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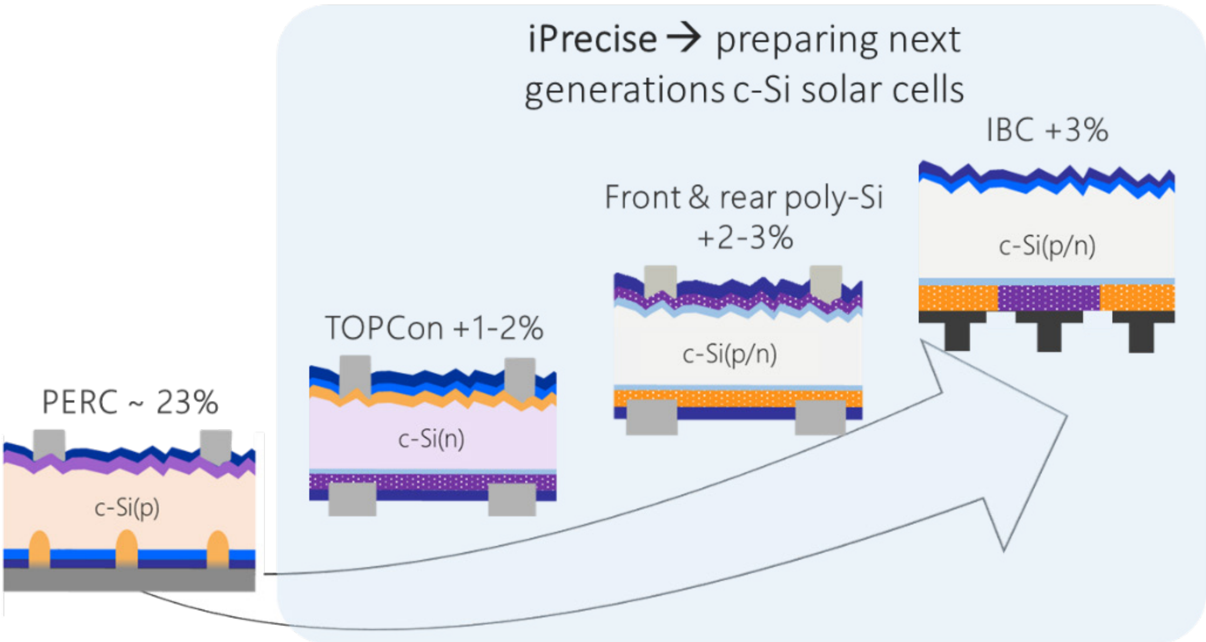
Final report

iPrecise

Industrial passivating contacts approaches for high efficiency c-Si Solar cells



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Swiss Federal Office of Energy SFOE
Research Programme Photovoltaics
CH-3003 Bern
http://www.bfe.admin.ch
energieforschung@bfe.admin.ch

Agents:
Ecole Polytechnique Fédérale de Lausanne (EPFL)
Photovoltaics and Thin Film Electronics Laboratory (PV-Lab)
Maladière 71b, 2000 Neuchâtel
pvlab.epfl.ch

Centre Suisse d'Electronique et de Microtechnique (CSEM)
Sustainable Energy Center
Rue Jaquet-Droz 1, 2000 Neuchâtel
https://www.csem.ch/

Authors:
Audrey Morisset, EPFL, audrey.morisset@epfl.ch
Christophe Allebé, CSEM, christophe.allebe@csem.ch
Bertrand Paviet-Salomon, CSEM, bertrand.paviet-salomon@csem.ch
Franz-Josef Haug, EPFL, franz-josef.haug@epfl.ch
Christophe Ballif, EPFL, CSEM, christphe.ballif@epfl.ch

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

The primary objective of the iPrecise project was to prepare the next generation of solar cells based on crystalline silicon (c-Si). To do so, the development of materials and processes was undertaken to increase the conversion efficiency of c-Si solar cells while ensuring compatibility with sustainable and large-scale manufacturing.

First, we investigated sputtering as an alternative to fabricate n-type polycrystalline silicon (poly-Si) passivating layers featured on the rear side of the TOPCon solar cell structure, which is becoming mainstream in manufacturing in 2024. Compared to more conventional fabrication methods based on Chemical Vapor Deposition (CVD), sputtering presents the advantage of being more directional and not based on hazardous or toxic gases. Despite these advantages, when the project started, it was not clear if sputtered poly-Si materials could meet the performance of poly-Si fabricated by CVD. Within this project, we could demonstrate very high surface passivation and electrical properties for sputtered poly-Si materials, meeting properties obtained with CV-Deposited poly-Si layers.

Following these developments, we integrated sputtered poly-Si contacts on the rear side of large-area TOPCon solar cells, which led to the demonstration of conversion efficiencies up to 22.8%. Additionally, we investigated solutions for the patterning of poly-Si layers to integrate them on the front side of TOPCon and thus fabricate Double Side (DS-)TOPCon devices. The first approach we investigated was based on the use of a mask during deposition of the poly-Si layer. After optimization of the poly-Si structure and its contacting with metal fingers, we could demonstrate small-area DS-TOPCon devices with efficiencies up to 21.7%. This result remained among the best reported in the literature for such a device structure along the project.

Additionally, we performed modelling to assess the potential of DS-TOPCon as an upgrade to standard TOPCon. Our results indicate that the resistance associated to the poly-Si contact should be lowered for DS-TOPCon to significantly overcome the performance of TOPCon, and this, to values that may be challenging to achieve practically.

Along the project, the development of high-efficiency c-Si devices was supported with advanced characterizations. First, we performed a comprehensive study based on electron microscopy, which allowed us building a model describing the penetration of Al-based commercial pastes through the SiN_x/poly-Si passivating stack located on the rear side of TOPCon devices. Additionally, we developed a method to evaluate the structure and composition of the nanometric SiO_x layer located at the poly-Si/c-Si interface allowing for in-situ analysis of representative samples. This method supported the development of SiO_x layers featuring improved thermal stability, which eventually enabled enhancing the performance of the poly-Si contact.

Overall, this project allowed for the development of new technological bricks for the fabrication of high-efficiency c-Si solar cells along with scientific insights into their working principle. Key achievements were disseminated through the publication of seven scientific articles and twenty-three contributions to international scientific conferences. The insights gained in iPrecise will also benefit the developments of next-generation perovskite-on-silicon tandem devices.

Zusammenfassung

Das Hauptziel des iPrecise-Projekts war die Vorbereitung der nächsten Generation von Solarzellen auf Basis von kristallinem Silizium (c-Si). Zu diesem Zweck wurde die Entwicklung von Materialien und Prozessen unternommen, um den Wirkungsgrad der c-Si-Solarzellen zu erhöhen und gleichzeitig die Kompatibilität mit einer nachhaltigen und grosstechnischen Fertigung zu gewährleisten.

Zunächst haben wir das Sputtern als Alternative zur Herstellung von n-dotierten polykristallinen Silizium (Poly-Si) Passivierungsschichten untersucht, die auf der Rückseite der mittlerweile weit verbreiteten TOPCon-Solarzellenstruktur verwendet werden. Im Vergleich zu herkömmlicheren Herstellungsverfahren auf Basis der chemischen Gasphasenabscheidung (CVD) bietet das Sputtern den Vorteil, dass es richtungsweisender ist und nicht auf gefährlichen oder giftigen Gasen basiert. Trotz dieser Vorteile war zu Beginn des Projekts nicht klar, ob gesputterte Poly-Si-Materialien die Leistung von Poly-Si, das durch CVD hergestellt wurde, erreichen könnten. Innerhalb dieses Projekts konnten wir sehr hohe Oberflächenpassivierung und elektrische Eigenschaften für gesputterte Poly-Si-Materialien nachweisen, die den mit CVD-abgeschiedenen Poly-Si-Schichten erzielten Eigenschaften entsprechen.

Nach diesen Entwicklungen haben wir gesputterte Poly-Si-Kontakte auf der Rückseite von grossflächigen TOPCon-Solarzellen integriert, was zur Demonstration von Wirkungsgraden von bis zu 22,8 % führte. Zusätzlich haben wir Lösungen für das Strukturieren von Poly-Si-Schichten untersucht, um sie auf der Vorderseite von TOPCon zu integrieren und somit Double Side (DS-)TOPCon Geräte herzustellen. Der erste Ansatz, den wir untersuchten, basierte auf der Verwendung einer Maske während der Abscheidung der Poly-Si-Schicht. Nach der Optimierung der Poly-Si-Struktur und ihres Kontakts mit Metallfingern konnten wir DS-TOPCon-Geräte mit kleiner Fläche und Wirkungsgraden von bis zu 21,7 % demonstrieren. Dieses Ergebnis gehörte während des gesamten Projekts zu den besten, die in der Literatur für eine solche Gerätearchitektur berichtet wurden.

