The race for the best silicon bottom cell: Efficiency and cost evaluation of perovskite–silicon tandem solar cells

Christoph Messmer1,2 | Baljeet S. Goraya1 | Sebastian Nold1 | Patricia S.C. Schulze1 | Volker Sittinger3 | Jonas Schön1,2 | Jan Christoph Goldschmidt1 | Martin Bivour1 | Stefan W. Glunz1,2 | Martin Hermle1

1Photovoltaics, Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany
2INATECH, University of Freiburg, Freiburg, Germany
3Chemical Vapour Deposition, Fraunhofer Institute for Surface Engineering and Thin Films IST, Braunschweig, Germany

Correspondence
Christoph Messmer, Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany.
Email: christoph.messmer@ise.fraunhofer.de

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Abstract
Perovskite–silicon tandem solar cells have shown a rapid progress within the past 5 years in terms of their research cell efficiency and are currently being investigated as candidates for the next generation of industrial PV devices. This raises the question of which silicon bottom cell will be most suitable for tandem application. Currently, the silicon heterojunction (SHJ) technology dominates in tandem research achieving world records. However, it is an open issue of how to transfer these research results to industrial mass production, which is driven by cost reduction and resource efficiency and includes challenges like upscaling and long-term stability. Therefore, it is highly relevant for the PV industry to get reliable and predictive estimates on the efficiency and cost potential, as well as technologically feasible solutions. In this work, we elaborate on silicon bottom cell concepts based on the PERC, TOPCon, and SHJ technology combined with two different interconnection concepts. For each tandem device, the efficiency potential is investigated by means of an experimentally validated simulation model. Second, we evaluate the bottom cell concepts in terms of all-in cell costs per piece. Bringing the efficiency potential and cost evaluation together allows us to assess the different tandem cell concepts in terms of all-in module cost per watt peak. Our results show that perovskite–silicon tandem devices are promising candidates to significantly reduce the levelized cost of electricity and, in particular, that the “race” for the best silicon bottom cell is still open to all the investigated bottom cell technologies.

KEYWORDS
cost analysis, perovskite–silicon tandem solar cells, photovoltaics, Quokka3, Sentaurus TCAD, simulation

1 INTRODUCTION

As the pursuit for highest efficiency and cost reduction of PV technologies goes on, silicon-based solar cells are about to reach their technological efficiency limit.1,2 Increasing the power conversion efficiency of solar cells is one key driver to further decrease the in part of the LCOE arises from module and installation costs3–5 that depend on the area. Therefore, the interest in tandem...
application is strongly increasing, among which perovskite–silicon tandem solar cells are currently being investigated as a candidate for next generation PV devices combining low costs\textsuperscript{5,6} and high efficiency. Recent publications have shown the potential of monolithic perovskite silicon tandem cells, surpassing the current 26.7% world record cell efficiency for single-junction c-Si solar cells\textsuperscript{7} with a tandem efficiency of 28% certified efficiency by Oxford PV\textsuperscript{8}, and the current world record of 29.15% certified tandem efficiency published by Helmholtz Center Berlin.\textsuperscript{9} Currently, the silicon heterojunction (SHJ) bottom cell technology, which provides high open-circuit voltages,\textsuperscript{10} dominates in tandem research, and also the latest Pero–Si tandem world records are based on SHJ bottom cells. However, at this stage of development, the question is raised of how to transfer these research results to industrial mass production, which will be driven by cost reduction and resource efficiency including challenges like upscaling and long-term stability. Therefore, the race for the best-suited silicon bottom cell with respect to industrial mass production is not yet decided since the requirements for a silicon bottom cell with respect to performance, costs, and compatibility with the subsequent industrial processing steps of the tandem cells are different compared with that of the single junction solar cells. Different designs of the perovskite top cell as well as candidates for interconnection layers\textsuperscript{11,12} and tunneling junctions\textsuperscript{13–16} are currently investigated. At this stage of development, it is highly relevant for the PV industry to get reliable and predictive estimates based on a holistic view, as well as technologically feasible solutions. Therefore, a systematic evaluation of tandem bottom cells from cost and efficiency perspective is needed.

