSi 4T tandem efficiency (world record for a 4T tandem module on cell)

Appendix I Overview HIPER project deliverables

D. Nr.	Description	Due	Owner
M1.1	Selection of bottom cell technologies for second year of project	M12	All
D1.1	Optimized c-Si bottom cell with Voc of at least 700mV	M2	TNO
D1.2	Report on optical characterization and modeling, see eranet application in appendix for detailed description.	M12	iTS
D1.3	Bottom cell with efficiency higher than 10.4%	M24	TNO
M2.1	Selection of top cell technologies	M12	All
D2.1	Semi-transparent perovskite cell with 18% efficiency	M18	TNO
D2.2	Semi-transparent perovskite cell with bandgap of 1.7 eV; sufficient efficiency for 28% tandem target	M18	UVEG
D2.3	Determine the effect of passivation layers on efficiency and lifetime of perovskite cell	M18	TUE
M3.1	Selection of tandem cell technology	M12	All
M3.2	Tandem cell with efficiency >28%	M24	All
D3.1	Soft deposition of highly transparent (85%) and conductive electrode (35 Ohm sq)	M24	TNO
D3.2	Report on tandem cell performance: 28% cell efficiency and 25% module efficiency	M24	TNO
D4.1	Report on passivation layers	M24	TUE
D4.2	Preliminary LCA report on perovskite/cSi tandem cells and modules, see eranet application in appendix for detailed description.	M12	iTS
D4.3	LCA report on perovskite/cSi tandem cells and modules, see eranet application in appendix for detailed description.	M24	iTS
D4.4	Preliminary cost analysis report on perovskite/cSi tandem cells and modules	M12	TNO
D4.5	Final cost of ownership and LCOE report for perovskite/cSi tandem cells and modules	M24	TNO
D5.1	Midterm project assessment	M12	TNO
D5.2	Exploitation plan	M24	TNO

Appendix II Dissemination

The HIPER project contributed to the dissemination of project results through peer reviewed publications and presentations

- Scientific contributions:

1. V. Zardetto, F. di Giacomo, H. Lifka, M.A. Verheijen, C.H.L. Weijtens, L.A. Black, S. Veenstra, W.M.M. Kessels, M. Creatore, *Surface fluorination of ALD TiO_2 electron transport layer for efficient planar perovskite solar cells*, Adv. Mat. Interfaces 5, 1701456 (2018).
2. Y. Kuang, V. Zardetto, R. van Gils, S. Karwal, D. Koushik, M.A. Verheijen, L.E. Black, C. Weijtens, S. Veenstra, R. Andriessen, W.M.M. Kessels, and M. Creatore, *Low-Temperature Plasma-Assisted ALD SnO_2 as Electron Transport Layer in Planar Perovskite Solar Cells,* ACS Mater. Appl. Interfaces (2018) 10, 36, 30367-30378.
3. Zhang, D., Najafi, M., Zardetto, V., Dorenkamper, M., Verhees, W., Zhou, X., Senes, A., Gutjahr, A., Romijn, I., Veenstra, S., Geerligs, B., Creatore, M., Aernouts, T. & Andriessen, R.*, Highly near-infrared-transparent perovskite solar cells and their application in high-efficiency 4-terminal perovskite/c-Si tandems,* 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion, WCPEC 2018, p. 3575-3577.
4. M. Jaysankar, B. A.L. Raul, J. Bastos, C. H. Burgess, C. Weijtens, M. Creatore, T. Aernouts, Y. Kuang, R. Gehlhaar, A. Hadipour and J. Poortmans, *Minimizing voltage loss in wide-bandgap perovskites for tandem solar cells.* ACS Energy Lett. (2019) 4,1, 259-264.
5. D. Koushik, M. Jošt, A. Dučinskas, C. Burgess, V. Zardetto, C. Weijtens, M. A. Verheijen, W. M.M. Kessels, S. Albrecht, M. Creatore; Plasma-Assisted Atomic Layer Deposition of Nickel Oxide as Hole Transport Layer for Hybrid Perovskite Solar Cells; Journal of Materials Chemistry C [under review].
6. Interface Studies of Metal Oxides Grown Directly on Hybrid Perovskite by Atomic Layer Deposition [Manuscript under preparation].
7. F. Palazón; D. Pérez-del-Rey; S. Marras; M. Prato; M. Sessolo; H. J. Bolink; L. Manna, Coating Evaporated MAPI Thin Films with Organic Molecules: Improved Stability at High Temperature and Implementation in High-Efficiency Solar Cells, ACS Energy Lett. 3, 835-839 (2018).
8. V. S. Chirvony; J. P. Martínez-Pastor, *Trap-Limited Dynamics of Excited Carriers and Interpretation of the Photoluminescence Decay Kinetics in Metal Halide Perovskites*, J. Phys. Chem. Lett. 9, 4955−4962 (2018).
9. J. Ávila; L. Gil-Escrig; P. P. Boix; M. Sessolo; S. Albrecht; H. J. Bolink,, *Influence of doped charge transport layers on efficient perovskite solar cells*, Sustain. Energ. Fuels. 2, 2429–2434 (2018).
10. J. Ávila; C. Momblona; P. Boix; M. Sessolo; M. Anaya; G. Lozano; K. Vandewal; H. Míguez; H. J. Bolink, *High voltage vacuum-deposited CH3NH3PbI3–CH3NH3PbI3 tandem solar cells,* RSC Adv. 8, 35719-35723 (2018).