Darüber hinaus haben wir Modellierungen durchgeführt, um das Potenzial von DS-TOPCon als Upgrade gegenüber dem Standard-TOPCon zu bewerten. Unsere Ergebnisse zeigen, dass der Widerstand, der mit dem Poly-Si-Kontakt verbunden ist, gesenkt werden muss, damit DS-TOPCon die Leistung von TOPCon signifikant übertreffen kann, und dies auf Werte, die praktisch schwer zu erreichen sein könnten.

Im Laufe des Projekts wurde die Entwicklung von hocheffizienten c-Si-Geräten durch fortschrittliche Charakterisierungen unterstützt. Zunächst haben wir eine umfassende Studie auf Basis der Elektronenmikroskopie durchgeführt, die es uns ermöglichte, ein Modell zu erstellen, das die Penetration von kommerziellen Al-basierten Pasten durch die SiNx/Poly-Si-Passivierungsschicht auf der Rückseite der TOPCon-Geräte beschreibt. Darüber hinaus haben wir eine Methode entwickelt, um die Struktur und Zusammensetzung der nanometrischen SiOx-Schicht an der Poly-Si/c-Si-Grenzfläche zu bewerten, die eine In-situ-Analyse von repräsentativen Proben ermöglicht. Diese Methode unterstützte die Entwicklung von SiOx-Schichten mit verbesserter thermischer Stabilität, was letztendlich die Leistung des Poly-Si-Kontakts verbesserte.

Insgesamt ermöglichte dieses Projekt die Entwicklung neuer technologischer Bausteine für die Herstellung hocheffizienter c-Si-Solarzellen sowie wissenschaftlicher Erkenntnisse über deren Funktionsprinzip. Wichtige Ergebnisse wurden durch die Veröffentlichung von sieben wissenschaftlichen Artikeln und drei und zwanzig Beiträgen auf internationalen wissenschaftlichen Konferenzen verbreitet. Die im Rahmen von iPrecise gewonnenen Erkenntnisse werden auch die Entwicklungen der nächsten Generation von Perowskit-auf-Silizium-Tandemgeräten unterstützen.

Résumé

L'objectif principal d'iPrecise était de préparer la prochaine génération de cellules solaires à base de silicium cristallin (c-Si). Pour ce faire, le développement de matériaux et de procédés a été entrepris afin d'augmenter l'efficacité de conversion des dispositifs solaires en c-Si tout en garantissant la compatibilité avec une fabrication durable et à grande échelle.

Nous avons tout d'abord étudié la pulvérisation cathodique comme alternative à la fabrication de la couche passivante à base de silicium polycristallin (poly-Si) présente sur la face arrière de la structure de cellule solaire TOPCon, qui devient majoritaire dans l'industrie en 2024. Par rapport aux méthodes de fabrication plus conventionnelles basées sur le dépôt chimique en phase vapeur (CVD), la pulvérisation cathodique présente l'avantage d'être plus directionnelle et de ne pas nécessiter de gaz dangereux ou toxiques. Malgré ces avantages, au début du projet, il n'était pas clair si les matériaux poly-Si pulvérisés pourraient égaler les performances du poly-Si fabriqué par CVD. Dans le cadre de ce projet, nous avons pu démontrer des propriétés électriques et de passivation pour les matériaux poly-Si pulvérisés égalant les propriétés obtenues avec des couches poly-Si fabriquées par CVD.

A la suite de ces développements, nous avons intégré les contacts poly-Si pulvérisés à l'arrière de cellules solaires TOPCon de surface industrielle, ce qui a permis de démontrer des rendements de conversion allant jusqu'à 22,8 %. De plus, nous avons étudié des solutions pour la structuration des couches de poly-Si afin de les intégrer en face avant de dispositifs TOPCon double face (DS-TOPCon). La première approche que nous avons étudiée était basée sur l'utilisation d'un masque lors du dépôt de la couche de poly-Si. Après optimisation de la structure de la couche et de sa mise en contact avec des doigts métalliques, nous avons pu démontrer des dispositifs DS-TOPCon de petite surface avec des rendements allant jusqu'à 21,7 %. Ce résultat est resté parmi les meilleurs rapportés dans la littérature pour une structure DS-TOPCon tout au long du projet.

De plus, nous avons effectué des modélisations pour évaluer le potentiel de la structure DS-TOPCon par rapport à la TOPCon standard. Nos résultats indiquent que la résistance de contact associée au contact poly-Si devrait être réduite pour que la structure DS-TOPCon dépasse significativement les performances de la TOPCon standard, et ce, à des valeurs qui pourraient être difficiles à atteindre en pratique.

Tout au long du projet, le développement de dispositifs solaires c-Si à haut rendement a été soutenu par des caractérisations avancées. Tout d'abord, nous avons réalisé une étude approfondie basée sur des analyses de microscopie électronique. Cela nous a permis de construire un modèle pour décrire la pénétration des pâtes commerciales à base d'aluminium à travers l'empilement passivant SiN_x/poly-Si situé à l'arrière de la structure TOPCon. De plus, nous avons développé une méthode pour évaluer la structure et la composition de la couche nanométrique de SiO_x située à l'interface poly-Si/c-Si. Cette méthode a permis le développement de couches de SiO_x présentant une meilleure stabilité thermique, ce qui a permis d'améliorer les propriétés des contacts poly-Si.

Globalement, ce projet a permis le développement de nouvelles briques technologiques pour la fabrication de cellules solaires en c-Si à haut rendement ainsi que de meilleures connaissances scientifiques sur leur principe de fonctionnement. Les résultats marquants du projet ont été diffusés à la communauté scientifique grâce à la publication de sept articles et de vingt-trois contributions à des conférences internationales. Les connaissances acquises durant le projet iPrecise bénéficieront également aux développements de dispositifs tandem pérovskite-sur-silicium de nouvelle génération.

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1 Introduction

The iPrecise project was devoted to the development of next generation crystalline silicon (c-Si) solar cells. During the project, the mainstream industrial solar cell structure shifted from Passivated Emitter and Rear Cell (PERC) to Tunnel Oxide Passivated Contact (TOPCon). The TOPCon structure consists of a boron-doped diffused emitter on the front side and a phosphorus-doped polycrystalline silicon (poly-Si) passivating contact on the rear. Its steady implementation into production will sustain the conversion efficiency increase of about 0.4-0.5% abs/year that has characterized the silicon photovoltaic (PV) field for the last twenty years. However, in coming two to five years, the TOPCon conversion efficiency will eventually reach a limit of about 26% in production.

At the beginning of the project, the optimal solar cell structure(s) to follow on TOPCon had not yet been identified. The project was devoted to the research and development of materials and processes to upgrade the TOPCon concept and enable higher conversion efficiency while ensuring compatibility with production. The work was more particularly focused on two aspects:

1) the optimization of poly-Si passivating contacts for integration on both the rear and front sides of c-Si solar cells,

2) the investigation of Ag-lean metallization strategies for decreasing the TOPCon production costs while improving sustainability in terms of natural resource usage.

2 Context

2.1 Background / State of the art

When the project started in March 2021, the TOPCon structure was on the verge of being industrially ready. Since then, the TOPCon technology has been steadily deployed in production and is expected to represent half of the global production capacity by the end of 2024, with about 90% installed in China [1].

The year 2023 has been marked by a very intense competition between Chinese cells and modules manufacturers leading to overproduction capacities and thin or even negative margins for companies involved. As a result, the price gap between products manufactured in China and in other regions of the world such as Europe or the US has increased of about 30% compared to early 2023 [2]. It is thus currently difficult for PV companies based in Europe or in the US to remain profitable in such a competitive and fast-moving context. Some of them are nonetheless surviving such as Q-cells and Meyer Berger and some initiatives for setting-up the production of TOPCon cells and modules are currently taking place in Europe. This includes two projects of gigafactories in France carried out by start-ups Holosolis and Carbon.

To cope with the current economic pressure and support local manufacturing of PV products, it is thus important for regions such as Switzerland and Europe to preserve know-how and innovation capabilities related to PV technologies. The R&D efforts should particularly be focused on:

- Preparing the next generation(s) of solar cells and modules to sustain the efficiency increase of about 0.5% abs/year while ensuring scalable and sustainable fabrication process.
- Protecting any novel concepts (e.g., solar cell structure, process sequence or materials) found along the way with proper Intellectual Property (IP) whenever applicable.

2.2 Motivation of the project

In this context, the primary motivation of iPrecise was to support the development and deployment of PV in Switzerland and Europe. To do so, we investigated novel technological solutions to enhance the performance of c-Si solar cells, especially TOPCon. Additionally, we placed a strong emphasis on the development of sustainable materials and processes to minimize the carbon footprint associated with the resulting devices. The project also contributed to maintaining a high-level of expertise and innovation in the field of PV in Switzerland. On top of the technological developments the project allowed for:

- The training of several scientists to the optimization of materials and processes for application in c-Si solar cells and to the fabrication and characterization of full Si PV devices. The trained personnel include two post-docs, three PhD students, two engineers and height MSc students. On top of developing their technical skills, the scientists involved in the project improved their general knowledge in renewable energies as well as their scientific creativity and ethic. These scientists will most likely remain part of the Swiss or European Si PV community after completion of the project and thus keep supporting the developments in the field.
- Maintaining the visibility of PV-Lab and CSEM as institutes committed to research and development in the field of PV. So far, the project outcome includes seven articles published in peer-reviewed scientific journals (with four additional manuscripts submitted or in preparation), and twenty-three contributions to international scientific conferences (including fourteen oral presentations). More details about the scientific dissemination associated to the project can be found in part 6.

2.3 Goals

The main goal of iPrecise was to develop novel materials and processes to enhance the efficiency of TOPCon solar cells while ensuring scalable and sustainable fabrication sequence. More specifically, the following objectives were targeted:

- Further optimize the performance of poly-Si contacts fabricated by PECVD and sputtering. A special emphasis was put on the development of poly-Si layers fabricated by sputtering to strengthen the IP acquired by CSEM on this technology.
- Develop solutions for patterning poly-Si layers for their integration on the front side of TOPCon devices (structure referred to as Double-Side (DS-)TOPCon).
- Reduce the amount of critical raw materials used in TOPCon solar cells. We notably focused on investigating Ag-lean metallization strategies for contacting (p-type) poly-Si contacts.

3 Approach and methodology

The methodology implemented in iPrecise to reach the set objectives relies on two main features:

- **Multidisciplinary approach** – The iPrecise project relied on a team composed of scientists from CSEM and EPFL (PV-Lab) featuring a broad range of skills, spanning from opto-electronic to material science. Over the course of the project, we could thus perform in-depth characterizations (e.g., TEM, XPS, XRR) to elucidate the interrelation between materials and functional properties of the fabricated thin-films and devices. In parallel, we frequently reassessed the project's technological targets to ensure they remain aligned with trends of the global PV market. On top of allowing for efficient and accurate developments, this approach enables the generation of new scientific outputs that were disseminated through contributions to scientific journals and conferences (see part 6).
- **Incremental developments** – The development of new materials and processes were first performed on very simple structures (e.g., single material on one or both sides of glass or c-Si substrates). After validation of the functional properties on test samples, the sample structure was incrementally complexified towards the fabrication of complete solar cells. In most cases, we first fabricated small area devices of 2 cm^2 before moving to larger areas of up to 156.75x156.75 cm^2 (M2). This approach enables any limitations to be detected and corrected timely, thus ensuring steady developments towards set technological goals.

4 Results and discussion

In this part, the main results obtained throughout the project are presented in the form of "highlights" sorted per WP. For some of these highlights, a scientific article describing the work was already published at the time of writing this report. In that case, only a short summary of the results is provided and a reference to the associated publication is provided. The different milestones (MLs) initially foreseen are recalled together with mitigation strategies applied whenever the initial targets were not met timely.

4.1 WP1 – Materials developments

Highlight 1.1 – Sputtered poly-Si(n) contact enabling high surface passivation and low contact resistivity

Poly-Si based passivating contacts rely on the formation of a shallow n+ doped diffusion tail at the surface of the Si substrate, which supports chemical passivation provided by the thin SiO_x and promotes electron extraction. However, if too deep, this highly doped diffused region leads to increased Auger recombination, jeopardizing achieving optimum electrical performance for the associated passivating contact structure. From an industrial point of view, the ideal approach is to form this highly doped diffused region by in-situ doping the poly-Si layer followed by a high thermal annealing. For sputtered poly-Si materials, achieving a sufficiently high active doping density after annealing is quite challenging when relying on Si:P sputtering targets due to the high volatility of phosphorus (P) compared to Si. Consequently, with standard PVD target manufacturing methods (e.g., spraying, sintering), most of the active P species evaporate and are not incorporated into the Si target, which limits the maximum P doping to 3-4% in the target. Alternative target manufacturing techniques have been tried to improve the P content of the PVD targets, especially cold isostatic pressing, unfortunately without much success. Nonetheless, by tuning different process parameters including the P content of the Si:P target, the sputtering parameters (such as power, Ar flow, time), and the annealing temperature, we achieved sufficient in-situ doping to fulfil **ML2** (> $5x10^{19}$ cm^{-3}). We thus kept investigating the in-situ doping approach and achieved a broad spectrum of doping profiles in the poly-Si/SiO_x/Si structure with surface concentration ranging from $2.7x10^{19}$ to $3.8x10^{20}$ cm^{-3} and diffusion depth from ~100 to ~600 nm. An optimum doping profile was obtained with the target containing 3% of P and enabled reaching iV_{oc} > 730 mV and contact resistivity of 2 mOhm.cm^2. These values are as good as the ones obtained with ex-situ doped passivating contacts and fulfil target metrics set in **ML1**. These developments and achievements are described in more details in a recently published manuscript, see ref. [3].

Highlight 1.2 – Ag-free metallization for PECVD poly-Si(p) fired contact

In WP1, we also investigated the development of Ag-free metallization strategies for contacting p-type PECVD poly-Si layers. First, we investigated a process consisting in the deposition of Al-based metal pads on top of the SiN_x coating layer (either by screen-printing of Al-based commercial paste or sputtering of pure Al) followed by firing in the range 450-800 °C. The firing enables the Al to diffuse through the SiN_x dielectric and contact the poly-Si layer underneath. Firstly, by tuning the composition of the SiN_x layer and the firing temperature, we could find a preliminary optimum between contacting Al to the poly-Si layer and limiting the passivation damage induced by Al penetration in the Si wafer. The work performed also allowed us to unravel the interactions between Al and the passivating stack consisting of the SiN_x/poly-Si(p), which was elusive in the literature at the time of publication (see *Highlight 5.1*). These results are described in more details in the associated publication [4]. However, these developments did not allow reaching the target metrics set in **ML1** (contact resistance of 5 mΩ.cm^{-2} together with iV_{oc} of 730 mV). We thus investigated an alternative metallization strategy consisting of removing the SiN_x top layer and sputtering the metal electrode directly on top of the poly-Si(p) layer. Different materials were tested as metal electrode, including Al and Mo. Doing so, we could achieve a contact resistance down to 5 mΩ.cm^{-2} together with an iV_{oc} of 720 mV, thus thinning the gap with targets set in **ML1**. These results are described in more details in ref. [5].

We note that, to date, the development of a cost-effective Ag-free metallization strategy for contacting poly-Si layers is still elusive. It currently remains a critical milestone to be achieved for ensuring a secured and sustainable TW-scale deployment of Si PV technologies in coming years. This topic is still of primary interest at CSEM and EPFL PV-Lab and is notably addressed in the SFOE-funded project COMET, which investigates metallization strategies based on copper for TOPCon devices. We note that the current Si PV modules contain about 10-15 mg of Ag per watt, which corresponds to 1 to 1.5 cents per watt (cts/W) at the current Ag price. The Ag content is Si PV devices will become critically important if the price of Ag rises, for example, due to speculation. A tenfold increase in the price of Ag would result in an increase in the cost of modules by 10 to 15 cts/W.

4.2 WP2 – Advanced patterning sequence

Highlight 2.1 – Development of a process for poly-Si patterning based on a mask during deposition

In WP2, we firstly focused on the development of a process for poly-Si patterning based on the application of a hard-mask during deposition of the poly-Si(n) layer (either by PECVD or sputtering). We successfully implemented a process for poly-Si patterning consisting of two following depositions: 1) a full-area poly-Si layer of about 10 nm to ensure surface passivation and 2) poly-Si lines deposited through a hard mask with thickness and width of about 100 nm and 100 µm, respectively. These developments led to the fabrication of proof-of-concept solar cells featuring patterned poly-Si(n) on the front side with conversion efficiency up to 21.7%. This study is described in more details in ref. [6].

Performing this work, we observed that the deposition rate of the poly-Si layer through the mask was reduced by a factor three compared to full area deposition, resulting in long deposition time for the poly-Si lines and thus hindering the cost-competitiveness of this process. We thus dedicated some efforts to develop a patterning process for poly-Si holding more potential for industrial manufacturing. A second limitation we noted is that the minimum width accessible for poly-Si lines fabricated with a hard mask is about 100 µm, which still represents significant coverage of the front side, especially when comparing to recent improvements in screen-printing metallization, which allows for finger width as small as 20-30 µm.

Highlight 2.2 – Development of a process for poly-Si patterning compatible with industrial manufacturing

At an early stage of the project, we had considered two different poly-Si patterning approaches compatible with industrial manufacturing. Both approaches consist in full-area deposition of a thick poly-Si layer (~100 nm) followed by selective wet-etching through exposure to a KOH-based solution to form the poly-Si lines. The fabrication of a patterned KOH-resistive mask on top of the poly-Si layer was intended either by 1) inkjet printing of an organic paste on top of the poly-Si layer, or 2) lasering of the poly-Si to promote local surface oxidation and crystallization.

At M16 of the project, we decided to focus our efforts on the first approach based on inkjet since it held more potential for successful implementation within the project's timeline (**ML3 and ML4**). A schematic illustrating the different steps of this process is represented in Figure 1.

We developed a process sequence in which we fully etch the poly-Si layer in between the poly-Si lines, followed by cleaning and re-passivation of the exposed c-Si regions with SiN_x. The choice of this sequence was motivated by preliminary experiments and modelling that indicated it to give the best compromise between process implementation and final device performance. Figure 2 illustrates the height profile of poly-Si lines fabricated either with a hard mask during PECVD or through inkjet-printing of an organic mask followed by poly-Si selective etching. As can be seen, conformal poly-Si lines could be obtained with both approaches. One additional advantage of the approach based on inkjet is that it could allow to fabricate thinner poly-Si lines down to 50 µm.

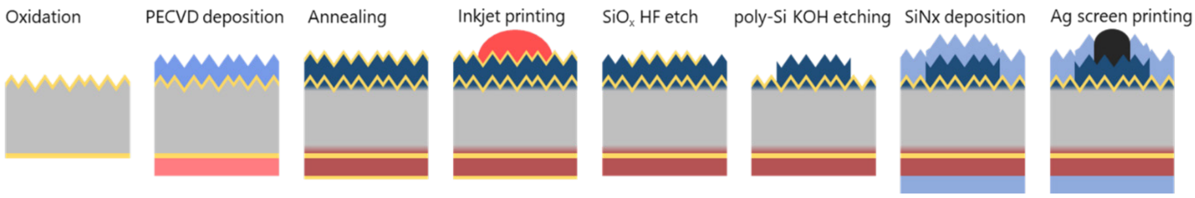

Figure 1. Process flow for the fabrication of Double-Side (DS-)TOPCon solar cells featuring a patterned poly-Si(n) layer on the front side following a sequence based on inkjet masking.

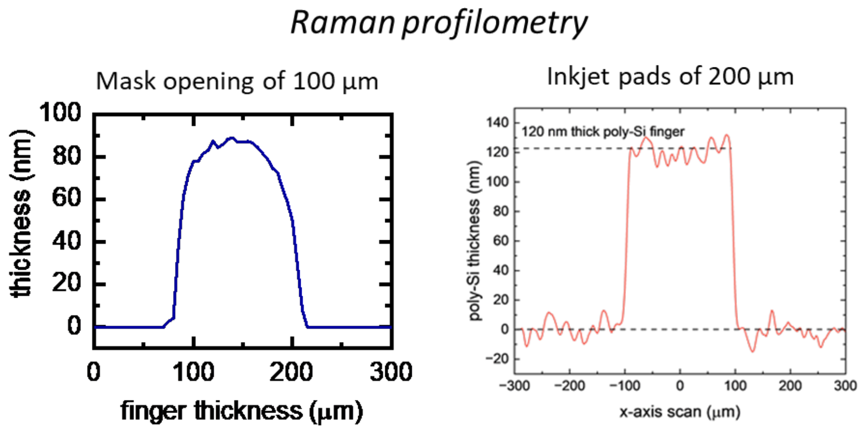

Figure 2. Height profile of poly-Si lines measured by Raman profilometry [7]. The poly-Si lines were fabricated using either a hard mask during poly-Si deposition (left) or inkjet masking followed by poly-Si selective etching (right).

4.3 WP3 – Solar cell integration

Highlight 3.1 – Proof-of-concept solar cells featuring patterned poly-Si on the front side

In WP3, we worked on the integration of materials and process sequences developed in WP1 & 2 for the fabrication of small area proof-of-concept solar cells. First, with the initial patterning approach based on hard mask during poly-Si deposition, we fabricated solar cells featuring ~100 nm thick poly-Si(n) lines localized below the front metal fingers. The optimization of the firing temperature for contacting the metal fingers to the poly-Si lines through the top SiN_x layer allowed us to find the best compromise between surface passivation and efficient charge collection through the front stack. These developments led to the demonstration of devices with up to 21.7% conversion efficiency. This figure is still among the best results reported in the literature for such a structure [8–10]. These developments are described in detail in ref. [6].

Highlight 3.2 – Implementation of industrial-compatible poly-Si patterning in baseline for solar cell fabrication

After development of the industrial-compatible patterning process in WP2, we worked on its implementation in our baseline for fabricating full devices. Before producing full solar cells, we had to optimize: 1) the surface re-passivation of the c-Si surface left exposed after selective etching of the poly-Si layer and 2) the alignment of the metal fingers to the poly-Si lines on the front side (last two steps in Figure 2). The surface re-passivation was achieved through the implementation of a sequence consisting of surface wet cleaning followed by SiN_x deposition and firing. The front SiN_x layer (together with firing) thus fulfils the surface re-passivation of the exposed front Si regions after KOH etching on top of anti-reflective coating and hydrogenation of the Si wafer bulk and surfaces. A key enabler to reach high surface passivation of the front side after KOH selective etching and re-passivation was to apply an extended exposure to KOH up to 240 s. As illustrated in Figure 3, even though the poly-Si layer is likely fully etched after 60 s, the surface passivation is only fully recovered after SiN_x re-passivation when a KOH exposure of at least 240 s is applied. We hypothesize that prolongating the KOH exposure enables for a cleaner Si surface (e.g., elimination of surface residues) allowing for better surface re-passivation. Figure 4 illustrates the poly-Si lines obtained after KOH etching. Well-defined 200 µm-thick poly-Si lines could be obtained with the process based on inkjet. As also shown in Figure 4, we could obtain a good alignment between the 50 µm-thick Ag fingers and the 200 µm-thick poly-Si lines. From these developments we could fabricate proof-of-concept solar cells following a process compatible with industrial manufacturing. However, the performance obtained with the resulting devices are so far limited due to difficulties in achieving low enough contact resistances at the metal/poly-Si interface. In parallel to these technological developments, we built a semi-empirical model to evaluate the potential of the DS-TOPCon structure (see *Highlight 5.3*). The results of this modelling study notably indicated that the metal/poly-Si contact resistivity should be lower than 1 mΩ.cm^2 for the DS-TOPCon to represent a cost-effective alternative to standard TOPCon. Considering the challenge in reaching such low contact resistivity values, especially with PECVD poly-Si layers, as a mitigation strategy, we decided to also investigate the fabrication of standard TOPCon through a simplified process flow based on the versatility of PECVD (as described in next paragraph).

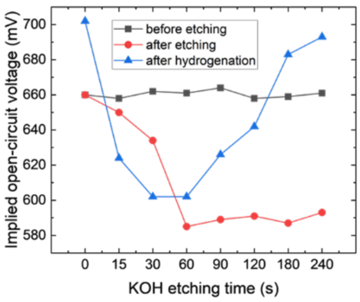

Figure 3. iV_{oc} measured at different steps of the process (see Figure 1) as a function of the KOH exposure time applied for poly-Si selective etching.

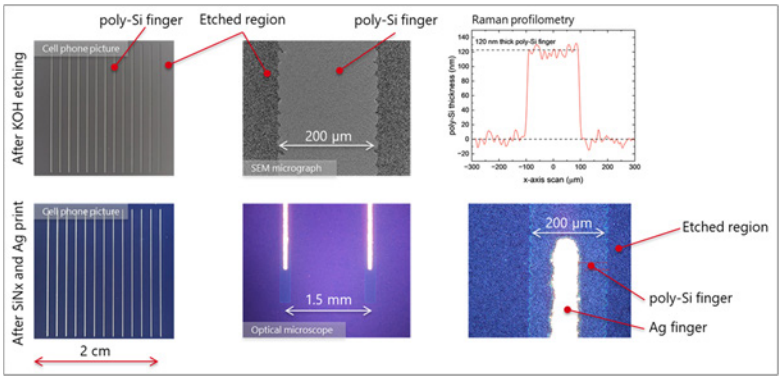

Figure 4. Various observations of the patterned poly-Si lines after KOH etching (top) and after SiN_x deposition and metallization (bottom).

Highlight 3.3 – Proof-of-concept TOPCon solar cells featuring co-annealed front and rear sides

Considering the challenge of implementing the poly-Si patterning sequence and reaching high efficiency devices featuring patterned poly-Si on the front, as a mitigation and based on the knowledge developed in the project, we developed an alternative process to simplify the fabrication of TOPCon devices. The process flow currently followed to fabricate industrial TOPCon devices and the simplified process flow developed in this project are both represented in Figure 5. For simplifying the TOPCon process we leveraged our know-how in thin-film fabrication by PECVD. We first developed a B-diffused emitter for application on the front side. The B-diffusion is obtained from the deposition of a B-rich SiO_x layer by PECVD followed by tube furnace annealing. By varying the B concentration in the SiO_x doping layer and the thermal budget, we could tune the B-diffusion to enable high surface passivation and efficient charge collection to the metal contacts. Then, we optimized the rear side poly-Si(n) contact to be compatible with the thermal budget applied for B-diffusion on the front. After such optimizations, we could fabricate first proof-of-concept TOPCon solar cells with front B-emitter and rear poly-Si contact activated through a single annealing step. Within only three optimization iterations, and notably by tuning the firing temperature applied for forming the front metal contact, we could achieve up to 21% conversion efficiency, as illustrated in Figure 6. These developments represent a significant simplification of the TOPCon fabrication process and are associated with the demonstration of very encouraging results within limited developments. Noticeably, there is room for further improving the performance of such co-annealed TOPCon devices by reducing the surface doping associated to the boron emitter, and applying the novel proprietary method referred to as LECO (laser enhanced contact optimization) [11].

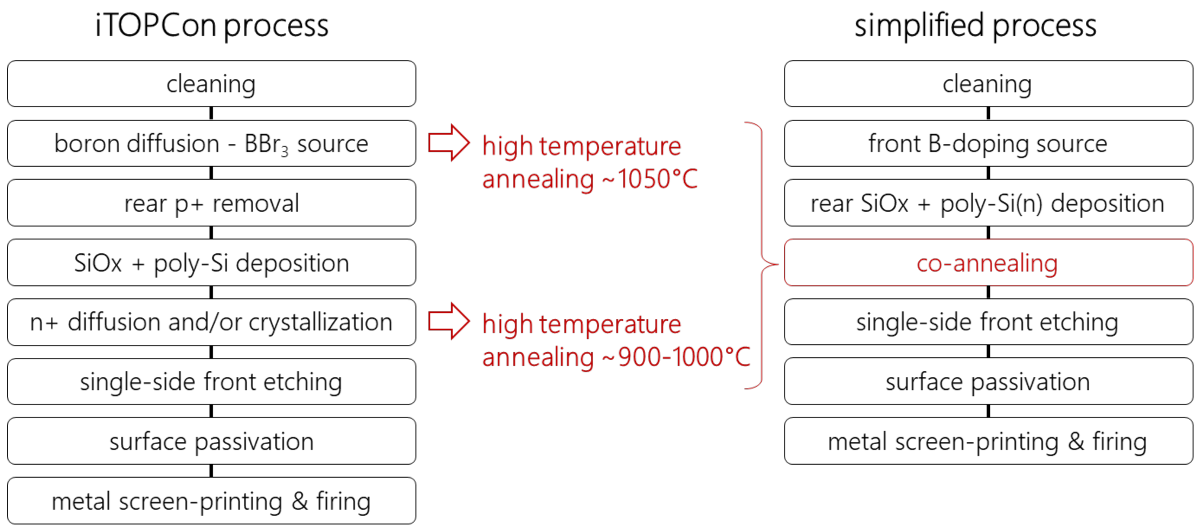

Figure 5. Process flow currently applied in the industry for fabrication of TOPCon devices (left) versus simplified process considered in this work (right).

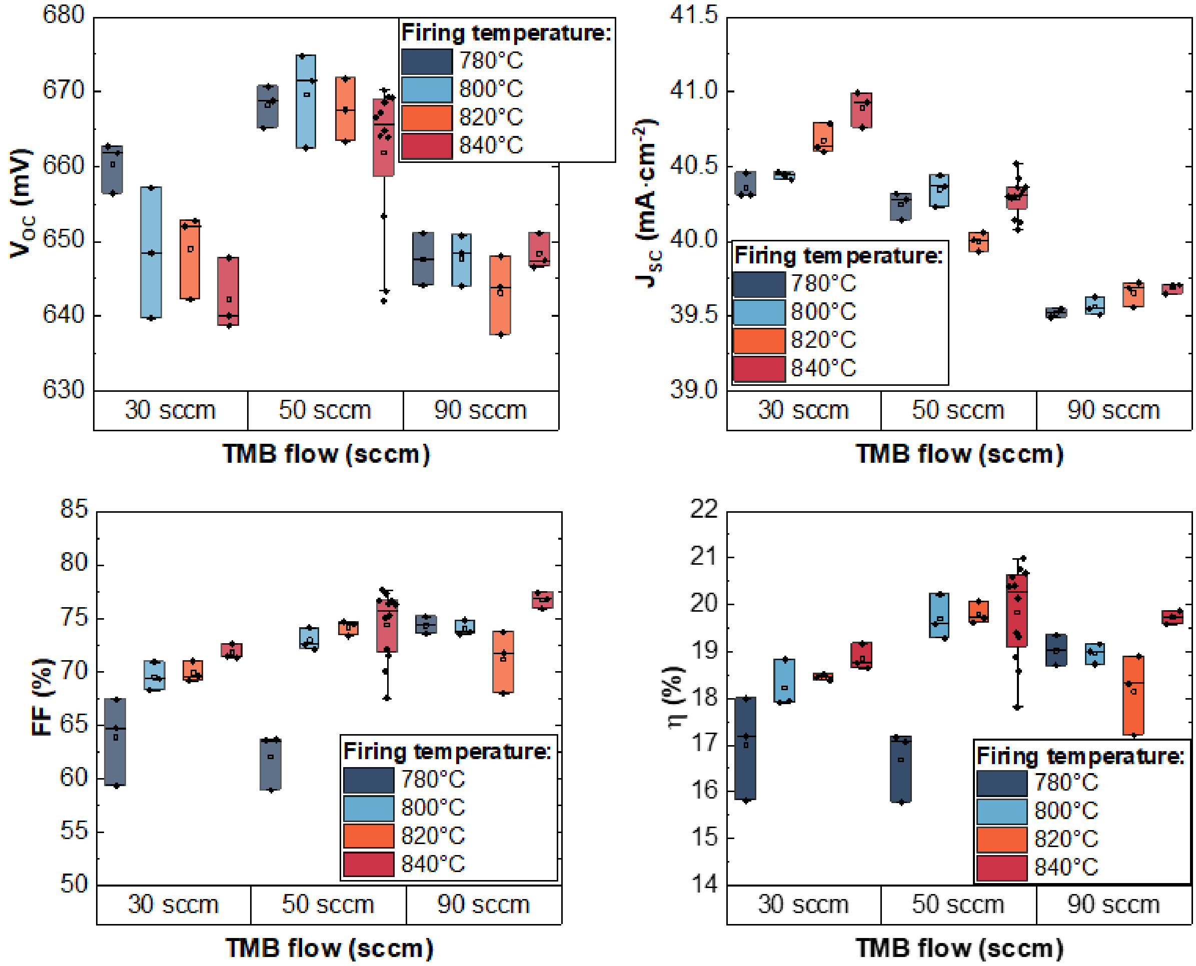

Figure 6. IV parameters measured on TOPCon devices featuring an active surface area of 2x2 cm2 and fabricated through co-annealing of the front B-emitter and the rear poly-Si(n) passivating contact. The TMB flow for doping of the front SiOx:B doping source and the firing temperature for front metallization were varied between 30 and 90 sccm and 780 and 840 °C, respectively.

4.4 WP4 – Solar cell upscaling and stability

Highlight 4.1 – Large area n-type TOPCon solar cells integrating sputtered poly-Si on the rear side

The first important milestone of WP4 was to demonstrate high-efficiency TOPCOn devices integrating sputtered poly-Si contacts on the rear side. To do so, we relied on single-side textured precursors provided by an industrial partner featuring a diffused B-emitter on the front. These precursors were then further processed at CSEM with the fabrication of the sputtered poly-Si contact on the rear, using plasma-assisted ex-situ doping and an annealing temperature of 900 °C. Figure 7 shows the certified solar cell results obtained. The V_{oc} of 697 mV and fill factor (FF) of 80.5% are promising values. Co-processed symmetrical samples featuring B-diffused emitter and AlO_x/SiN_x passivating stack on both sides are characterized by a recombination current density in the passivated region ($J_{0,pass}$) of 30 fA/cm^2, a recombination current density in the metallized region ($J_{0,met}$) of 370 fA/cm^2, and a contact resistivity (ρ_c) of 4.1 mΩ.cm^2. Co-processed symmetrical samples featuring passivating contacts and SiN_x on both sides featured $J_{0,pass}$ of 9 fA/cm^2, $J_{0,met}$ of 67 fA/cm^2, and ρ_c of 20 mΩ.cm^2. Simulations performed with these values as inputs suggest the potential for TOPCon devices integrating sputtered poly-Si to reach an efficiency of 25% upon improvement of the front side and fine-tuning of the Si wafer characteristics (e.g., resistivity, thickness). More details about this part of the work can be found in ref. [12]. The target set at the beginning of the project was to demonstrate 25% conversion efficiency with such a device structure on a surface area of at least 100 mm^2 (**ML5**). Our best practical demonstration by the end of the project remained of 22.8%. We identified that the first order lever to practically reaching 25% was to improve the surface passivation and electrical contact on the front side that both strongly depend on the B-diffusion profile. Throughout the project, the standard Si wafer size processed in the industry increased from M2 and M6 (156x156 mm^2 and 166x166 mm^2) to M10 and G12 (182x182 mm^2 and 210x210 mm^2, respectively). This prevented us from benefiting from state-of-the-art pre-diffused precursors since such wafer size could not be processed in CSEM facilities (limited to M6 at the time). To overcome this limitation and be able to demonstrate the full potential of sputtered poly-Si contacts, an upgrade of CSEM facilities using CSEM's own funds has been undertaken in 2023 to enable processing Si wafers up to G12. A home-made PECVD Kai-M tool has been built in 2023 and is expected to be up & running in Q3 2024, and a new wet-bench has been purchased in 2023 and is expected to be installed in Q1 2025. In addition, various home-made custom characterization tools suitable for G12 wafers are currently being built at CSEM (PL, EQE, IV). Together, these upgrades are worth several millions CHF and show the commitment of CSEM to keep its competitive edge in the fierce PV competition.

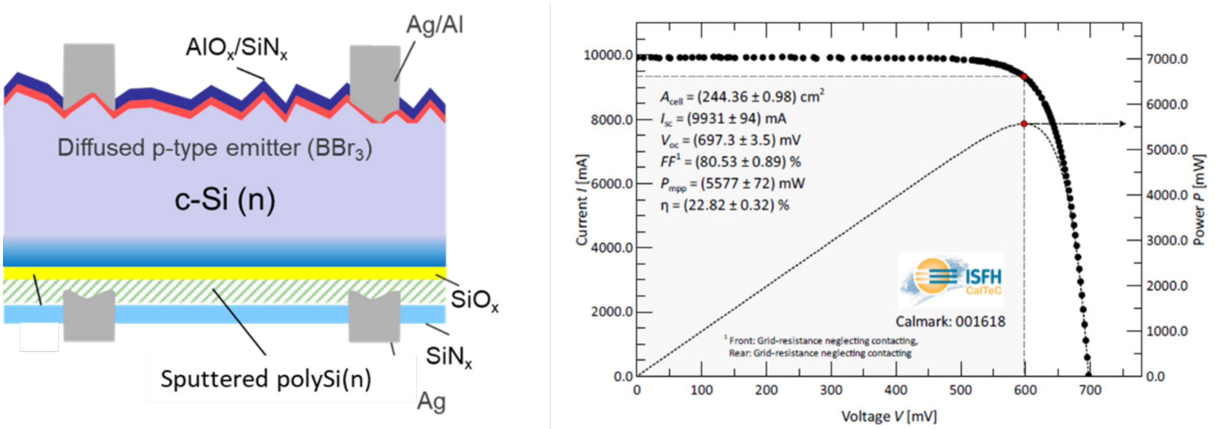

Figure 7. Schematic of the TOPCon solar cell integrating sputtered poly-Si on the rear side (left).
IV curve and main IV parameters of M2 size TOPCon-like solar cells featuring sputtered poly-Si passivating contact on the rear side (right).

Highlight 4.2 – Stability of n- and p-type poly-Si layer under light-soaking up to 1000h

In WP4, we also investigated the surface passivation stability of poly-Si layers developed in the project. To do so, we assembled a set-up consisting of a lamp and a hotplate to expose samples simultaneously to light (1 sun) and moderate temperature (200 °C), a process referred to as light-soaking. We investigated the stability of n- and p-type poly-Si layers at different stage of their fabrication process (namely, after thermal activation through firing or long-annealing and after hydrogenation) and deposited on different types of substrates (FZ- or Cz-grown Si wafers). We exposed these samples to light-soaking for up to 1000 h during which we monitored their effective lifetime and surface passivation level. Our main findings were the following:

- The surface passivation stability depends on the doping type and thermal budget applied to the poly-Si layer. We notably found that the surface passivation provided by fired poly-Si layers was degrading after a couple of days of light-soaking, which represents a limit to their further development and commercialization.
- For samples fabricated from Cz Si wafers, the lifetime associated to hydrogenated n-type poly-Si layers was observed to first degrade and then regenerate upon light-soaking, as illustrated in Figure 8. This trend is in good agreement with other light-soaking experiments reported in the literature for similar sample structures [13–15]. The lifetime associated to p-type poly-Si layers was found stable upon light-soaking both after annealing and hydrogenation. These are important findings since it indicates these passivating contact stacks have the potential to pass stability tests when integrated in commercial solar cells and modules. We note that the lifetimes of hydrogenated n-type poly-Si layers after exposure to 1000 h of light-soaking surpassed the ones initially measured. This result suggests that accelerated post-treatments may boost the performance of TOPCon solar cells and modules, similarly as what was demonstrated for SHJ products [16,17].

When writing the project, we anticipated the demonstration of 4-cells encapsulated module incorporating the developed large area device passing the IEC tests (**ML6**). However, due to the challenges faced in integrating the developed technological bricks (sputtered poly-Si on the rear and patterned poly-Si on the front) into devices approaching 25%, we decided to keep the focus on the development of high-efficiency solar cells for the last six months of the project rather than tackle module integration and testing. However, the light-soaking tests described above suggest that accelerated post-treatments may benefit TOPCon solar cells and modules thus this approach may be of interest in the future.

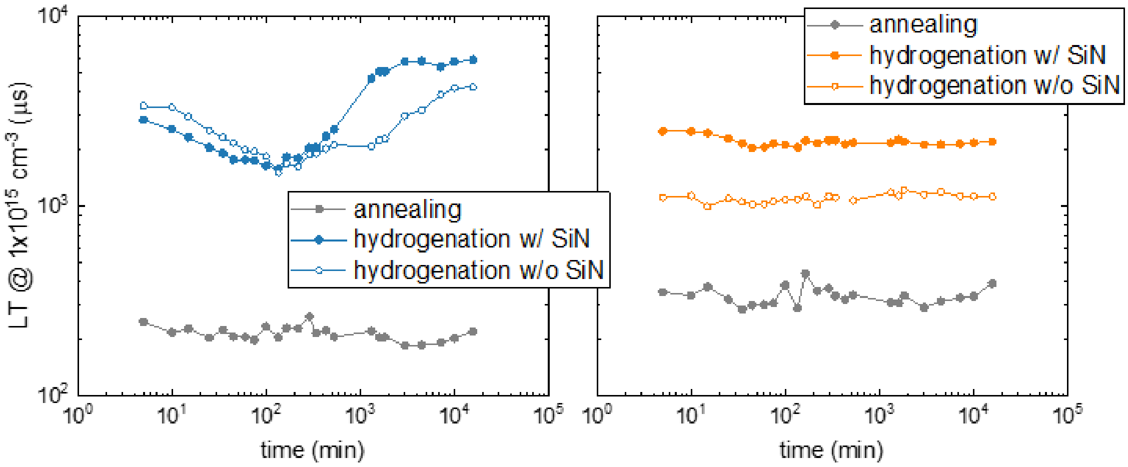

Figure 8. Evolution of the minority carrier lifetime of symmetrical samples featuring poly-Si(n) (left) and poly-Si(p) (right) passivating stacks through exposure to light-soaking (1 sun, 200 °C) at different fabrication steps.

4.5 WP5 – Characterization and modelling

Highlight 5.1 – Characterization of the contact formation between Al and SiN_x on poly-Si passivating stack

In WP1, we worked toward the development of Ag-free metallization strategies to contact p-type poly-Si layers, notably by replacing Ag with Al (see *Highlight 1.2*). At an early phase of the project, the development of an Al-based metallization strategy to contact the poly-Si layer through the SiN_x dielectric coating appeared quite challenging. More specifically, it appeared difficult to control the Al diffusion to reach the poly-Si layer without diffusing further to the Si substrate, where it would damage surface passivation. We thus undertook in-depth microscopy analyses along the technological developments to unravel the interactions between Al and the SiN_x/poly-Si passivating stack underneath. The main finding was that the ability of Al to diffuse through the SiN_x layer (and thus to contact the poly-Si) strongly depends on the composition of the SiN_x layer. A Si-rich SiN_x layer will promote Al diffusion whereas an N-rich layer will block it. Considering these findings, we could tune the composition of the SiN_x layer to enable a better compromise between contacting Al to the poly-Si layer while limiting passivation damage induced by Al penetration into the Si wafer. These results are detailed in ref. [4].

Highlight 5.2 – Modelling and characterization for the integration of p-type poly-Si contact on the rear side of Si solar cells

In WP5, we performed a study coupling characterizations and modelling in view of integrating the p-type fired poly-Si layer on the rear side of Si solar cells with local metal contacts. More specifically, the goal of the study was to characterize and model the different contributions to the total resistance of the metal/poly-Si stack with a view to improving the performance of the final device. Through this study, we could demonstrate that increasing the thermal budget applied to the poly-Si layer can effectively mitigate resistive losses and enhance contact electrical performance. Following this result, it appeared that an oxide layer that can withstand high thermal budgets is key for obtaining simultaneously high surface passivation quality and good electrical properties for the targeted structure. We investigated three different oxides grown either by HNO_3 immersion, UV-O_3 exposure or N_2O plasma oxidation. The latter appeared as a promising candidate for an application in devices submitted to high thermal budgets. These results are presented in more details in ref. [5]. An additional manuscript covering the developments and advanced characterization of N_2O oxides has also been submitted to the journal ACS Applied Materials and Interfaces.

Highlight 5.3 – Modelling to evaluate the potential and first order limitation(s) of Si solar cells featuring patterned poly-Si on the front

In WP2 & 3, we worked on the development of patterned poly-Si(n) layers and their integration on the front side of Si solar cells. Performing this work, we realized that the development of a poly-Si patterning sequence compatible with industrial manufacturing and its implementation in our R&D labs were quite challenging (see *Highlight 3.2*). We thus developed a model to evaluate if the performance gain from integrating a poly-Si layer on the front of the device would justify the added process complexity and cost compared to industrial TOPCon. We found that to minimize absorption losses, the width of the poly-Si lines on the front side should be the smallest possible and the poly-Si should be totally removed in between these lines. In practice, using inkjet, one could aim for poly-Si lines with a width down to 50 µm. This should still enable a good alignment with ~20 um-wide metal fingers, which is the current industrial mainstream. Following this, we found that for such a front structure, the contact resistance between the metal and the poly-Si lines should be reduced to at least 1 $m\Omega.cm^{-2}$ to have a chance to surpass performances currently achieved with industrial TOPCon devices (Table 1). However, this project also enlightened that such low values for the metal/poly-Si contact resistance were challenging to achieve when combining PECVD poly-Si layers with firing-through metallization (see *Highlights 1.1 & 1.2*).

Table 1. Simulation of the performance of TOPCon solar cells based on the recombination current densities in the passivated ($J_{0,p}$) and metallized ($J_{0,m}$) regions as well as the rear side contact resistivity (ρ_c) and sheet resistance (R_{sheet}). The parameters were either extracted from the characterization of test samples at PV-Lab (1st column) or from the literature (2nd and 3rd columns).

	PVLab	Literature data*	Best TOPCon**
Simulation input (front side)			
$J_{0,p}$ / $J_{0,m}$ (fA.cm^2)	15 / 400	2 / 40	2 / 300
ρ_c (mΩ.cm2)/ R_{sheet} (Ω.sq)	15 / 500	1 / 200	0.7 / (80-300)
Output			
Voc (mV)	**703**	**737**	**730**
Jsc (mA.cm^2)	**40.8**	**42.3**	**41.8**
FF (%)	**81.0**	**84.9**	**85.9**
Efficiency (%)	**23.25**	**26.5**	**26.3**

*Simulated using optimised grid design compared to "Pvlab" simulation
**Using published values from DAS Solar:
https://taiyangnews.info/new-world-record-for-highest-voc-of-topcon-cells

5 Conclusion and perspectives

In conclusion, within the iPrecise project, we successfully demonstrated new materials and processes to upgrade the TOPCon structure. First, we demonstrated the potential of poly-Si contacts fabricated by sputtering to achieve high surface passivation and efficient transport of charge carriers to the metal. We optimized the fabrication process of the poly-Si layer, particularly the phosphorus content of the sputtering target and the annealing temperature. This enabled us to reach an optimal active doping concentration in the layer and at the c-Si surface. After optimization, we integrated the sputtered poly-Si contact on the rear side of large-area TOPCon devices, achieving conversion efficiencies of up to 22.8%.

Additionally, we investigated methods to pattern the poly-Si layer for its integration on the front side of Double Side (DS-)TOPCon devices. We successfully developed two methods for patterning the poly-Si layer. The first method uses a hard mask during PECVD deposition of the poly-Si layer, and the second method involves full-area deposition of the poly-Si layer followed by selective etching through a mask fabricated by inkjet. By integrating the poly-Si layer patterned through the first method, we demonstrated small-area DS-TOPCon solar cells with efficiencies of up to 21.7%. While the conversion efficiency targets set initially were not met by the end of the project, the values achieved with TOPCon featuring sputtered poly-Si and DS-TOPCon devices – 22.8% and 21.7%, respectively – remained among the best reported in the literature during the project. Finally, we explored solutions to reduce the amount of silver required to fabricate TOPCon devices. We tested contacting the SiN_x/poly-Si passivating stack with a paste composed of aluminum and silver. Our results showed that the composition of the SiN_x layer is a key parameter to control to enable contacting the poly-Si layer with the metal without damaging the c-Si surface passivation. By fine-tuning the SiN_x composition, we improved the balance between charge carrier collection to the metal and surface passivation level.

Throughout the project, we also performed characterizations and modelling to support the technological developments. Notably, we built a model to assess the potential of DS-TOPCon as an upgrade to standard TOPCon. Our results indicate that the contact resistance associated with the poly-Si contact needs to be lowered for DS-TOPCon to significantly outperform TOPCon, which may be challenging to achieve practically. Additionally, we conducted a comprehensive study using electron microscopy, allowing us to model the penetration of aluminum through the SiN_x/poly-Si passivating stack. Lastly, we developed a method to evaluate the structure and composition of the nanometric SiO_x layer at the poly-Si/c-Si interface, allowing for in-situ analysis of representative samples. This method supported the development of thin SiO_x layers with improved thermal stability, ultimately enhancing the performance of the poly-Si contact.

The timeframe of the project was also marked by an increasing competition from Chinese solar cell and module manufacturers, making it challenging for PV companies located in other regions such as Europe, Switzerland and the US to remain economically sustainable. In this context, it is important for European and Swiss R&D institutes to sustain their efforts in generating and protecting IP related to next-generation PV technologies. This will contribute to maintaining a dynamic and innovative PV environment and support the development of already established or emerging local companies. In that view, EPFL PV-Lab and CSEM will continue their efforts in investigating solutions for highly efficient, scalable, and sustainable Si PV devices. Following iPrecise, the collaboration between the two teams will continue in the frame of other projects including two SFOE-funded projects, namely:

- COMET, a project dedicated to the development of Ag-free metallization strategies for TOPCon solar cells. The COMET project leverages the methodology developed in iPrecise for studying and modelling Cu diffusion and contacting poly-Si layers.
- BESTOBOT, a project dedicated to the development of TOPCon and SHJ devices for integration as the bottom sub-cell in perovskite-on-silicon (PK-Si) tandem devices. BESTOBOT will leverage many of the concepts demonstrated in iPrecise, including the tunnel recombination junction based on poly-Si layers, the thin SiO_x layer grown by N_2O plasma, the modelling of carrier transport in multi-layer stacks, and the characterization of thin-films' structure and composition. We note that for such tandem devices, the front metal contact is relocated on top of the PK sub-cell, which alleviates the challenge of achieving ultra-low contact resistivity for the front Si contact. In the context of BESTOBOT, we will thus be able to make the best of the thin full-area Si passivating layers developed in iPrecise.
- Leveraging the CHESS and iPrecise projects, bilateral developments are ongoing to set-up building blocks for the fabrication of Interdigitated Back Contacted (IBC-)TOPCon devices. This concept still requires large R&D efforts to demonstrate its efficiency potential at a competitive manufacturing cost. These developments will also support potential alternative processing of standard TOPCon, which may become relevant again in coming months to support a regrowing European industry. In that view, EPFL and CSEM teams are still committed to set-up and maintain bilateral contacts with most major PV companies in Europe (including historical players and new initiatives), as well as with various equipment manufacturers in Switzerland and Europe.

6 Publications

6.1 Oral presentations

Short name	Details
Meyer_2021_sipv	*Localisation of front side passivating contacts for direct metallisation of high-efficiency c-Si solar cells* 11th Silicon PV conference, online (2021) **Among 10 best abstracts**
Morisset_2021_pvtagung	*Technologies PV pour modules en silicium monocristallin : récents progrès et perspectives* 19e Congrès Photovoltaïque National, Bern (2021)
Allebé_2022_sipv	*Sputtered Poly-Si for the Formation of Passivating Contacts on the rear of Large Area n-PERT C-Si Solar Cells* 12th International Conference on Crystalline Silicon Photovoltaics, Konstanz, Germany (2022)
Morisset_2022_sipv	*In Situ Monitoring the Fabrication of p-type Poly-Si Passivating Contacts via X-ray Scattering* 12th International Conference on Crystalline Silicon Photovoltaics, Konstanz, Germany (2022)
Haug_2022_ipvc	*Fireable passivating contacts for c-Si solar cells* 49th IEEE Photovoltaic Specialists Conference, Philadelphia (2022)
Allebé_2022_wcpec	*Sputtered Poly-Si and its Implementation in Passivating Contacts on the rear of Industrial N-PERT Solar Cells* 8th World Conference on Photovoltaic Energy Conversion, Milan, Italy (2022)
Morisset_2023_sipv	*Impact of doping type and thermal budget on long-term stability of poly-Si passivating contacts* 13th International Conference on Crystalline Silicon Photovoltaics, Delft, The Netherlands (2023)
Allebé_2023_ieee	*Sputtering for poly-Si based passivating contacts* 50th IEEE Photovoltaic specialists conference, San Juan, Puerto Rico (2023)
Hurni_2023_eupvsec	*Localization of front-side passivating contacts for direct metallization of high-efficiency c-Si solar cells* 40th European Photovoltaic Solar Energy Conference and Exhibition, Lisbon, Portugal (2023)
Morisset_2023_eupvsec	*Towards leaner fabrication of high-efficiency TOPCon c-Si solar cells* 40th European Photovoltaic Solar Energy Conference and Exhibition, Lisbon, Portugal (2023)
Descoeudres_2023_eupvsec	*Sputtered poly-Si layers for the formation of n- and p-type passivating contacts* 40th European Photovoltaic Solar Energy Conference and Exhibition, Lisbon, Portugal (2023)
Haug_2024_eupvsec	*Impact of Rapid Thermal Processing on Bulk Lifetime and Surface Recombination Velocity of Crystalline Silicon with Passivating Tunnel Oxide Contacts* 41th European Photovoltaic Solar Energy Conference and Exhibition, Vienna, Austria (2024)
Hurni_2024_eupvsec	*Towards Leaner (Double Side) TOPCon Fabrication*

	41th European Photovoltaic Solar Energy Conference and Exhibition, Vienna, Austria (2024)
Libraro_2024_eupvsec	*Development and Characterization of N2O-plasma Oxide Layers for High-Temperature Passivating Contacts* 41th European Photovoltaic Solar Energy Conference and Exhibition, Vienna, Austria (2024)

6.2 Poster presentations

Short name	**Details**
Morisset_2021_eupvsec	*Front integration of thin poly-Si(n) passivating contacts in both-side contacted high-efficiency c-Si solar cells* 38th European Photovoltaic Solar Energy Conference and Exhibition, online event (2021)
Meyer_2021_eupvsec	*Localisation of front side passivating contacts for direct metallization of high-efficiency c-Si solar cells* 38th European Photovoltaic Solar Energy Conference and Exhibition, online event (2021)
Libraro_2022_sipv	*Interactions between Aluminium and Poly-Si based Contact Stacks during Fire-through Metallization* 12th International Conference on Crystalline Silicon Photovoltaics, Konstanz, Germany (2022)
Haug_2022_sipv	*p- and n-type fired passivating tunnel oxide contacts for crystalline silicon solar cells* 8th World Conference on Photovoltaic Energy Conversion, Milan, Italy (2022)
Morisset_2023_pvt	*Development of passivating contacts using cost-competitive deposition method for high-efficiency silicon solar cells* 21st Swiss PV days, Berne, Switzerland (2023)
Hurni_2023_sipv	*Localization of front side passivating contacts for direct metallization of high-efficiency c-Si solar cells* 13th International Conference on Crystalline Silicon Photovoltaics, Delft, The Netherlands (2023)
Hurni_2024_sipv	*Toward Lean Fabrication of TOPCon c-Si Solar Cells based on Plasma Deposited Boron Diffusion Source and Poly-Si(n) Passivating Contact* 14th International Conference on Crystalline Silicon Photovoltaics, Chambéry, France (2024)
Morisset_2024_sipv	*Development and characterization of N2O-plasma oxide layers for high-temperature passivating contacts* 14th International Conference on Crystalline Silicon Photovoltaics, Chambéry, France (2024)
Sakakibara_2024_eupvsec	*Investigating Interfacial Phenomena in Copper-Covered, n-Type Polysilicon-Based Contacts by Electron Microscopy* 41th European Photovoltaic Solar Energy Conference and Exhibition, Vienna, Austria (2024)

6.3 Peer-reviewed publications

Short name	Details	Status
Haug_2021_pss	F.-J. Haug, A. Morisset, P. Wyss, M. Lehmann, A. Hessler-Wyser, Q. Jeangros, A. Ingenito, C. Ballif, C.N.S. Kumar, S. Eswara, N. Valle, Passivating Poly-silicon Recombination Junctions for Crystalline Silicon Solar Cells, Phys. Status Solidi RRL – Rapid Res. Lett. 15 (2021) 2100272. https://doi.org/10.1002/pssr.202100272	published
Haug_2022_solmat	F.-J. Haug, S. Libraro, M. Lehmann, A. Morisset, A. Ingenito, C. Ballif, *Impact of rapid thermal processing on bulk and surface recombination mechanisms in FZ silicon with fired passivating contacts*, Sol. Energy Mater. Sol. Cells. 238 (2022) 111647. https://doi.org/10.1016/j.solmat.2022.111647	published
Libraro_2023_solmat	S. Libraro, M. Lehmann, J.J. Diaz Leon, C. Allebé, A. Descoeudres, A. Ingenito, C. Ballif, A. Hessler-Wyser, F.-J. Haug, *Interactions between aluminium and fired passivating contacts during fire-through metallization*, Sol. Energy Mater. Sol. Cells. 249 (2023) 112051. https://doi.org/10.1016/j.solmat.2022.112051	published
Ingenito_2023_solmat	A. Ingenito, C. Allebé, S. Libraro, C. Ballif, B. Paviet-Salomon, S. Nicolay, J.J. Diaz Leon, *22.8% full-area bifacial n-PERT solar cells with rear side sputtered poly-Si(n) passivating contact*, Sol. Energy Mater. Sol. Cells. 249 (2023) 112043. https://doi.org/10.1016/j.solmat.2022.112043	published
Morisset_2023_ami	A. Morisset, T. Famprikis, F.-J. Haug, A. Ingenito, C. Ballif, L.J. Bannenberg*, In Situ Reflectometry and Diffraction Investigation of the Multiscale Structure of p-Type Polysilicon Passivating Contacts for c-Si Solar Cells*, ACS Appl. Mater. Interfaces 14 (2022) 14. https://doi.org/10.1021/acsami.2c01225	published
Libraro_2023_solmat_2	S. Libraro, A. Morisset, J. Hurni, E. Genc, L. Antognini, L.J. Bannenberg, T. Famprikis, C. Ballif, A. Hessler-Wyser, F.-J. Haug, *Understanding and mitigating resistive losses in fired passivating contacts: role of the interfaces and optimization of the thermal budget*, Sol. Energy Mater. Sol. Cells. 263 (2023) 112591. https://doi.org/10.1016/j.solmat.2023.112591	published
Allebé_2023_JPV	C. Allebé, A. Descoeudres, P. Wyss, P. Boillat, N. Pernès, B. Paviet-Salomon, C. Ballif, *Sputtering for the formation of Si-based passivating contacts*, IEEE	published

	Journal of Photovoltaics, vol. 14, no. 1, pp. 35-40, Jan. 2024, https://doi.org/10.1109/JPHOTOV.2023.3324998	
Libraro_2024_ami	S. Libraro, L. J. Bannenberg, T. Famprikis, D. Reyes, J. Hurni, E. Genc, C. Ballif, A. Hessler-Wyser, F-J. Haug, and A. Morisset, *Development and characterization of N2O-plasma oxide layers for high-temperature passivating contacts*	submitted to ACS Applied Materials and Interfaces
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