Towards industrial manufacturing of TOPCon

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Abstract

TOPCon is regarded as a possible follow-up technology to the passivated emitter and rear cell (PERC) concept. This paper presents the latest results for high-efficiency solar cells, and the progress made on migrating layer deposition to high-throughput tools, which are already in use in industry. Possible metallization approaches, and three different industrially relevant solar cell structures featuring TOPCon, are also discussed.

Introduction

In the last five years, the PV industry has witnessed a rally towards ever-increasing conversion efficiencies. For a long time, the industry's workhorse has been the Al back-surface field (BSF) solar cell, but this is now being replaced by the passivated emitter and rear cell (PERC), which enables conversion efficiencies above 21% in production and up to 23.6% in a production-near environment [1]. A detailed loss analysis of these solar cells reveals that minority-charge carrier recombination at the metal/semiconductor contacts is the dominant loss mechanism [2].

Two strategies to mitigate recombination losses have usually been employed: (1) the formation of a heavily doped c-Si region underneath the metal contact by diffusion or alloying (e.g. selective emitter or Al back-surface field) in order to reduce minority-charge carriers at the interface; and (2) the reduction of the metallized area fraction. A prime example of the latter strategy is the PERC structure, which features a dielectric rear passivation with local Al contacts, thereby increasing not only the open-circuit voltage (V_{oc}) but also the short-circuit current density (J_{sc}) (because of improved rear reflection of IR light). V_{oc} gains and fill factor (*FF*) losses, however, have to be carefully balanced by adapting both the pitch of the rear contact lines (or dots) and the base resistivity. Hence, a superior strategy that overcomes this limitation is a passivating contact that suppresses minority-charge carrier recombination and enables an efficient majority-charge carrier transport. The most well-known example is the a-Si:H/c-Si heterojunction (commonly referred to as HIT, HJT, SHJ) solar cell, with which open-circuit voltages as high as 750mV, as well as the world-record efficiency of 26.7%, were demonstrated. Despite these very impressive results, there are technological and economic reasons (e.g. high equipment cost) why the PV industry has not yet adopted this technology on a larger scale. One technological drawback is the low thermal stability of the a-Si:H passivation, which restricts the back-end process temperatures to about 200°C, thereby creating the need for low-temperature metallization, such as silver pastes, which are less conductive and more expensive than their high-temperature counterparts.

Tunnel oxide passivated contact (TOPCon) technology [3,4] was introduced in 2013; this technology tolerates higher back-end processing temperatures than conventional a-Si:H technology, and therefore holds the promise of a facilitated back-end processing. While low recombination current densities (J_o) are similarly possible, the contact resistivity (ρ_c) is much lower for TOPCon contacts than for a-Si:H/c-Si heterojunctions. Although different acronyms have been used for this kind of contact system, for the sake of simplicity TOPCon is used throughout this article.

TOPCon is based on the poly-Si emitter technology which was originally pioneered by the integrated circuit (IC) industry and which led to appreciable current–gain enhancement factors of high-speed bipolar junction transistors (BJTs). An excellent overview of the scientific contributions relevant to BJTs can be found in Post et al. [5]. The success of poly-Si emitter technology has inspired researchers to apply it to silicon solar cells, with the aim of boosting V_{oc}: for instance, Kwark et al. [6] demonstrated that poly-Si contacts benefited from a chemical oxide, and reported J_o values down to 10fA/cm² for the electron contact. In 1990 Gan and Swanson [7] introduced thermally grown interfacial oxide layers, which required very high annealing temperatures (~1,050°C) in order to break up the interfacial oxide layer.

The novelty of Fraunhofer ISE's approach was twofold: first, the TOPCon layer was realized by plasma-enhanced chemical vapour deposition (PECVD) instead of low-pressure chemical vapour deposition (LPCVD); second, its potential was demonstrated through the use of an n-type cell featuring a boron-diffused emitter and TOPCon as a full-area passivating rear contact (see Fig. 1). The

"TOPCon technology tolerates higher back-end processing temperatures than conventional a-Si:H technology."

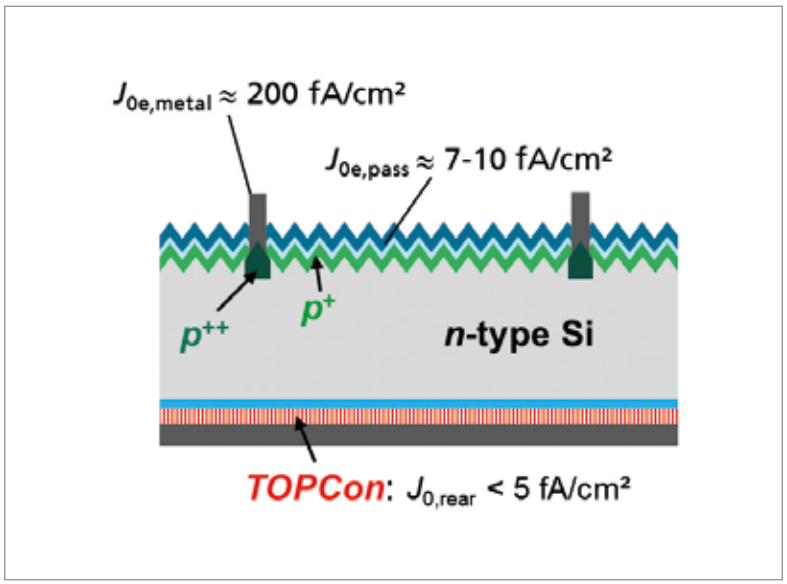

Figure 1. Schematic of an n-type solar cell featuring a boron-diffused emitter and a passivating rear contact (TOPCon).

first prototype achieved a conversion efficiency of 21.7%; by improving the light trapping and front metallization, however, a 23.7%-efficient solar cell has been demonstrated and was reported at the EU PVSEC conference in 2013 [3]. The implementation of a selective emitter further reduced front-side recombination losses, enabling an efficiency of 24.4% to be obtained half a year later [8]. Further improvements at the front and the rear have resulted in an efficiency of 25.8% [9,10], which is currently the world record for a two-side-contacted solar cell. The learning curve for Fraunhofer ISE's lab-type TOPCon solar cells is shown in Fig. 2.

