TOPCon – On the way to industrial maturity

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Abstract

The tunneling oxide passivating contact (TOPCon) solar cell concept is one of the most promising ways to realize carrier-selective contacts, as it offers an evolutionary upgrade to today's mainstream PERC. Currently, the PV industry is looking into different technologically feasible options for transferring this cell concept from laboratory research to industrial manufacturing. This paper gives an overview of the technological maturity of various TOPCon approaches with the goal of achieving the most cost-effective, resource-conserving and mass-production-capable implementation.

Introduction

The time required for new processes or process chains to transition from a successful laboratory demonstration to industrial mass production has been steadily reduced in the last 30 years.

"An accelerated transition of many production lines based on PERC technology to TOPCon can be expected in the coming years."

While it took considerably more than 10 years for a successful transfer of the passivated emitter and rear cell (PERC) concept to industrial production, solar cell concepts with passivating contacts, such as tunnel oxide passivating contact (TOPCon), have required less than five years between the demonstration of the principal potential in the laboratory to mass production capability (see Fig. 1).

As a result of this rapid development and the enormous expansion of (PERC-based) production capacities in recent years to currently more than 200GWp worldwide, an accelerated transition of many production lines based on PERC technology to TOPCon can be expected in the coming years. For this changeover to happen, various process routes are currently still being evaluated with regard to their suitability for the most cost-efficient, resource-conserving and mass-production-capable implementation possible. This

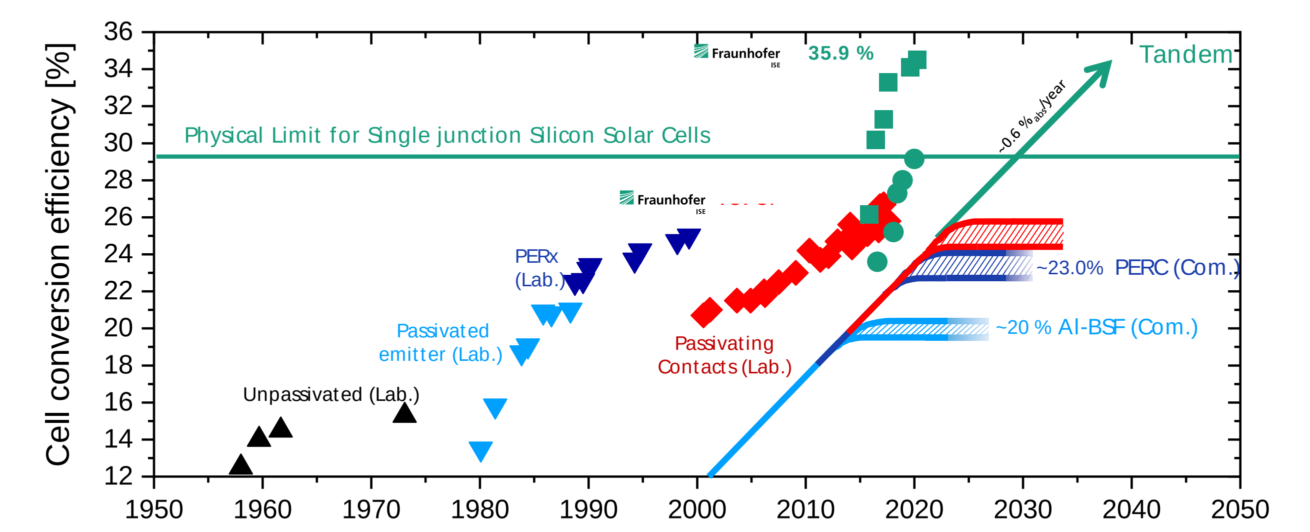

Figure 1. Evolution of laboratory and commercial solar cell conversion efficiencies. From PERC laboratory record cells to volume mass production, it took about ten years, while for TOPCon this time frame has already shortened to less than five years. (Graph adapted and extended from M. Hermle, ETIP PV Conference, Brussels (2017).)