The aim of this work is to evaluate the efficiency and cost potential of different silicon bottom cell concepts in terms of their application in future industrial perovskite–silicon tandem solar cells and modules. We focus on bottom cell concepts based on the PERC, TOPCon, and SHJ technologies. For each concept, a TCO-based recombination (ReCO) layer and a silicon-based tunneling junction (SiT) between top and bottom cell (which is needed for electrical and optical coupling in a 2-terminal device) has been investigated. For this, we elaborated and experimentally validated an optical simulation model in Sentaurus TCAD\textsuperscript{17} taking into account parasitic absorption of all layers, as well as the influence of the textured or planar front surface of the bottom cell. The electrical simulation model of the bottom cell in Quokka\textsuperscript{3} allows for detailed investigation of important cell parameters. In a second step, we evaluate the bottom cell concepts in terms of all-in cell costs per piece. We considered the cell manufacturing including wafer, equipment, process consumables, and waste disposal to get an estimate based on this comprehensive modelling for each tandem concept. Bringing the cost evaluation and efficiency potential together allows us to assess the different bottom cell concepts in terms of cost per watt peak and LCOE, which are decisive figures of merit for the choice of the future bottom cell technology for perovskite–silicon tandem solar cell applications. The following section will present our simulation approach, experimental validation of the optical model, and the methodology of the cost evaluation.

2 | APPROACH AND MODELLING

2.1 | Investigated bottom cell concepts

Figure 1 shows the four investigated silicon bottom cell concepts ("P\textsubscript{[E]}RC," "TOPerc," "TOPCon\textsuperscript{2}," and "SHJ"), each combined with two different interconnection concepts ("ReCO" and "SiT") towards the perovskite top cell (sketched in gray). The interconnection, which is needed for electrical and optical coupling of the two subcells, is either formed by a 20-nm-thick lowly doped recombination TCO layer (which we name “ReCO”), or it is based on a (polysilicon tunneling junction (which we name “SiT”). In the following, we describe the details of the different silicon bottom cell concepts:

1. P\textsubscript{[E]}RC is based on the standard PERC technology and features a passivated rear side with local Al-BSF contacts applied by laser contact opening (LCO) and a 1-Ω-cm p-type c-Si wafer with a minority carrier lifetime of 1 ms. We will investigate both monofacial and bifacial application. The monofacial rear side fully covered by aluminum is described by the Phong model with parameters according to Woehrle et al.,\textsuperscript{19} whereas the bifacial rear side has been validated by experimental data according to Messmer et al.\textsuperscript{20} The front side features a highly doped, shallow phosphorus emitter as internally developed by Fraunhofer ISE, which is directly contacted by 20 nm of TCO ("ReCO-P\textsubscript{[E]}RC") or 30 nm of p-type polysilicon ("SiT-P\textsubscript{[E]}RC"). We assumed that neither the TCO nor the polysilicon leads to a passivation of the silicon surface which means that we have an unpassivated emitter,\textsuperscript{14,21} therefore, we put the \{E\} in brackets.

2. TOPerc has the same rear side and absorber as the P\textsubscript{[E]}RC structure. However, the diffused n\textsuperscript{++}-emitter at the front side is replaced by 30-nm-thick n-TOPCon structure that forms the full-area passivating electron contact of the absorber. Figure 1 shows the Pero-ReCO-TOPerc concept where contact towards the top cell is again formed by 20-nm TCO, whereas for Pero-SiT-TOPerc, the 20 nm of poly-Si(p) on poly-Si(n) serves as a silicon tunneling junction.\textsuperscript{16} The free-carrier-absorption (FCA) of all poly-Si layers was experimentally validated in Messmer et al.\textsuperscript{20}