11. Y. El Ajjouri; F. Palazon; M. Sessolo; H. J. Bolink, *Efficient Photo- and Electroluminescence by Trap States Passivation in Vacuum-Deposited Hybrid Perovskite Thin Films*, ACS Appl. Mater. Interfaces, 10, 36187–36193 (2018).

12. D. Kiermasch; L. Gil-Escrig; H. J. Bolink; K. Tvingstedt, Effects of Masking on Open-Circuit Voltage and Fill Factor in Solar Cells, Joule 3, 1–11 (2019).

13. B. Dänekamp; N. Droseros; D. Tsokkou; V. Brehm; P. P. Boix; M. Sessolo; N. Banerji; H. J. Bolink, *Influence of hole transport material ionization energy on the performance of perovskite solar cells*, J. Mater. Chem. C 7, 523 (2019).

14. D. Kiermasch; L. Gil-Escrig; A. Bauman; H. J. Bolink; V. Dyakonov; K. Tvingstedt, *Unravelling steady-state bulk recombination dynamics in thick efficient vacuum-deposited perovskite solar cells by transient methods*, J. Mater. Chem. A 7, 14712-14722 (2019).

15. D. Perez-del-Rey; L. Gil-Escrig; K. P. S. Zanoni; C. Dreessen; M. Sessolo; P. P. Boix; H. J. Bolink, Molecular Passivation of MoO3: Band Alignment and Protection of Charge Transport Layers in Vacuum-Deposited Perovskite Solar Cells, Chem. Mater. (2019). DOI: 10.1021/acs.chemmater.9b01396.

16. Y. El Ajjouri, F. Locardi, M. C. Gélvez-Rueda, M. Prato, M. Sessolo, M. Ferretti, F. C. Grozema, F. Palazon; H. J. Bolink, *Mechanochemical Synthesis of Sn(II) and Sn(IV) Iodide Perovskites and Study of Their Structural, Chemical, Thermal, Optical and Electrical Properties*, Energy Technol. (2019). DOI: doi.org/10.1002/ente.201900788.

17. V. S. Chirvony; K. S. Sekerbayev; D. Pérez-del-Rey; J. P. Martínez-Pastor; F. Palazón; P. P. Boix; T. I. Taurbayev; M. Sessolo; H. J. Bolink*., "Short Photoluminescence Lifetimes in Vacuum-Deposited CH3NH3PbI3 Perovskite Thin Films as a Result of Fast Diffusion of Photogenerated Charge Carriers", J. Phys. Chem. Lett. 10, 5167−5172 (2019).*

18. A. Babaei; W. Soltanpoor; M. A. Tesa-Serrate; S. Yerci; M. Sessolo; H. J. Bolink, *Preparation and Characterization of Mixed Halide MAPbI3−xClx Perovskite Thin Films by Three-Source Vacuum Deposition,* Energy Technol. (2019). DOI: doi.org/10.1002/ente.201900784.

19. L.J. Geerligs, D. Zhang, G.J.M. Janssen, S.L. Luxembourg, *4-Terminal and 2-Terminal Tandem Modules in Bifacial Operation: Model Analysis and Comparison,* 35th Proc. EU PVSEC, Brussels 2018, session 2AV.3.23, 676-670, 2018. DOI: 10.4229/35thEUPVSEC20182018-2AV.3.23.

Conference presentations based on results from the project:

1. C. H. Burgess, F. Mardekatani Asl, V. Zardetto, H. Lifka, S. Veenstra, M. Creatore; *Interface Studies of Metal Oxides Grown Directly on Hybrid Perovskite by Atomic Layer Deposition,* 11th International Conference on Hybrid and Organic Photovoltaics, 12th-15th of May 2019

2. Dong Zhang et al., 27% efficient 4-T tandem with highly transparent perovskite top cell and back-contacted Si heterojunction bottom cell, oral presentation, 9th Silicon PV conference, 2019

3. Dong Zhang et al., High Efficiency 4-Terminal perovskite/c-Si Hybrid Tandem Solar Cells, oral presentation, 8th Silicon PV conference, 2018