Openbaar eindrapport TKI Urban Energy project HI-EFF

September 30, 2018

Targets of the project and project partners

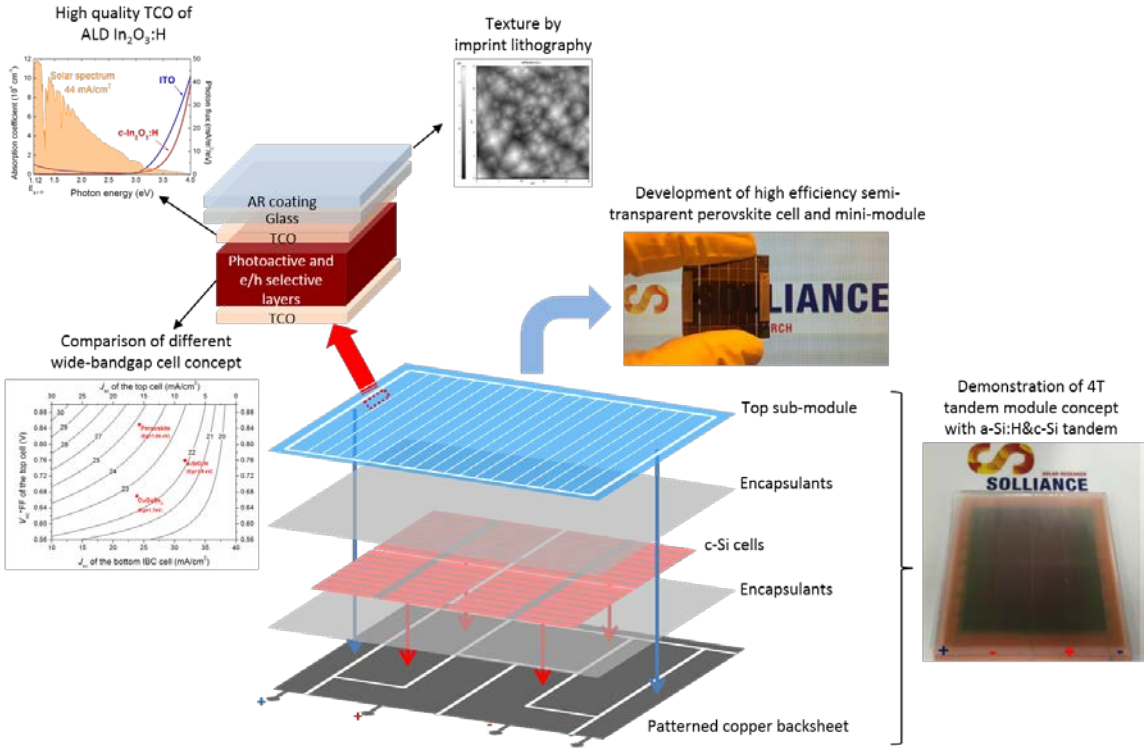
The "*High efficiency hybrid tandem cells with crystalline silicon and thin film photovoltaic technologies*" (HI-EFF) project was the first TKI project related to hybrid tandem solar cells in which research would be carried out to combine a crystalline silicon solar cell with a thin film solar cell technology to reach solar energy conversion efficiencies beyond those for crystalline silicon solar cells only. The motivation was that a further decrease of the kWh price of solar energy would mainly require an increase in the efficiency of the solar modules as the costs for module materials and installation etc. (the balance-of-systems or BOS costs) currently make up about 50% of the kWh price. A higher Wp per module will therefore directly lead to a reduced kWh price.

At the start of the project a major question was which thin film solar cell technology would be best suited for the combination with crystalline silicon solar cells. At that time there were 3 candidates for wide-bandgap absorber materials for the cell on top of crystalline silicon: thin film silicon solar cells, chalcopyrite cells from the CIGS family, and hybrid organic-inorganic perovskite cells. The project was aimed at addressing this question as well as on several other aspects related to hybrid tandem cells including optical coupling; light management; interconnects; transparent conductive oxides; lamination; integration; testing etc. These aspects have been addressed through a collaboration between the knowledge partners ECN, TNO, TU/e and the University of Valencia while directly cooperating with the companies Tempress, Eurotron, Solartek, SoLayTec, Rebel group and Deerns Nederland. This provided the opportunity to maintain a competitive edge in Dutch solar cell knowhow and equipment manufacturing with respect to the important trend to go to hybrid tandem solar cells in the near future.

Project result

One of the main outcomes of this project is that the research indicated that tandem cells with perovskite solar cells would be preferable over the other thin film technologies. The results clearly showed out that tandems with perovskite solar top cells would allow for higher conversion efficiencies of the tandem cells but also for ease of processing. Considering this project outcome as well as the general, worldwide consensus that tandems with perovskite solar cells would be most promising, the focus of the project has therefore been directed at this type of tandem cell. Largely due to this focus, a tandem solar cell of over 25% has been obtained through the realization of tandem solar cell with a conversion efficiency of 25.5%. This is quite an achievement and several ideas for future improvement have been generated in the project. The project has therefore paved the way to solar cells of 30% and solar modules of 25%. It is interesting to note that in June 2018, the company Oxford PV reported a crystalline silicon/perovskite tandem cells with a record efficiency of 27.3%.