Since that report of the 25.8% efficiency, numerous papers (e.g. [11–14]) have contributed to improving this passivating contact technology and promoting the understanding of the underlying physics of the contacting system. A detailed review of these activities will be published soon [15].

As shown above, outstanding conversion efficiencies have been demonstrated at the laboratory level, and so the next step needs to be the transfer of this technology to high-throughput tools in a pilot-line environment. Consequently, in the second part of the paper the following research topics will be addressed:

- The development of deposition processes on industrial production equipment.
- Metallization aspects.
- The integration into solar cell structures.

Working principle and fabrication steps

Fig. 3 shows schematically the process flow for the fabrication of a symmetrical lifetime sample

"TOPCon with the thermally grown oxide did not degrade at 900°C, but yielded excellent surface passivation quality."

featuring TOPCon on both sides. The fabrication of TOPCon requires the following three process steps:

1. The growth of an interfacial oxide layer.
2. The deposition of an amorphous (or polycrystalline) Si-based layer.
3. A high-temperature anneal.

After wafer cleaning, a thin interfacial oxide layer, typically 1.2 to 2nm thick, is grown. Such oxides can be wet-chemically grown in, for example, hot nitric acid (HNO_3) [4] or an O_3/H_2O bath [14], or they can be dry grown using a tube furnace [7,11] or a UV excimer or halogen lamp system [14]. The purpose of the interfacial oxide is to reduce dangling bonds, and thus interface-trapped charge density. It is worth noting that the as-grown oxides do not provide any surface passivation, but improve upon the high-temperature anneal.

Next, a Si-based layer is deposited either by LPCVD or by PECVD. These layers are usually a-Si or poly-Si based, but carbon or oxygen can also be added to the matrix. In most approaches the Si layer is doped during deposition; however, doping by (for example) ion implantation or $POCl_3$/BBr_3 diffusion, carried out ex situ, is feasible as well.

Provided that the Si layer is doped, the third process step is a furnace anneal in nitrogen, using process temperatures in the range 800–1,050°C. At these temperatures, the a-Si layer crystallizes, and dopants are electrically activated and partly diffuse through the oxide into the c-Si wafer. Optimum annealing temperatures supposedly have a beneficial impact on the stoichiometry of the SiO_x layer as well as of the c-Si/SiO_x interface. In addition, annealing in an oxygen-free atmosphere brings about the reaction $SiO_2 + Si \rightarrow SiO(g)$; this leads to the breakup of the oxide layer, which was investigated in great depth by Wolstenholme et al. [16]. This reaction mechanism can be used advantageously in order to facilitate transport through thicker (>1.5nm) oxides, which would otherwise pose a substantial tunnelling barrier. Feldmann et al. [17] demonstrated, by means of temperature-dependent *J–V* measurements, that tunnelling is the dominant transport path for thinner oxides.

A fourth process step, hydrogenation, is typically used in order to further enhance the passivation quality. Hydrogenation, with the use of atomic hydrogen (which can be sourced from H-containing films, such as Al_2O_3 or SiN_x, or from hydrogen plasma), reduces the interface-trapped charge density at the c-Si/SiO_x interface.

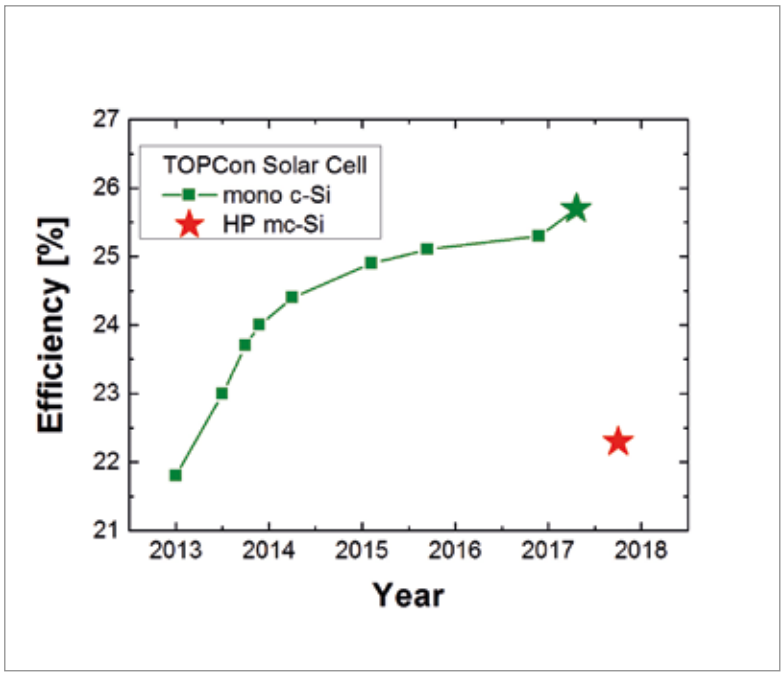

Figure 2. Evolution of the conversion efficiency of lab-type TOPCon solar cells.

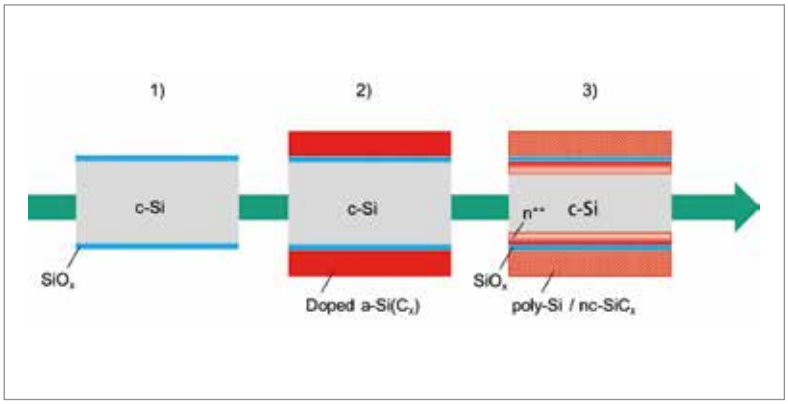

Figure 3. Steps involved in TOPCon fabrication: 1) interfacial oxide layer growth; 2) a-Si (or poly-Si) layer deposition; 3) high-temperature anneal.

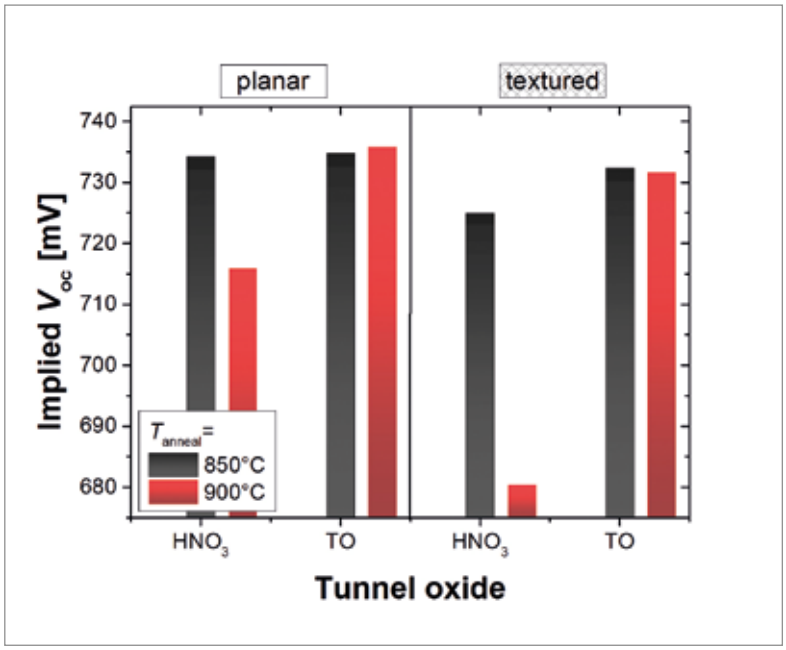

Figure 4. iV_{oc} achieved by n-TOPCon on planar and textured surfaces respectively. Two different interfacial oxides are compared.

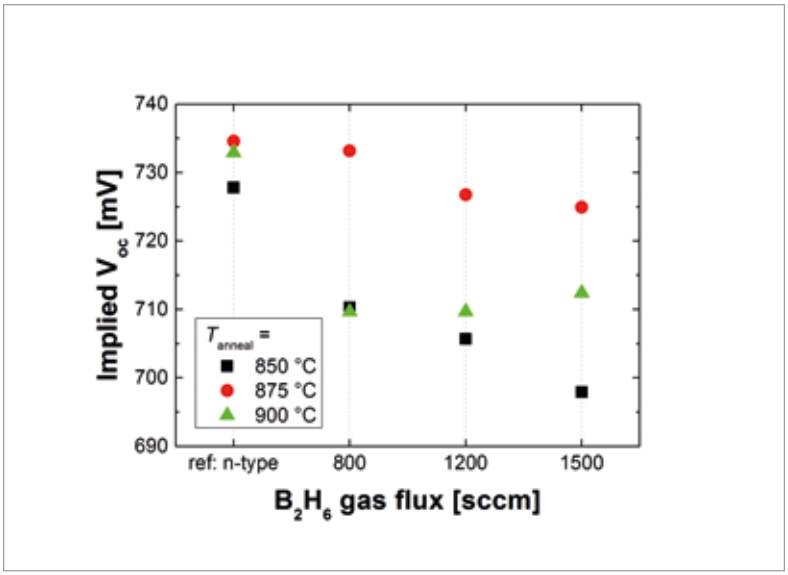

Figure 5. Measured iV_{oc} for asymmetrical samples featuring n-TOPCon on the front side and p-TOPCon on the rear [21].

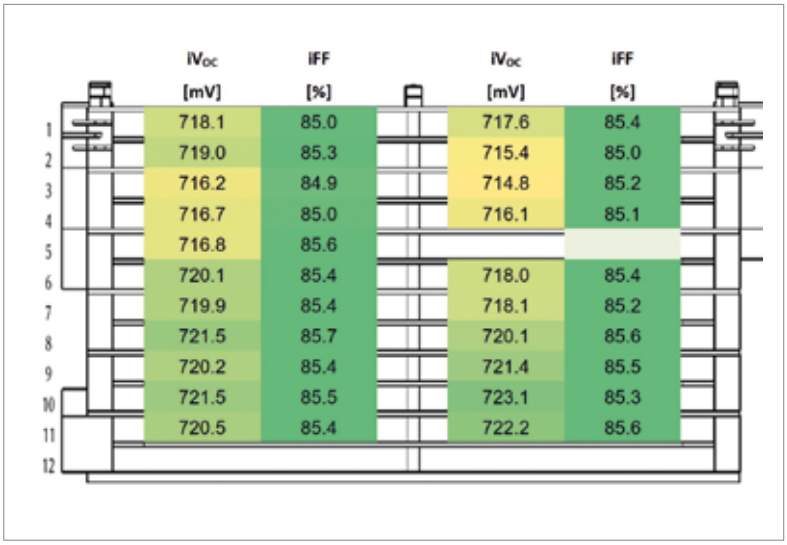

Figure 6. A side view of the PECVD carrier, listing the average iV_{oc} measured for each wafer [19].

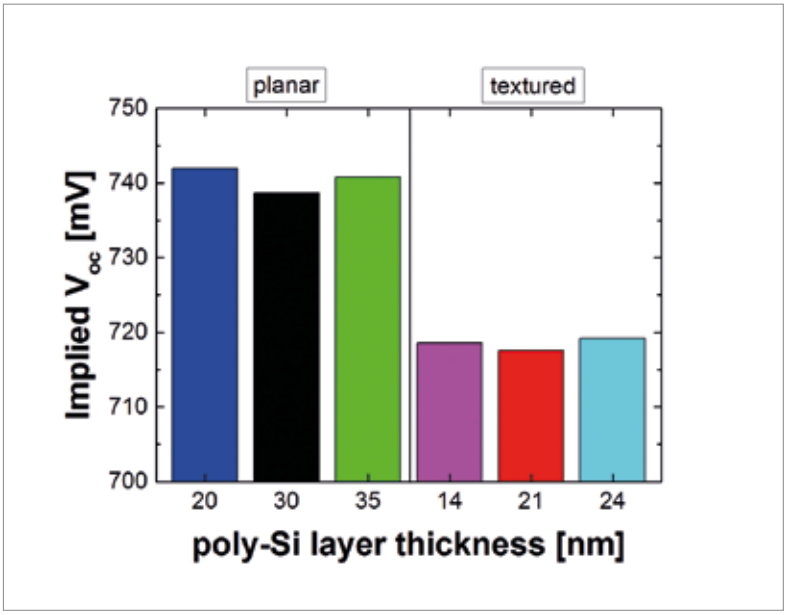

Figure 7. iV_{oc} achieved by n-TOPCon on planar and textured surfaces.

Industrial-scale deposition technologies

LPCVD is a state-of-the-art technology in the microelectronics industry for the deposition of amorphous or polycrystalline Si films. The crystallinity of the film is controlled by the deposition temperature, which also controls the deposition rate. The advantages of this technique are the high homogeneity of the layers, the good step coverage, the high reproducibility and the possibility of growing the required interfacial oxide layer in situ. The drawbacks of this technique are the inherently double-sided deposition and the relatively low deposition rates (e.g. 2.8nm/min at 550°C and 8.3nm/min at 615°C [18]). The former of these drawbacks always requires additional process steps, such as masking and/or single-side layer removal, if the poly-Si layer is to be applied only to one side of the cell.

An alternative method for depositing doped Si films is PECVD, which is a well-established process in the PV industry for the deposition of thin films, such as Al_2O_3 or SiN_x. It is usually regarded as a single-sided deposition technique, but a minimal wrap-around at the cell edges can occur, which can be addressed by inline wet-chemical etching. Moreover, Si alloys with oxygen or carbon can be easily realized by PECVD, and the process can be adapted to the needs of the particular surface of the solar cell. One challenge with PECVD films is the risk of blistering due to the usually large amounts of hydrogen incorporated within the Si layer; this puts restrictions on the maximum film thickness, but this issue is generally mitigated by using higher deposition temperatures (300–450°C) than those used for HJT cells. Another concern can be ion bombardment during deposition, which might inflict damage on the thin interfacial oxide layer.

In the following sections, the latest results achieved using either PECVD or LPCVD tools will be presented. (More details can be found in the authors' recent publications [19–22].)

Low-frequency direct plasma PECVD

The authors recently demonstrated that a centrotherm cPLASMA 2000 PECVD tool is capable of gently depositing doped a-Si layers onto a thin tunnel oxide [19]. The resulting surface passivation quality achieved with n-TOPCon (electron-selective contact) was excellent on both shiny-etched and textured surfaces. Fig. 4 shows the implied V_{oc} (iV_{oc}) measured on symmetrical structures incorporating n-TOPCon on both sides; in the experiment, a wet-chemical oxidation process (hot nitric acid – HNO_3) was compared with a thermally grown oxide (TO).

The authors' investigations of the stoichiometry of differently grown oxides have been reported in previous publications; the results hinted at a

correlation between stoichiometry and improved thermal stability as well as improved surface passivation quality [14]. Fig. 4 clearly shows that TOPCon featuring the wet-chemical oxide yields very high iV_{oc} values of ~730mV on planar surfaces, and up to 725mV on textured surfaces; however, the annealing process at 900°C led to a significant degradation, especially on textured surfaces. On the other hand, TOPCon with the thermally grown oxide did not degrade at 900°C, but yielded excellent surface passivation quality (iV_{oc} ~ 730mV on textured surfaces). Hence, there is only a subtle difference between the passivation quality on planar and textured surfaces, which is in agreement with other reports in the literature [23].

Fig. 5 shows Fraunhofer ISE's latest results for p-TOPCon, the hole-selective contact [21]. The influence of the diborane (B_2H_6) gas flux on the surface passivation quality provided by p-TOPCon was studied in a similar way to that for the electron-selective contacts. To this end, p-TOPCon was applied to the rear of solar cell precursors having n-TOPCon on the front side. The reference device, which is a symmetrical structure comprising n-TOPCon on both sides, achieved iV_{oc} values in the range 727 to 735mV for all three annealing temperatures; thus, the J_o contribution from n-TOPCon was less than 2fA/cm². The asymmetrical samples showed somewhat lower iV_{oc} values because of increased recombination at the hole-selective junction. For the optimum annealing temperature of 875°C, iV_{oc} decreased from 733mV to 725mV with increasing B_2H_6 gas flux; these values correspond to a J_o of about 2–6fA/cm², which is an excellent value for p-TOPCon. Furthermore, by means of surface photovoltage (SPV) and Suns-V_{oc} testing, it was verified that these layers not only serve as excellent surface passivation layers but also form a well-functioning pn junction with c-Si.

Building on these excellent results, a study of the homogeneity of the passivation over an entire wafer load has been carried out. To demonstrate the process, a horizontal wafer boat with 20 slots for 6" Cz wafers was used. The wafers were saw-damage etched and cleaned, and a thin interfacial oxide was grown in hot nitric acid. After the deposition of a ~35nm-thick a-Si(n) layer on both sides, the film thickness was checked: a mean layer thickness of 34.5±1.4nm (deviation $4\%_{rel}$) was measured by spectroscopic ellipsometry. A high-temperature anneal was performed at 850°C, as was an additional forming-gas anneal (5% H_2, 95% N_2), which slightly enhanced the initial surface passivation quality.

Fig. 6 shows a schematic of the wafer carrier; the corresponding iV_{oc} and implied fill factor (*iFF*) values are listed for each wafer. The average iV_{oc} is 719±2mV and demonstrates the good homogeneity of Fraunhofer ISE's process. Moreover, photoluminescence (PL) imaging revealed a very good level of homogeneity of surface passivation over each wafer.

Since the horizontal configuration of the wafer carrier is only used for research applications, whereas vertical boats are used exclusively in production, the process will be performed with a larger vertical boat in a next step. Besides uniformity over the process boat, the current work being done addresses process time and process gas utilization rate, both of which need to be improved to meet industrial requirements.

Radio-frequency PECVD

A modified MAiA tool from Meyer & Burger for TOPCon is also currently being evaluated; instead of microwave sources, the tool is equipped with radio-frequency plasma sources. In a previous study it was already shown that stacks of intrinsic and P-doped a-Si:H providing good surface passivation quality on textured surfaces can be realized with this system. Such processes have now been adapted to the needs of TOPCon (i.e. lower H content in order to avoid blistering); very encouraging iV_{oc} values of 740mV and 720mV have been achieved for planar and textured surfaces respectively (see Fig. 7). The work is still in the preliminary stages, and further evaluation and development of this process is planned.

"Industrial tools for both LPCVD and PECVD can be used to deposit the doped Si layer for TOPCon with high passivation quality."

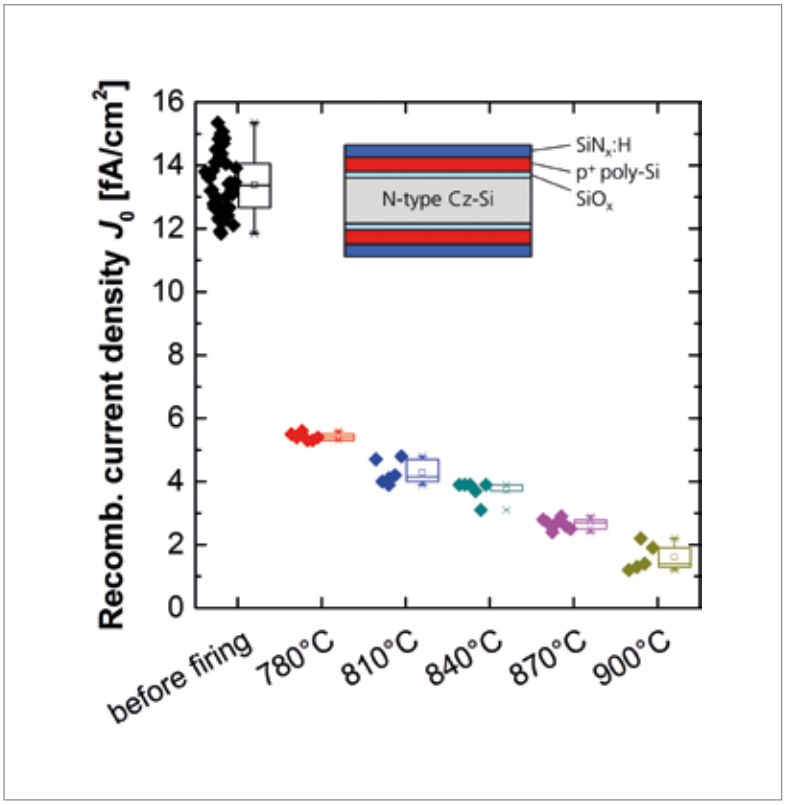

Figure 8. J_o for each side of symmetrical test structures with interfacial oxide, boron-doped poly-Si layer and SiN_x capping, determined after contact firing for different set temperatures [20].

LPCVD

In an initial experiment, a Tempress Spectrum system was used to deposit boron-doped poly-Si layers with a thickness of 300nm by LPCVD onto an interfacial oxide layer grown in situ. After thermal annealing at 900°C in a N_2 atmosphere, SiN_x layers were deposited on both sides by PECVD to yield symmetrical samples. The impact of different set firing temperatures on the resulting J_0 for each side is shown in Fig. 8.

Apparently, higher set firing temperatures lead to a decrease in J_0, presumably because of a more efficient hydrogen release from the SiN_x capping layer. In addition, the extraordinary quality of TOPCon is highlighted by the very low J_0, with values down to 1fA/cm²; including the n-type wafer, this corresponds to an iV_{oc} of up to 732mV for the symmetrical structure. In view of the applied oxide thickness, a low-resistive majority-carrier transport is expected for this structure. Future work will focus on decreasing the poly-Si layer thickness in order to improve throughput, and on further development of the process to allow full loads of more than 1,000 wafers.

To summarize, it has been demonstrated that industrial tools for both deposition techniques – LPCVD and PECVD – can be used to deposit the doped Si layer for TOPCon with high passivation quality.

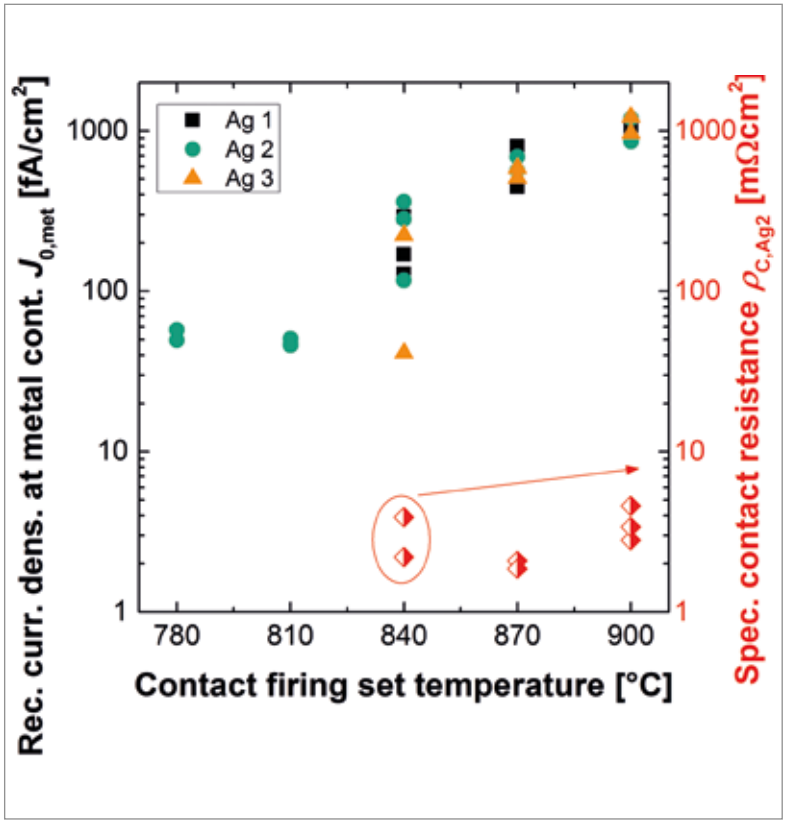

Figure 9. $J_{0,met}$ determined by PL imaging at the metallized sites, and ρ_c of screen-printed silver pastes (Ag 2) on boron-doped poly-Si layers, for different set firing temperatures (Adapted from Mack et al. [20].).

Metallization for TOPCon

To date, most of the solar cells incorporating TOPCon feature external contacts formed by the physical vapour deposition (PVD) of metals such as silver or aluminium. However, PVD is not yet a technology widely used in the Si PV industry today, and is mostly employed for contacting SHJ or interdigitated back contact (IBC) solar cells. Various solutions, such as silicides/polycides, have

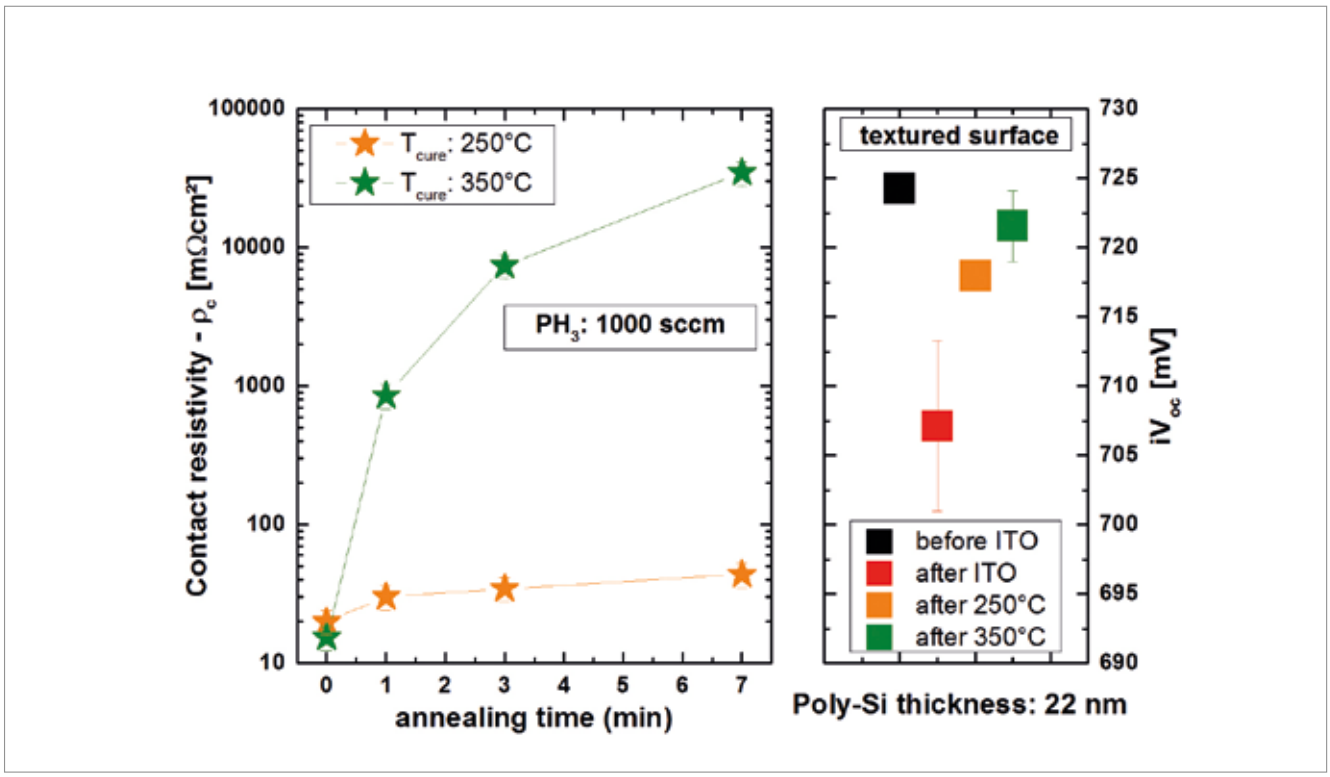

Figure 10. Contact resistivity (left) and iV_{oc} (right) of n-TOPCon/ITO stacks [22].

been developed by the microelectronics industry, but these are rather complex, and therefore not economically attractive for solar cell production. As an alternative option, the following metallization schemes can be envisioned: (1) screen-printed metallization, (2) a transparent conductive oxide (TCO)/metal stack, and (3) electrochemical solutions (plating). Since the third possibility is still at a very early development stage, the focus will be on the results obtained for approaches (1) and (2).

Screen-printed metallization

Screen printing is the standard metallization technique for solar cells and is therefore the preferred choice for cell manufacturers. In this approach, SiN_x is deposited onto TOPCon, a silver paste is then screen-printed, and the cells are finally subjected to a fast-firing step. The advantages are:

- Possibly high compatibility with front-side metallization (co-firing).
- Cost-effective and well-established process.
- Hydrogenation of TOPCon is without cost.

Mack et al. [20] reported on the contacting of 300nm p-type poly-Si films by SP-FT pastes. For this, commercially available silver pastes were used; these were originally developed for contacting diffused phosphorus emitters. The results of transfer length method (TLM) measurements are shown in Fig. 9. Two of the silver pastes allow the contacting of the poly-Si layer, with low ρ_c values of 2 to 4mΩcm², for set firing temperatures of 840 to 900°C. Apart from the low ρ_c values, these set temperatures are in the same range as the required temperatures for the front-side firing of solar cells, which indicates that there appears to be a process window for co-firing.

"The use of a TCO/metal stack instead of screen-printed metallization avoids the local depassivation of TOPCon."

The results, however, also show a significant interaction between the paste and the poly-Si, which is in line with the work of other authors [24]. First of all, the Ag paste partly consumes the underlying poly-Si film, and forms a highly recombination-active contact with the c-Si base. Significantly higher J_o values at the metallized areas have therefore been reported [20] (see Fig. 9), compared with non-metallized sites in Fig. 8. One strategy to reduce minority-carrier recombination at the metal contacts is an enhanced drive-in of dopants; however, this adversely affects the

Company/Institute	Area [cm²]	Cell type	TOPCon layer/ Deposition method	Metallization	η [%]	V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]
ISE [9,10]	4	Hybrid	n-SiC_x / PECVD	PVD Ag	25.8*	724	42.9	83.1
ISE [9,28]	4	Hybrid (mc-Si)	n-SiC_x / PECVD	PVD Ag	22.3*	674	41.1	80.5
ISE	100	Hybrid	n-SiC_x / PECVD	PVD Ag	23.4*	697	41.4	81.1
ANU [34]	4	Hybrid	n-poly-Si / PECVD + $POCl_3$ diffusion	PVD Ag	24.7	705	42.4	82.6
EPFL [35]	4	Hybrid	p-SiC_x / PECVD	PVD ITO/Ag	21.9	698	39.4	79.5
TU Delft [36]	7.84	Hybrid	p-poly-Si / LPCVD + B implantation	PVD Ag	20.8	656	40.7	75.2
ECN [25]	239	Hybrid	n-poly-Si / LPCVD	SP-FT Ag	21.5	676	39.7	80.4
Tempress [37]	239	Hybrid	n-poly-Si / LPCVD	SP-FT Ag	21.6	666	41.0	79.0
Meyer Burger [38]	239	Hybrid	n-poly-Si / PECVD	SP-FT Ag	21.2	676	40.3	79.3
GIT [39]	239	Hybrid	n-poly-Si / PECVD	PVD Ag	21.2	683	39.7	78.1
Jolywood [40]	239	Hybrid	n-poly-Si / n/a	SP Ag	22.4	688	40.8	81.4
ISFH [41]	4	IBC	poly-Si / LPCVD + implantation	PVD Al	26.1*	727	42.6	84.3
ISE [42]	4	IBC	poly-Si / LPCVD + implantation	PVD Al	23.7*	720	41.3	79.6
SunPower [29]	153	IBC	n/a	n/a	25.2	737	41.3	82.7
Trina Solar [30]	239	IBC	n-poly-Si / LPCVD	SP Ag	25.0	716	42.3	82.8
EPFL [43]	4	Top/rear	SiC_x / PECVD	PVD ITO SP Ag	22.6	720	38.8	81.0
ISFH [44]	244	Top/rear	poly-Si / LPCVD + implantation	PVD ITO SP Ag	22.3	714	38.5	81.1

**independently confirmed efficiency*

Table 1. Efficiency table, highlighting the results from different companies and institutes.

recombination current at the non-metallized sites [25]. As of today, TOPCon in combination with SP-FT paste cannot be considered to be a passivating contact, but rather a conductive surface passivation layer featuring local contacts. Significant improvement of this technology is expected from paste development rather than from an adaptation of TOPCon. Work is currently being carried out on integrating these layers and metal pastes as a rear contact in bifacial p-type solar cells, as well as on the development of lean process sequences.

TCO/metal stacks

TCOs, such as tin-doped indium oxide (ITO), are commonly used as electrodes for HJT solar cells. These particular oxides enable low-resistive contacts to be made to doped a-Si:H, provide a low sheet resistance required for lateral charge-carrier conduction to the metal grid, and serve as an anti-reflection coating at the front and as an optical spacer at the rear. TCOs can therefore be considered an attractive multifunctional contact material for TOPCon. The combination of TCO and TOPCon is also highly attractive because TOPCon's higher thermal stability potentially widens the process windows or facilitates the use of other deposition techniques, such as PECVD. The results obtained for sputtered ITO will be outlined next.

When sputtering TCO on TOPCon, a similar issue arises as with HJT cells: sputter-induced damage of the passivation quality. In a series of experiments, the influence of sputter deposition conditions (e.g. power, pressure) on differently prepared TOPCon structures (with respect to layer thickness, doping level and drive-in of dopants) was investigated. One decisive parameter for controlling the sputter damage is the TOPCon layer thickness, since very thin films are highly sensitive to sputter conditions, whereas thicker films seem not be affected by various sputter processes. In the case of very thin TOPCon layers, sputter damage will occur, which has to be cured by a thermal treatment.

Fig. 10 shows the impact of sputter deposition and subsequent thermal annealing [22]. In contrast to HJT cells, the issue of sputter damage is not completely resolved at T = 250°C; in fact, temperatures in the vicinity of 350°C are required to bring about an almost complete recovery of the initial surface passivation quality. Depending on the TCO material, such high annealing temperatures can either improve or degrade its bulk properties. For instance, at such high temperatures, ITO becomes less transparent (because of increasing free-carrier density) and exhibits a lower mobility; on the other hand, ZTO or AZO become *more* transparent and exhibit *higher* mobilities after annealing [26,27].

One thing that all materials screened so far

have in common, however, is that a contact barrier between TOPCon and TCO appears at 350°C, which results in a dramatic increase in contact resistivity (see Fig. 10). This issue can be elegantly circumvented by adapting the TOPCon contact as well as the sputter process, so that lower curing temperatures can be used. At a temperature of 250°C, for instance, contact resistivities below 40mΩcm² were measured, which is only about one-fifth of the values reported for HJT cells.

TOPCon integration into solar cells

Research in the PV community focuses mainly on three cell concepts:

1. Hybrid cell structures featuring a homojunction at the front and a TOPCon rear contact.
2. IBC cells with TOPCon contacts.
3. HJT-like solar cells with TOPCon top/rear contacts.

Table 1 summarizes the solar cell efficiencies achieved by different institutes and companies. Most papers currently report on the hybrid solar cell structure, because it can be a drop-in replacement for current PERT/PERC cells. On the laboratory scale, the best two-side-contacted cell is Fraunhofer ISE's n-type cell with a boron-diffused front emitter and a TOPCon rear contact. By transferring this solar cell concept to n-type high-performance mc-Si wafers, a world-record efficiency of 22.3% has been achieved [9,28].

The first large-area solar cell processed on industrial equipment was announced by Stodolny et al. [23] from the Energy Research Centre of the Netherlands (ECN), and reached an efficiency of 20.7%. While these cells feature screen-printed contacts, work on n-type cells with plated front metallization and a TCO/metal stack at the rear is currently under way at Fraunhofer ISE. As mentioned earlier, the use of a TCO/metal stack instead of screen-printed metallization avoids the local depassivation of TOPCon; moreover, thinner poly-Si layers can be used and mitigate the negative effect of free-carrier absorption on the short-circuit density. In consequence, this particular metallization strategy has a higher efficiency potential. In a first step, an n-type solar cell featuring a homogeneous boron-diffused front emitter and TOPCon rear contact was created on an area of 100mm × 100mm, with an independently confirmed efficiency of 23.4% being achieved. Future work is dedicated to reducing recombination at the front metal contacts by addressing the issue of laser-induced damage to the silicon crystal and implementing a selective emitter.

The IBC cell concept has the potential for very high efficiencies, as demonstrated by Kaneka's world-record solar cell. In early 2018, the Institute for Solar Energy Research in Hamelin (ISFH) demonstrated a 26.1%-efficient IBC cell (4cm²) featuring both polarities of the poly-Si contact at the rear [41]. Being several steps ahead of the PV community, SunPower already produces IBC cells and modules featuring passivating contacts (technology not disclosed), with efficiencies of up to 25.2% and 24.1% respectively [29]. By the beginning of 2018, Trina Solar announced an efficiency improvement from 24% to 25% [30]; one notable change to their IBC cell was the replacement of the phosphorus-diffused BSF by a phosphorus-doped poly-Si contact.

The third concept is quite similar to a HJT cell, but uses TOPCon contacts of both polarities. This configuration enables very high V_{oc} values similar to an IBC cell and has the potential for very high *FF*: for instance, Nogay et al. [31] demonstrated an *FF* of 84.0% on a planar solar cell, which confirms the excellent surface passivation and low contact resistivity values of TOPCon/TCO stacks. The drawback of this approach, however, is related to the significant parasitic absorption in the poly-Si layers. From simple solar cells, a J_{sc} loss of about 0.4mA/cm² per 10nm poly-Si layer thickness has been determined [32]; this is in agreement with optical calculations using the optical constants of poly-Si as input parameters [33]. Another challenge is sputter damage, which is more pronounced for the very thin films required for front-side application.

Conclusion

Progress towards the upscaling of TOPCon technology has been reported in this paper. It has been shown that TOPCon can be realized by both industrial-scale PECVD and LPCVD deposition systems, and that there is no difference in terms of passivation quality. The single-sided nature of PECVD is one strong advantage of this technique; on the other hand, LPCVD facilitates the growth of thicker poly-Si layers, which can presumably be more easily contacted using SP-FT pastes. Each technique therefore has its merits and drawbacks. It is difficult to determine at this stage the throughput of the different tools and perform reliable cost calculations, as process development is ongoing; the authors will therefore refrain from advocating the use of one technology over another.

The summary of the solar cell results obtained nicely underlines the potential of TOPCon to be a key enabling technology for high-efficiency solar cells; as a result, TOPCon is regarded by many as a follow-up technology to PERC. The next steps to be taken are the development of a cost-effective and non-damaging metallization scheme, and the integration into a lean and industry-feasible process flow.

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