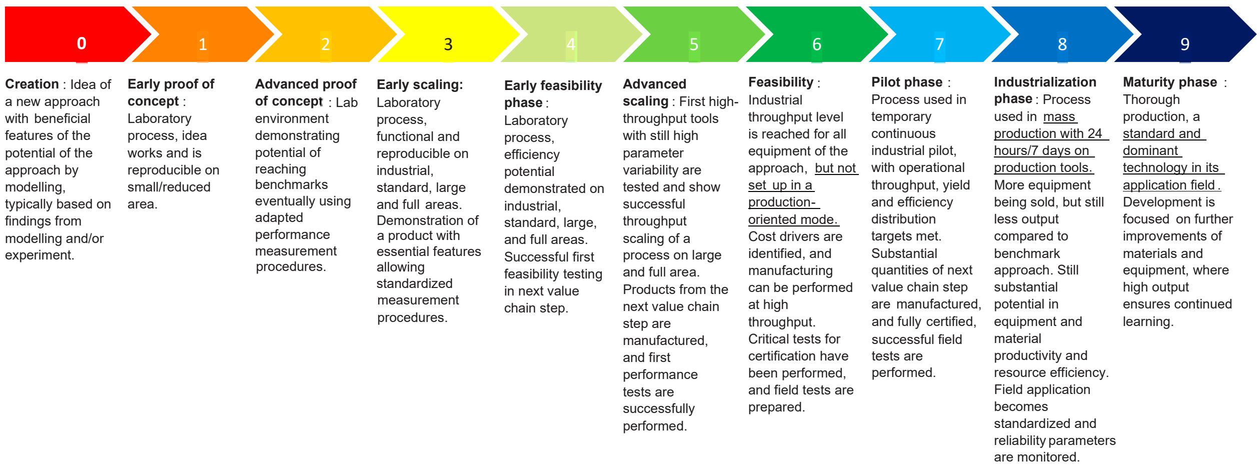

Figure 2. Technology readiness level (TRL) definition (adapted and extended from Baliozian et al. [1]) for assessing technological maturity.

paper presents the different process options and solar cell concepts and evaluates them with respect to their technological maturity.

Approach for assessing technological maturity

For the purpose of assessing the maturity of different PV technologies, Fraunhofer ISE has introduced a technology readiness scale for internal use that consists of ten different levels (gates) [1]. In comparison to earlier definitions by NASA [2] or the European Commission [3], Fraunhofer's scale is more quantitative and uses important selected parameters, namely area and conversion efficiency of the device as well as throughput (i.e. number of devices produced per unit time of production). Further, the definitions of these levels can be integrated into road-mapping in order to obtain better future projections. Fig. 2 shows the different technology readiness levels (TRL), or gates, used for the analysis in this work.

Principal process flow and upgradability from existing PERC production lines

Currently, the industrial version of the front-junction TOPCon cells on n-type c-Si, referred to as the *industrial TOPCon* (i-TOPCon) cell [4,5], is widely seen as the potential evolutionary upgrade to the incumbent p-PERC cells. The i-TOPCon cell design envisions a process route that benefits from processing similar to that for a PERC cell, thus requiring integration of only few additional process steps in the cell process chain. The cell architecture is reported to yield high efficiencies of greater than 24.0% in volume production [6] by leading cell manufacturers, with record efficiency claims of up to 25.5% on industrial wafers of sizes up to 210 × 210mm [7–9].

Fig. 3 summarizes the typical process steps used in creating an i-TOPCon cell. Note that the process flow is non-exhaustive and various process routes and a wide range of technology options for the TOPCon concept are currently under consideration by the PV industry in terms of both their technological and their economic viability. The process flow is largely dictated by the choice of the tunnel oxide (TO) formation and the amorphous (a-Si) or poly-silicon (poly-Si) layer deposition technology, and depends on whether the a-Si or poly-Si layers are doped in situ or require a subsequent external doping process. If technologically feasible, two or more process steps are combined within a single tool to ensure a lean process flow.

As a rule, boron doping is performed using a tube diffusion process to form the p^+ emitter on a textured n-type c-Si substrate. This is followed by an inline wet-chemical process for single-sided removal of the rear-side emitter. During emitter removal, the borosilicate glass (BSG) layer is usually kept intact at the front to act as a barrier against wet or dry chemicals, which are used later during wrap-around removal of the parasitic a-Si or poly-Si layer at the front side. Typically, a wet-chemical, UV light, plasma or thermal process then forms a thin TO layer at the rear surface, followed by deposition of the Si layer [10]. In some cases, the TO formation and Si layer deposition might be performed in situ in one process using a single tool.

The deposited Si layer itself might be intrinsic (nominally undoped) or phosphorus doped in situ. *Intrinsic layers* require a successive doping process ex situ, conventionally performed in a $POCl_3$-based tube furnace process that simultaneously also crystallizes the Si layer to form a fully crystalline poly-Si layer. For *phosphorus-doped in situ layers*, crystallization is achieved by a thermal annealing step. If single-sided poly-Si deposition is not warranted, a wrap-around removal process is required to remove unwanted poly-Si residuals on the textured front side. The wrap-around removal is normally performed using a wet-chemical process [10], although a dry alternative was reported recently [11]. In both cases, the remaining BSG layer on the front side serves as an etch barrier and is subsequently removed, typically in a wet-chemical process.

The next steps are dielectric surface passivation and anti-reflective coating (ARC) of the front and rear sides and a hydrogenation stage, which aims to improve the passivation property of the TOPCon structure. In an industrial scenario, the latter is generally performed by depositing hydrogen-rich dielectrics, for example an amorphous silicon nitride layer (a-SiN_x:H) by plasma-enhanced chemical vapour deposition (PECVD), which act as an efficient hydrogen source during the contact-firing step. Front and rear metallization is typically achieved by using screen-printed Ag-based pastes, followed by a fast-firing process to form the external contacts. This process yields a bifacial cell structure, as shown in Fig. 3(e).

Solar cell concepts based on TOPCon device features

Besides the 'standard' configuration of an industrial TOPCon solar cell featuring a diffused front junction (FJ) [12], with a TRL classification of 9 in Fig. 4, there are other options for implementing passivating contacts in a device structure: as the rear emitter in a back-junction (BJ) configuration [13,14] or as both contacts of an interdigitated back-contact (IBC) solar cell [15]. Currently, the highest conversion efficiencies achieved on a laboratory scale using these architectures are 25.8% (TOPCon FJ) [13], 26.0% (TOPCon BJ) [13] and 26.1% (IBC) [15].

Among the above-mentioned cell architectures, the IBC concept offers the highest potential in terms of monofacial conversion efficiency, as both contact polarities are located at the rear of the cell.

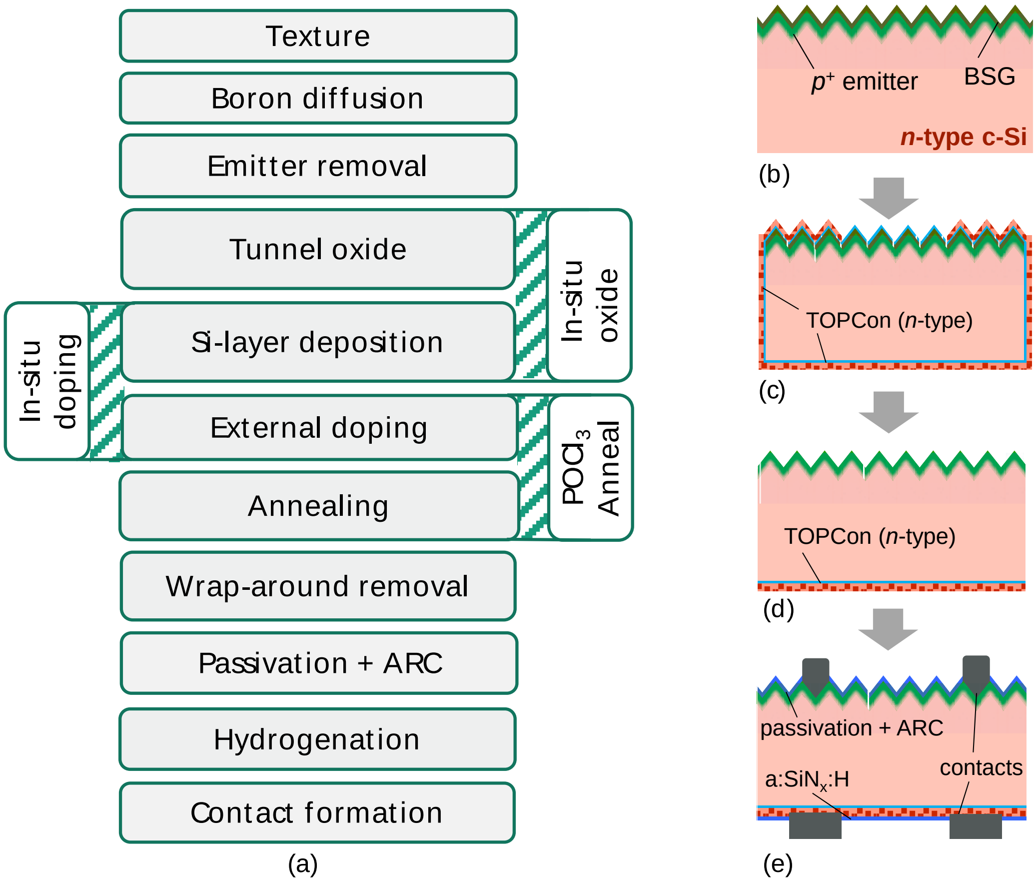

Figure 3. (a) Typical process flow for an i-TOPCon cell with the potential combination of two processes in a single process step. Schematic cross sections of cell precursors after some crucial process steps in typical TOPCon processing: (b) after texturing, boron emitter diffusion and single-sided emitter removal; (c) after TOPCon deposition, doping and annealing; (d) after wrap-around removal of poly-Si(n) at the front and the edges; (e) after dielectric layer deposition and contact formation.

However, it is also the most complex architecture for transfer to mass production, because several structuring steps are required during fabrication. Up to now, only the company SunPower/Maxeon has mastered the transition of such an IBC cell structure to industrial mass production, also demonstrating the highest efficiencies available in the market [16]. Known realizations of IBC with passivating contacts, such as the POLO IBC cell from ISFH [15], have been demonstrated on large-area industrial wafers in a laboratory environment, therefore having a designated TRL of 4 (Fig. 4).

Both-side contacted cells, on the other hand, have an additional advantage of high bifacial power gain, which is especially relevant for large-scale power plants. For the BJ cell concept (TOPCoRE), the n-TOPCon stack acts as a rear emitter on a p-type Si substrate. The main advantage of this configuration is that the whole c-Si substrate contributes to the charge-carrier transport towards the local front-side contacts, which makes a full-area highly conductive layer at the front surface obsolete, such as the full-area B diffusion in the case of the n-TOPCon cell. Consequently, the front-surface recombination can be significantly reduced. However, a localized p^{++} region is placed under the contact to limit the recombination and allow the formation of a low-ohmic contact. Since the minority carriers (here electrons) are collected at the rear junction, a high diffusion length (i.e. a high-quality base material with a diffusion length much greater than the cell thickness) is a primary requirement for the BJ concept. Additionally, the

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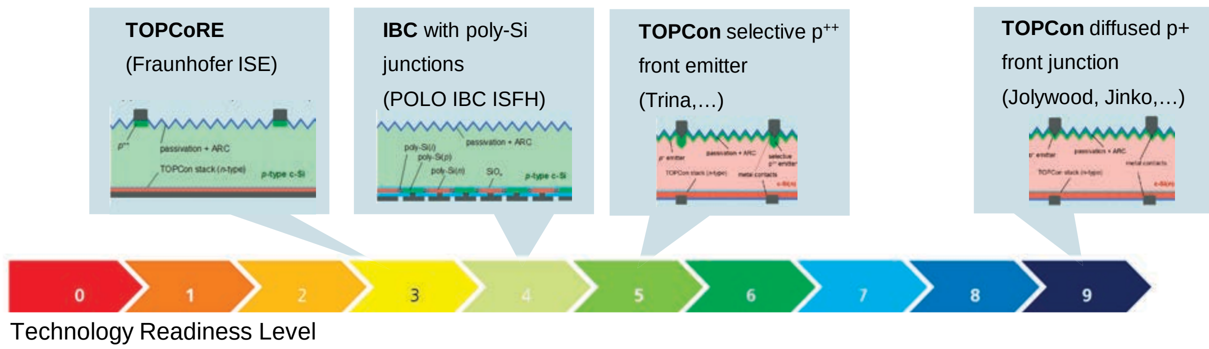

Figure 4. Different cell architectures featuring passivating contacts and their classification within the TRL scheme.

omission of a conductive front surface (p^+ front-surface field) has been found to not limit the majority transport to the front contacts unless very high resistive wafers are being used [13].

The cell architecture yielded conversion efficiencies of up to 26% in small-area devices with evaporated contacts on a laboratory scale, with a clear advantage in fill factor *FF* (more than $1\%_{abs}$) and open-circuit voltage V_{oc} (8mV) achieved by the n-type front-junction TOPCon cell. The transfer of this process to mass production is expected to encounter challenges in solving light and elevated temperature-induced degradation (LeTID), which is more critical for industrial standard p-type Cz Si than for n-type Cz Si; therefore, the overall TRL readiness of the TOPCoRE cell concept is not higher than 3 (Fig. 4).

Silicon layer deposition as the main differentiator – technical maturity of the different approaches

Typically, amorphous or partly crystalline silicon layers are first deposited and then subjected to a high-temperature step to form a poly-Si layer. Depending upon the deposition technology, the doping of poly-Si is performed either during the deposition process (in situ doping) or in a subsequent process, such as gas phase diffusion or ion implantation (ex situ). Importantly, the choice of the Si deposition technology dictates almost all the other important cell processing steps before metallization, especially based on whether the technology allows an in situ TO formation, in situ doping and a true single-sided deposition. Although several deposition methods are under investigation, most notable are chemical vapour deposition (CVD) and physical vapour deposition (PVD). CVD is performed either at low pressure (LPCVD), by means of PECVD, or at atmospheric pressure (APCVD), all using silane (SiH_4) as a silicon precursor and optionally phosphine (PH_3) or diborane (B_2H_6) as dopant gases.

LPCVD

Currently, industrial screen-printed TOPCon solar cells on n-type substrates are almost all based on LPCVD a-Si/poly-Si deposition technology, to which a TRL of 9 is assigned (see Fig. 5). LPCVD has been used as one of the important established processes in semiconductor facilities to deposit highly conformal layers of a-Si/poly-Si layers in low-pressure conditions [17]. The main advantages of this technology are:

1. Possibility of in situ TO formation by thermal oxidation.
2. Excellent thickness uniformity along the wafer and the boat in the case of intrinsic layers.
3. Pin-hole-free layers with good step coverage.
4. Large number of wafers per batch.
5. Option of in situ doping with a constant doping profile [18].

The last of the above advantages, however, still comes at the expense of reduced layer uniformity and deposition rates, and therefore lower throughput.

Some of the most promising technologies that are close to production readiness apart from LPCVD are briefly discussed below.

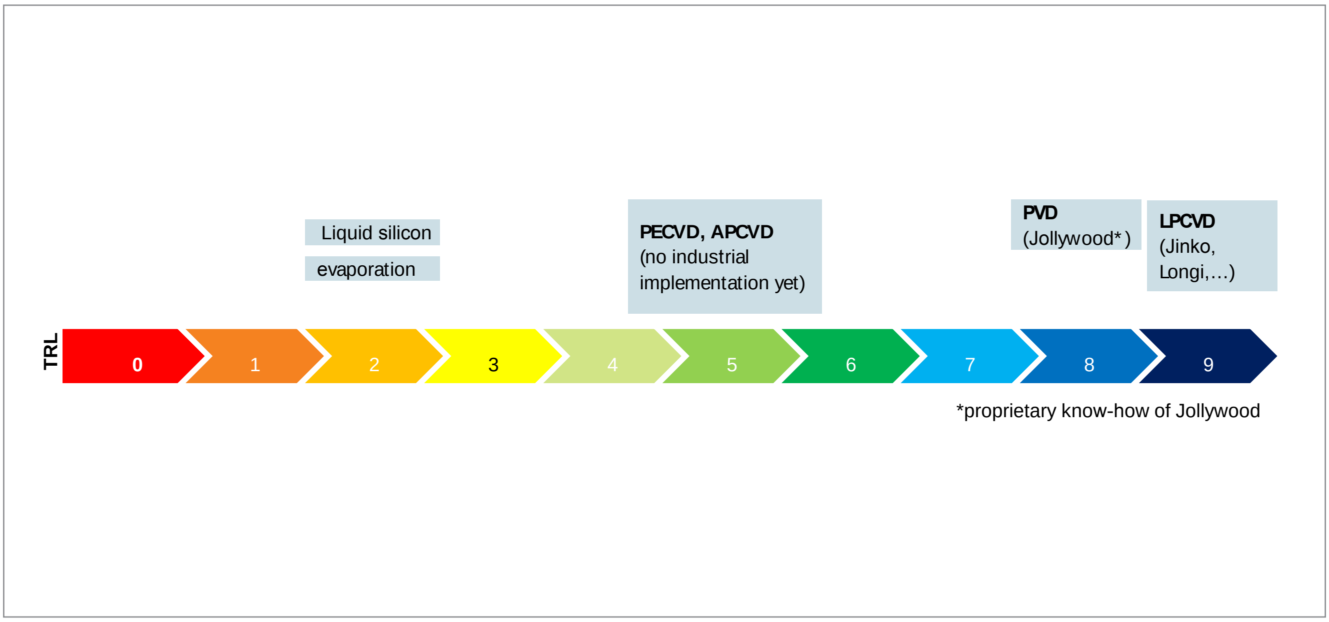

Figure 5. Technology readiness level (TRL) of different approaches for the formation of the poly-Si layer.

PECVD

PECVD is a well-proven technology in the PV industry for depositing dielectric passivation layers, and one of the most promising candidates for a-Si deposition. In fact, the International Roadmap for Photovoltaics (ITRPV) predicts a rapid adoption of this technology for a-Si deposition rather than LPCVD in the near future [19].

PECVD deposition of a-Si layers offers higher deposition rates than with LPCVD technology, thus promising greater cost effectiveness. Another advantage of using PECVD is the possibility of doping a-Si layers in situ; however, it should be pointed out that layer homogeneity and deposition rates in that case are also impacted. One of the challenges is to avoid blistering in thick layers (d > 100nm), which are currently still required for industrial TOPCon architecture because of the potential penetration of the poly-Si layer by the metallization.

Although PECVD is loosely considered a single-sided deposition process, avoiding the wrap-around of a-Si layers in an industrially feasible manner remains a major technological challenge for equipment manufacturers. Industrial tools allowing depositions in either batches [20] or an inline mode [21] are available, and cell integration results have also been published in the literature [20]. An advantage of the PECVD approach might be the option to implement a plasma oxidation step for in situ TO formation before the deposition of the a-Si layer, enabling a lean combined process for TO formation and Si layer deposition, similar to the LPCVD approach. To the authors' knowledge, a PECVD deposition process for TOPCon structures has not yet been implemented in any cell production, which is why a TRL of 4 to 6 is assigned to this technology (Fig. 5).

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APCVD

Atmospheric pressure chemical vapour deposition (APCVD) is another potential technology for depositing intrinsic and doped amorphous or partly crystalline layers in an inline mode at high deposition rates [22]. The process utilizes thermal dissociation of silane (SiH_4), which is inserted in a heated chamber using injector heads. Since the chemical reactions occur directly at the heated substrate, APCVD is also expected to provide good single-sidedness with a small wrap-around similar to that for the PECVD process.

Furthermore, in situ doping is reportedly easily achieved by directly inserting doping precursors in the SiH_4 flow, and cell integration results have been demonstrated [23]. Here, the TO layer needs to be formed before the APCVD process, for example in a wet-chemical process subsequent to the rear emitter removal. APCVD of silicon layers appears to have not yet been implemented in cell production, indicating a similar TRL as PECVD.

PVD

PVD as another industrial applicable production method and is capable of depositing high-quality a-Si layers using a silicon target, with the major benefit of providing true single-sidedness [24]. Both the silicon and an appropriate dopant element can be deposited using solid, non-toxic targets. Since

PVD is a vacuum-based inline process, a plasma oxidation for TO formation might be implemented in a separate chamber before the deposition.

The company Jolywood, a pioneer in industrial TOPCon cell manufacturing, is presumably also using PVD in their most recent production lines as their primary deposition technique (based on a technology called *POPAID* (plasma oxidation and plasma-assisted in situ doping deposition) introduced by the equipment manufacturer Jiangsu Jietai Optoelectronics Technology Co., Ltd. – JTech) [25]. PVD is therefore already in use industrially, but not yet as a mainstream technology, which is reflected in its TRL level of 8 (Fig. 5).

Metallization – decisive for cost and silver usage reduction

A key challenge in industrially upscaling the TOPCon solar cell concept lies in the metal contacting of the solar cells. The metallization on the TOPCon side especially has revealed itself to be challenging, as the tunnel oxide should not be damaged in order to guarantee its full functionality as a carrier-selective contact. As a state-of-the-art metallization technique for i-TOPCon solar cells, screen printing of Ag–Al and Ag is used on the front and rear sides, respectively.

The dominant loss mechanism of an i-TOPCon solar cell is associated with recombination induced by the metal electrodes on the emitter side and, to a reduced degree, on the TOPCon side [26]. The contact formation process, which typically takes place at peak temperatures in excess of 700°C, is industrially performed using a fast-firing oven (FFO). At those temperatures, the dielectric capping layers, mostly amorphous SiN_x, covered by the screen-printed electrode, are etched by glass frit components within the paste. Then, oxygen ions on both sides react with the crystalline or poly-Si, creating etching pits that facilitate the creation of an ohmic contact [27]. On the front, the metallization significantly increases carrier recombination, while on the rear, the etching pits consume the poly-Si, potentially reaching the thin oxide layer and consequently de-passivating the contact. The contact formation process on both sides is fuelled by elevated firing temperatures. On the one hand, the higher temperature leads to low-ohmic contacts and thus a high fill factor *FF*; however, on the downside, this comes with increased metal-induced recombination, mainly decreasing V_{oc} and ultimately limiting the conversion efficiency potential.

"The limited supply of silver and the increasing cost of raw materials will be critical factors for an increasing PV market heading towards terawatt scale within the next decade."

LECO

At Fraunhofer ISE, laser-enhanced contact optimization (LECO) [28] as a post-firing treatment is applied to reduce the contact firing temperature, which enables higher V_{oc} and simultaneously higher *FF* values on i-TOPCon solar cells. The LECO process locally applies a very intense laser pulse to the solar cell, which is held at a constant reverse voltage of 10V or higher. The resulting local current flow of several amperes is responsible for significantly reducing the contact resistivity between the semiconductor and the metal electrode [29].

By using a lower firing temperature in combination with LECO post treatment, an efficiency gain of up to +0.6%$_{abs}$ can be demonstrated, compared with the optimum for a firing temperature variation [30]. This gain originates from decoupling the dependence on temperature of V_{oc} and short-circuit current density J_{sc} on the one hand and *FF* on the other during the contact firing procedure. The LECO process enables one to benefit from high V_{oc} and J_{sc} values using low firing temperatures, while simultaneously achieving high *FF* values as if the firing had taken place at higher temperatures. As a result, a reduction in the optimal peak firing temperature of 20–40°C is observed. Moreover, metal-induced recombination is lowered because of the reduced firing temperatures of up to 40°C, mainly on the boron emitter side, leading to the observed gains in V_{oc} [30]. On both sides of the solar cell, the lower temperatures allow thinner and lighter-doped layers, and potentially the use of additional or thicker dielectric layers, which are more resilient to penetration by metal pastes, reduced metal area fraction and extended co-firing conditions.

Finally, LECO-treated i-TOPCon solar cells do not show any signs of LeTID using accelerated testing conditions. Furthermore, the LECO improved state does not degrade under these conditions, giving significant confidence in enduring, high module performance for these kinds of solar cell.

Ni/Cu/Ag contacts

Recent publications point out that the limited supply of silver and the increasing cost of raw materials will be critical factors for an increasing PV market heading towards terawatt scale within the next decade [31,32]. Conventional technology evolution (as expected according to the ITRPV [19]) is not sufficient to overcome these limitations, especially in the case of solar cell designs with silver contacts on both sides.

Electroplating of Ni/Cu/Ag contacts has been found to be a suitable candidate for metallizing bifacial TOPCon solar cells [33,34]. Plating is a lead-free metallization technique which allows narrow contact geometries (<25µm) and low contact resistivities (ρ_c < 1mΩcm^2) [35]. Furthermore, with the use of mainly Cu as the main conductive

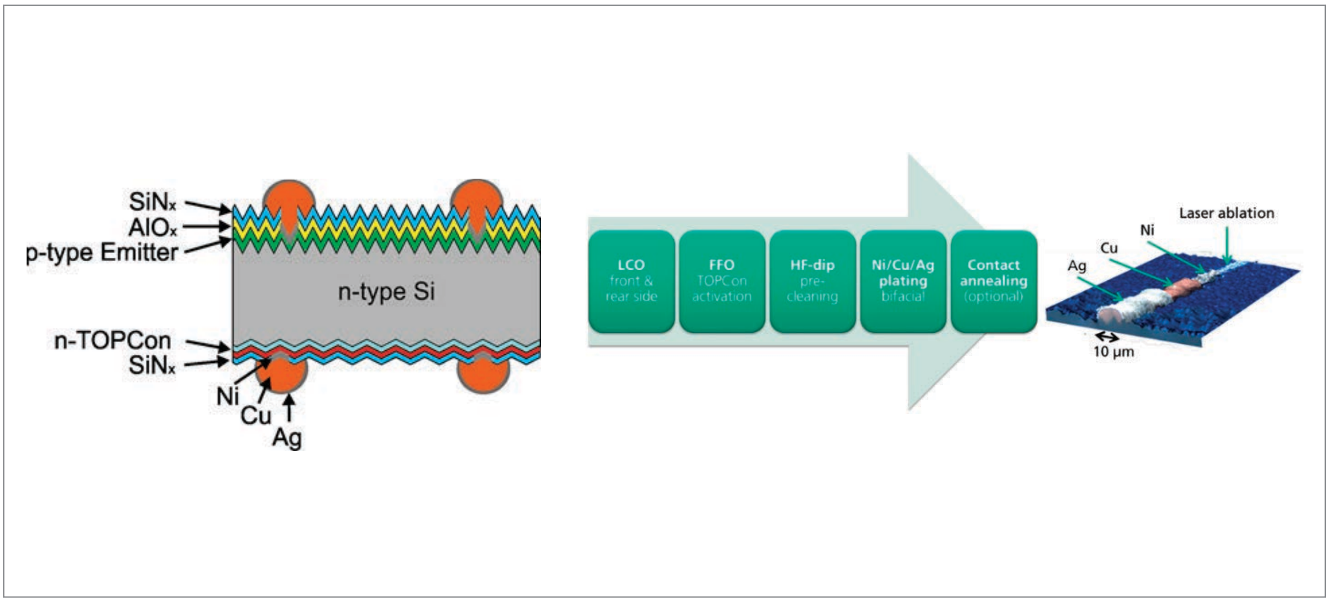

Figure 6. Structure and process sequence for the manufacture of a bifacial TOPCon solar cell, based on laser structuring and Ni/Cu/Ag plating.

Cell area 267.85cm^2 (full area)	η [%]	J_{sc} [mA/cm^2]	V_{oc} [mV/cm^2]	FF [%]
Screen printing	23.5	40.7	705	81.9
Plating	24.0	41.0	715	82.0

CalLab PV Cells

Table 1. Certified record efficiencies for full-area (M2), nine-busbar, industrial TOPCon solar cells (the poly-Si layers were fabricated by LPCVD) [37].

component, a significant cost reduction is realizable, resulting in a cost of ownership (COO) advantage of around 45%, compared with screen printing [35].

The electroplating process developed at Fraunhofer ISE is illustrated in Fig. 6. Laser contact ablation of the ARC on the front and rear defines the grid pattern. After the necessary TOPCon activation via a short high-temperature firing step, single-side plating processes are applied to deposit a stack of a thin nickel seed layer (<0.5µm), copper bulk finger (1–10µm) and a thin surface-finish layer (<0.5µm) of either silver or tin. On industrial precursors, this plating approach yielded record efficiencies of up to 24.0%, compared with 23.5% using the suppliers R&D screen-printing metallization approach shown in Table 1.

A further advantage of the process, demonstrated in Kluska et al. [36], is the low contact recombination of the local contact opening (LCO) patterning, even for poly-Si thicknesses of down to 60nm on the TOPCon rear side. This would enable a reduction in the poly-Si thickness, and consequently an increase in process throughput, in the TOPCon deposition process.

Fig. 7 takes a closer look at the COO for the metallization backend for TOPCon solar cells. The main cost driver for screen-printed contacts is the cost of silver paste and its dependency on the volatile raw material price of silver. However, the more advanced stage in the learning curve for screen-printing-tool manufacturing means that equipment costs are fairly low. Since plating technology is at the beginning of its learning curve in PV, the equipment costs are significantly higher than for screen printing, but the costs of consumables are much lower.

Conclusion

The paper has summarized the current status of TOPCon implementation in industrial mass manufacturing and is intended to offer guidelines for the technology readiness levels of various process technologies along the process chain. While technology progress is visible in all steps of the process chain options, to date LPCVD still represents the only viable and industrially fully adopted process solution for the Si layer deposition, which represents the core process of any new TOPCon greenfield installation or upgrade from existing PERC. For future growth, technology development drivers are not only production-cost

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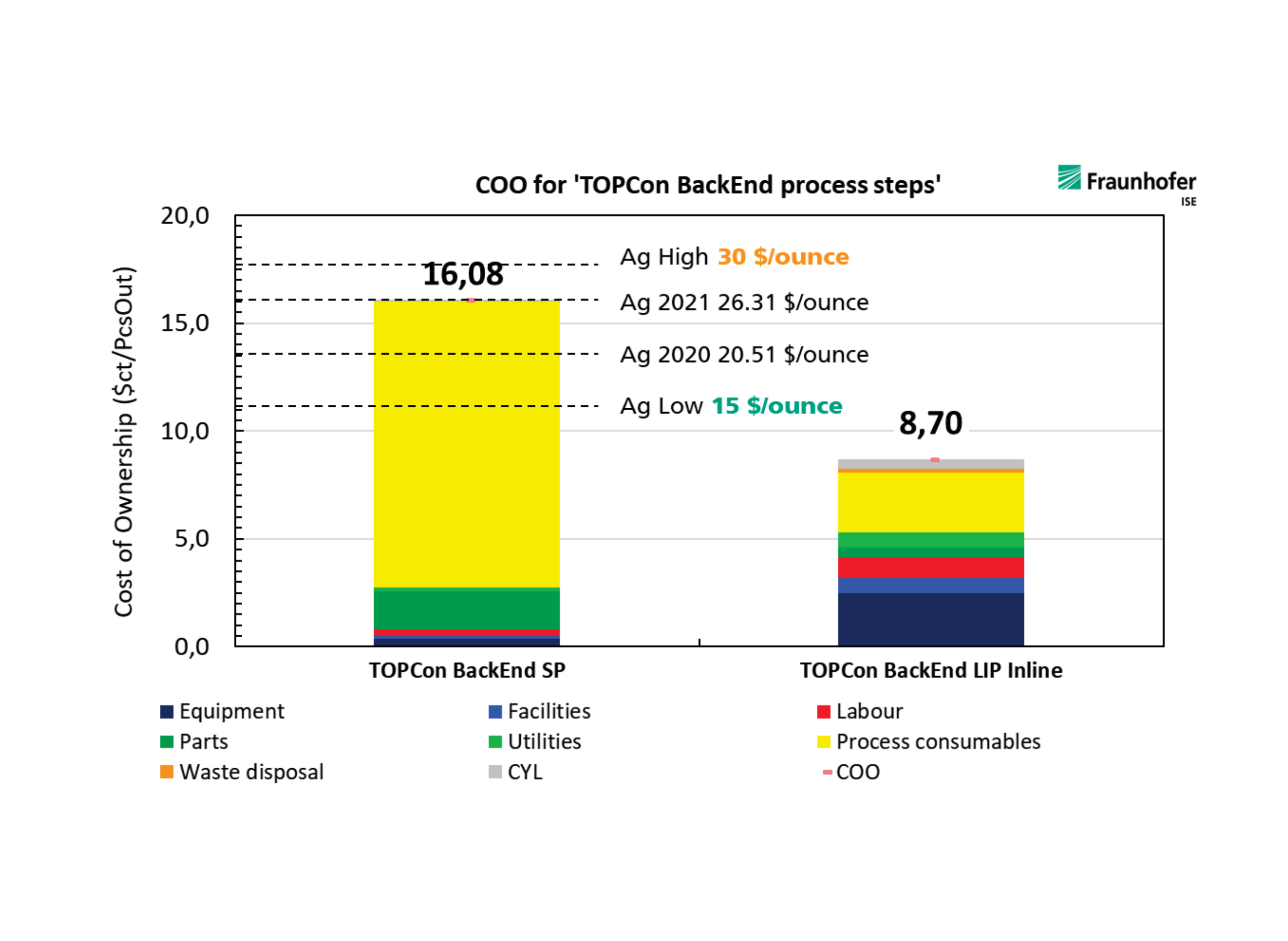

Figure 7. Cost of ownership (COO) comparison of a screen-printed-based metallization (120mg total Ag consumption) and the proposed Ni/Cu/Ag plating approach. Different Ag source material prices (indicated by the horizontal dashed lines) highlight the significant impact on metallization cost.

related but also arise from resource-criticality aspects. In metallization, therefore, alternative approaches for the current mainstream silver usage in screen printing will be one of the major topics for development in the near future.

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