Apart from the demonstrator cell with high conversion energy, the project partners have acquired many new insights, developed new technologies and have had major breakthroughs with respect to all kinds of aspects related to tandem cell design, device manufacturing, materials, and processing. Among these are development of new transparent conductive oxides, the realization of new spatial atomic layer deposition (ALD) processes; the breakthrough of ALD in the field of perovskites, the realization of cells and mini-modules, etc. Also a model for the cost-of-ownership of monolithically interconnected perovskite cells has been developed and the costs for tandem cells has been assessed.



Potential for application and spin-off

The perspectives for hybrid tandem cells of crystalline silicon/perovskites are very bright. Due to the intensive research efforts worldwide – including those within this project – it has become clear that such tandem cells will very likely be commercialized. Companies such as Oxford PV have publically announced that they are focusing on this technology. With the knowledge and IP position obtained through this project, Dutch industries and knowledge institutes are well-positioned to play a major role in this rapidly-developing area. In retrospect, it can be concluded that the project was very timely and extremely relevant considering the trends going on in the worldwide photovoltaics research domain and solar energy market.

Contribution to targets of TKI Urban Energy

The targets of the TKI Urban Energy are a sustainable infrastructure and a reinforcement of the knowledge position. The HI-EFF project has contributed towards reaching this goal through the generation of Dutch knowledge that will lower the kWh price of solar energy through the realization of highly efficient tandem solar cells. Furthermore, in the context of the HI-EFF project, solutions and opportunities have been found and traced based on equipment that is being developed in the Netherlands. This reinforces both the knowledge position and the Dutch economy.

Publications related to the HI-EFF project

1. D. Zhang, W. Soppe, and R. E. I. Schropp, *Design of 4-terminal Solar Modules Combining Thin-film Wide-Bandgap Top Cells and c-Si Bottom Cells*, Energy Procedia 77, 500 (2015).
2. D. Zhang, W.J.H. Verhees, M. Dörenkämper, W. Qiu, K. Bakker, A. Gutjahr, S. Veenstra, R. Gehlhaar, U.W. Paetzold, W. Soppe, I. Romijn, L.J. Geerligs,T. Aernouts and A.W. Weeber, *Combination of advanced optical modelling with electrical simulation for performance evaluation of practical 4-terminal perovskite/c-Si tandem modules*, Energy Procedia 92, 669 (2016).

3. D. Koushik, W.J.H. Verhees, Y. Kuang, S. Veenstra, D. Zhang, M.A. Verheijen, M. Creatore and R.E.I. Schropp, *High-efficiency humidity-stable planar perovskite solar cells based on atomic layer architecture,* Energy Environ. Sci. 10, 91 (2017).
4. V. Zardetto, B. L. Williams, A. Perrotta, F. Di Giacomo, M. A. Verheijen, R. Andriessen, W.M.M. Kessels and M. Creatore, *Atomic layer deposition for perovskite solar cells: research status, opportunities and challenges,* Sustainable Energy Fuels 1, 30 (2017)
5. Y. Kuang, B. Macco, B. Karasulu, C.K. Ande, P.C.P. Bronsveld, M.A. Verheijen, Y. Wu, W.M.M. Kessels, R.E.I. Schropp, *Towards the implementation of atomic layer deposited In2O3:H in silicon heterojunction solar cells,* Sol. Energy Mater. Sol Cells, 163, 43 (2017).
6. L. Gil-Escrig, C. Momblona, M.-G. La-Placa, P. P. Boix, M. Sessolo, H. J. Bolink, *Vacuum Deposited Triple-Cation Mixed-Halide Perovskite Solar Cells,* Adv. Energy Mater. 8, 1703506 (2018).
7. D. Koushik, W.J.H. Verhees, D. Zhang, Y. Kuang, S. Veenstra, M. Creatore, and R.E.I. Schropp, *Atomic Layer Deposition Enabled Perovskite/PEDOT Solar Cells in a Regular n-i-p Architectural Design,* Adv. Mater. Interfaces 4, 1700043 (2017).
8. 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).
9. 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,* accepted for publication in ACS Mater. Appl. Interfaces (2018).
10. D. Koushik, D. Zhang, M. Najafi, V. Zardetto, B. Macco, S. Veenstra, W.M.M. Kessels, and M. Creatore, *Broadband Transparent High-Mobility ALD In_2O_3:H Electrode for Efficient Perovskite Semi-Transparent and Tandem Photovoltaics*, submitted for publication (2018).

Contact person for more information

Prof.dr.ir. W.M.M. (Erwin) Kessels
Faculteit Technische Natuurkunde
Technische Universiteit Eindhoven
P.O. Box 513
5600 MB Eindhoven
Tel: 040 247 3477

Meer exemplaren van dit rapport zijn verkrijgbaar via de Technische Universiteit Eindhoven (sectretariaat.pmp@tno.nl).

Subsidieregeling

Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken, Nationale regelingen EZ-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland.