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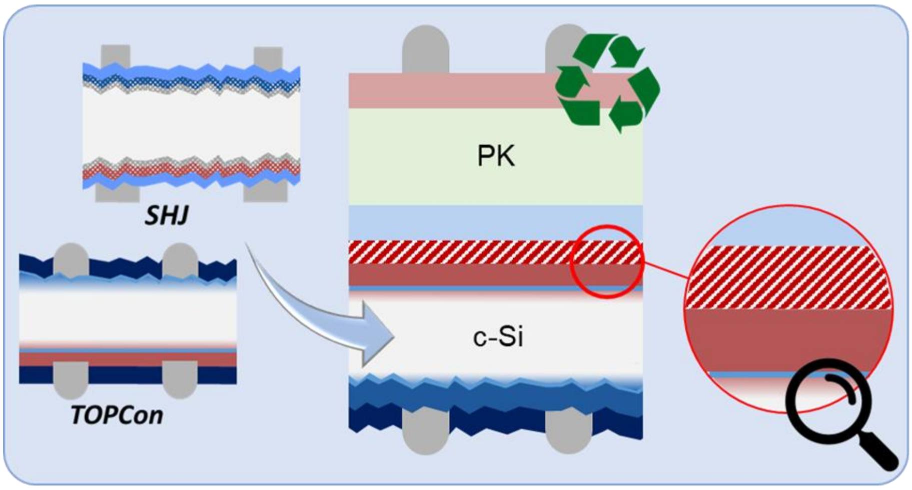
BESTOBOT

Approaches for highly efficient and stable solar cells with reduced carbon footprint



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Summary

The goal of BESTOBOT is to develop stable and ultra-high efficiency (>30%) perovskite-on-silicon (PK/Si) tandem solar cells while minimizing their carbon footprint and ensuring a commercially viable production process. The focus of the project is on overcoming key challenges associated with the silicon bottom cell to facilitate the widespread adoption of PK/Si tandems starting from 2030. This includes the development of an interlayer-free strategy to interconnect the PK- and Si-based sub-cells forming the tandem device. Moreover, the project aims to reduce the reliance on critical raw materials of mainstream Si solar cells featuring passivating contacts that could limit their sustainable scalability to the Terawatt-scale. The success of the project hinges on the expertise of the research team in fabricating both PK- and Si-based high-efficiency PV devices. Central to our approach is a comprehensive understanding of the fundamental mechanisms governing the interaction between the top and bottom sub-cells, thereby optimizing the performance and reliability of the final tandem structure.

Résumé

L'objectif de BESTOBOT est de développer des cellules solaires tandem pérovskite-sur-silicium (PK/Si) stables et ultra-efficaces (>30%), tout en minimisant leur empreinte carbone et en garantissant un processus de production commercialement viable. Le projet se concentre sur la résolution des principaux défis associés à la cellule inférieure en silicium afin de faciliter l'adoption des tandems PK/Si à partir de 2030. Cela comprend le développement d'une stratégie sans couche intermédiaire pour interconnecter les sous-cellules basées sur PK et Si formant le dispositif tandem. De plus, le projet vise à réduire la quantité de matières premières critiques nécessaire à la fabrication de cellules solaires silicium nouvelle génération, qui pourrait limiter leur production à l'échelle du térawatt. Le succès du projet repose sur l'expertise de l'équipe de recherche dans la fabrication de dispositifs PV haute efficacité, à la fois basés sur PK et Si. Au cœur de notre approche se trouve une compréhension approfondie des mécanismes fondamentaux régissant l'interaction entre les sous-cellules supérieure et inférieure, optimisant ainsi les performances et la fiabilité de la structure tandem finale.

Contents

1 Introduction

1.1 Context and motivation

The BESTOBOT project aims to accelerate the deployment of high-efficiency perovskite/silicon (PK/Si) tandem solar cells by leveraging PV-Lab and CSEM expertise in Silicon Heterojunction (SHJ) and TOPCon technologies. The project addresses key challenges in the design of the silicon bottom-cell and its interconnection with the PK top-cell. Ultimately, our goal is to demonstrate PK/Si tandem devices achieving over 30% efficiency, fabricated through scalable processes and with minimal reliance on critical raw materials.

1.2 Project objectives

The first objective of the project consists in defining the optimal interconnection and silicon bottom cell structure. This involves studying the impact of Si wafer properties, surface preparation, and p-n junction location on PK/Si tandem performance. We aim to develop multifunctional interconnection layers, optimize Si texturing for optical and electrical performance, and benchmark different wafer types. Advanced modelling and characterization are applied to guide the definition of ideal bottom-cell architecture.

The second objective aims at developing SHJ and TOPCon bottom cells optimized for PK/Si tandems. Our work includes optimizing passivating contacts, developing Ag-free metallization solutions, and integrating the best interconnection structures identified earlier. Emphasis is placed on lean, sustainable, and scalable process flows compatible with industrial production.

The third objective focuses on demonstrating highly efficient and stable PK/Si tandem devices. Here, the most promising materials and processes are combined to fabricate PK/Si tandems with >30% efficiency and reduced Ag/In content. Stability will be validated through reliability testing, targeting <10% degradation after 1000h under standard conditions.

2 Approach, method, results and discussion

Building on the baseline established in 2024 for weekly fabrication of TOPCon bottom cells and PK/TOPCon tandems, we achieved several important advancements in 2025.

First, guided by optical modelling, we focused on integrating a textured surface on the front side of TOPCon bottom cells. Initially, the passivation level of poly-Si(n) was lower on textured silicon surfaces compared to polished surfaces. To address this, we implemented an additional hydrogenation step based on the deposition of a thin sacrificial AlOx layer on top of poly-Si, followed by thermal activation. This approach enabled high surface passivation on textured surfaces without causing damage during etching of the AlOx layer. As a result, we achieved a conversion efficiency of 31.3% with a PK/Si tandem device based on a TOPCon bottom cell featuring a textured front side.

Another major focus in 2025 was the reduction of indium content in SHJ and TOPCon bottom cells. For SHJ bottom cells, we worked on replacing the rear ITO layer with AZO. This resulted in a conversion efficiency of 22.9% at 0.5 sun illumination, compared to 23.5% with ITO. In parallel, we developed an indium-free material to serve as the recombination junction between SHJ or TOPCon bottom cells and the PK top cell. After exploring different options, we selected a Si-based layer that provides all required functionalities: low contact resistivity with the poly-Si(n) layer, transparency, thermal stability up to at least 400 °C, and high lateral resistance. Using this layer, we demonstrated a conversion efficiency of 23.3% at 0.5 sun illumination with a TOPCon precursor integrating the indium-free recombination junction on the front side. This is only 0.2% lower than the reference TOPCon precursor featuring a standard ITO recombination layer on the front.

Finally, we worked on developing a method for metallizing the rear side of TOPCon bottom cells that reduces silver consumption compared to the standard approach. This method builds on developments initiated in the COMET project for contacting poly-Si(n) layers. In BESTOBOT, we aim to adapt it for contacting the poly-Si(p) layer featured on the rear side of TOPCon bottom cells. So far, we have confirmed that the proposed metallization sequence does not damage the surface passivation provided by the poly-Si(p) layer, and we have achieved promising contact resistivity values.

3 Conclusions and outlook

In 2025, we achieved key milestones that significantly advance PK/Si tandem technology, including the integration of TOPCon bottom cells featuring textured front side, enabling efficiencies up to 31.3%. We also made substantial progress toward reducing critical material usage by developing an indium-free recombination layer and a silver-saving metallization approach, while maintaining high device performance. These developments strengthen the technological foundation for next-generation high-efficiency, sustainable solar cells.

In 2026, we will focus on further increasing the efficiency of SHJ and TOPCon bottom cells while continuing to reduce their reliance on indium and silver. These improved bottom cells will be integrated into complete PK/Si tandem devices and submitted to reliability testing to validate long-term performance.

4 Publications and other communications

4.1 Peer-reviewed publications

Short name	**Details**	**Status**
Genc_2025_jpv	Ezgi Genc, Julien Hurni, Arnold Mülle, Christof Vockenhube, Takashi Koida, Audrey Morisset, Christophe Ballif, and Franz-Josef Haug *nc-SiC by PECVD for High-Temperature Passivating Contacts* **https://doi.org/10.1109/JPHOTOV.2025.3577294**	Published
Genc_2025_solmat	Ezgi Genc, Julien Hurni, Christophe Allebé, Bertrand Paviet-Salomon, Christophe Ballif, Audrey Morisset, Franz-Josef Haug *Co-annealing of PECVD boron emitters and poly-Si passivating contacts for leaner TOPCon solar cell fabrication* **https://doi.org/10.1016/j.solmat.2025.113713** Link to article in PV Magazine International	Published **Highlighted in PV Magazine International**
Schaller_2025_solmat	Thibault Schaller, Ezgi Genç, Julien Hurni, Ludovica Lunghi, Christophe Ballif, Audrey Morisset, Franz-Josef Haug *Boron-emitter development for TOPCon c-Si solar cells based on plasma-deposited boron diffusion source and poly-Si (n) passivating contact* **https://doi.org/10.1016/j.solmat.2025.113808** Link to article in PV Magazine International	Published **Highlighted in PV Magazine international**

Hurni_2025_ees	Julien Hurni, Kerem Artuk, Thibault Schaller, Jonathan S. Austin, Reyu Sakakibara, Bertrand Paviet-Salomon, Audrey Morisset, Fan Fu, Christophe Ballif, Christian M. Wolff, Franz-Josef Haug *Over 31%-Efficient Perovskite-TOPCon Solar Cells Enabled by AlOx-based Hydrogenation and Front Sub-micron Texturing* **https://doi.org/10.1039/D5EL00105F**	Accepted for publication in EES Solar **Picked up as HOT paper by EES editors**

In 2025, we published four manuscripts on the research performed in OFEN-funded projects iPrecise and BESTOBOT. Two of these papers were picked up and highlighted in dedicated online articles in PV Magazine International, a global media platform for the solar and energy storage industries and research communities. Additionally, our latest paper published in EES was picked up and featured as HOT by the journal's editors.

4.2 Contributions to conferences

Short name	**Details**	**Presentation type**
Morisset_2024_eupvsec	Audrey Morisset et al. *Development and Characterization of N2O-Plasma Oxide Layers for p-type Fired Poly-Si Contacts* 41st Photovoltaic Solar Energy Conference and Exhibition, Vienna, Austria (2024)	Oral
Hurni_2024_eupvsec	Julien Hurni et al. *Towards leaner TOPCon fabrication* 41st Photovoltaic Solar Energy Conference and Exhibition, Vienna, Austria (2024)	Oral
Allebe_2025_eupvsec	Christophe Allebé et al. *n- and p-type based passivating contacts by PVD and PECVD* 41st Photovoltaic Solar Energy Conference and Exhibition, Vienna, Austria (2024)	Poster
Hurni_2025_sipv	Julien Hurni et al., presented by Franz-Josef Haug *Optimization of TOPCon-based Bottom* *Cells for High Open Circuit Voltage (>2V) Perovskite/Silicon Tandems* 15th International Conference on Crystalline Silicon Photovoltaics, Oxford, UK (2025)	Oral
Schaller_2025_sipv	Thibault Schaller et al. *Boron-Emitter Development for TOPCon c-Si Solar Cells Based on Plasma Deposited Boron Diffusion Source and Poly-Si(n) Passivating Contact* 15th International Conference on Crystalline Silicon Photovoltaics, Oxford, UK (2025)	Oral
Hurni_2025_eupvsec	Julien Hurni et al. *Optimization of TOPCon-based Bottom Cells for High Open-Circuit Voltage (>2V) Perovskite/Silicon Tandems* 42nd European Photovoltaic Solar Energy Conference and Exhibition, Bilbao, Spain (2025)	Oral
Schaller_2025_eupvsec	Thibault Schaller et al., presented by Franz-Josef Haug	Oral

	Gallium-Emitter Development for Lean TOPCon c-Si Solar Cells based on Plasma-Deposited Gallium Diffusion Source 42nd European Photovoltaic Solar Energy Conference and Exhibition, Bilbao, Spain (2025)	