3. TOPCon\textsuperscript{2} has the same front side as Pero-TOPerc, but the rear side is made of ~100 nm of p-TOPCon and Si\textsubscript{N}, which is forming the passivating hole contact of the absorber. It is locally contacted by fired screen-printed silver fingers that allow for smaller finger widths (30 μm) as compared with the Al fingers (100 μm) of P\textsubscript{[E]}RC and TOPerc. The c-Si wafer can be either p- or n-type, denoted as TOPCon\textsuperscript{2}(p) or TOPCon\textsuperscript{2}(n), respectively. Again, both a TCO ("Pero-ReCO-TOPCon\textsuperscript{2}") and silicon tunneling junction ("Pero-SiT-TOPCon\textsuperscript{2}") were investigated. For this concept, we only elaborate on the bifacial device since the full deposition of silver on the rear side for monofacial application is economically not feasible.

4. SHJ features a 1-Ω-cm n-type c-Si wafer with a minority carrier lifetime of 12 ms. The rear side features 8-nm intrinsic and 15-nm p-type amorphous silicon that forms the passivating hole contact. It is textured, and for the bifacial application, 70 nm of moderately
A doped TCO is used at the rear to account for lateral transport towards the screen-printed silver fingers. The latter are assumed to be slightly thicker (35 μm) compared with Pero-TOPCon2 due to low-temperature processing. Since monofacial SHJ bottom cells are used as the current standard in lab cells, we also elaborate on the fully deposited Ag rear side. For this, we use a lowly doped TCO, since lateral transport is not needed, and current is improved by the reduced FCA. The front side of the “Pero-ReCO-SHJ” concept is made of 8-nm a-Si(i) and 8-nm a-Si(n) which are followed by the TCO. For the “Pero-SiT-SHJ,” the a-Si(n) is replaced by 20 nm of n-type micro-crystalline silicon (μcSi), and the tunneling junction is completed by 20 nm of p-type micro-crystalline silicon.15

For each concept, we investigate planar and textured front side as well as monofacial and bifacial application (where feasible). More details on the simulation parameters can be found in Tables 1 and 2. The following subsection will provide experimental validation for the optical model of our simulation approach.

### 2.2 Optical model and experimental validation

For a validation of the optical simulation model, we focus on experimental data of a tandem device published by Schulze et al.,33 which is schematically shown in Figure 2a. This monolithic tandem device features a planar p-i-n top cell with a band gap adapted perovskite absorber [FA0.75Cs0.25Pb(I0.8Br0.2)3]. The C60/SnOx/ITOtop/MgF2 layer stack on top of the perovskite serves as an anti-reflection coating and electron transport layer and provides lateral conductivity towards the metal contacts, whereas the PFN/PTAA layer underneath the perovskite is used as a hole transport layer. An analogue to Figure 1, this cell concept features an interconnection layer and silicon bottom cell based on the “Pero-ReCO-SHJ(p)” concept, that is, a 70-nm-thick ITO as recombination layer and a standard silicon heterojunction (SHJ) with a 250-μm-thick p-type c-Si absorber. The front side of the SHJ bottom cell features 8-nm a-Si(i) and 8-nm a-Si(n) forming the electron contact towards the perovskite top cell. The rear contact of the c-Si bottom cell features 8-nm intrinsic and 15-nm p-type amorphous silicon forming the passivating hole contact. A moderately doped ITOrear is used at the rear side that is fully covered by silver, to account for good reflection and light trapping properties of the monofacial and textured rear side.

Optical modelling of the whole silicon-perovskite tandem device was performed with Sentaurus TCAD17 using raytracing in the c-Si bottom cell and transfer-matrix-method (TMM) for all thin layers including the perovskite top cell. The model allows for monofacial and bifacial cell architectures, as well as for textured and planar front and rear sides and was extended to tandem devices from Messmer et al.20 The Ag front metal contact is neglected in the optical model, since only the active cell area is measured. Optical data were taken from recent measurements at Fraunhofer IST and ISE. For this, single films of ITO, PTAA, SnOx, and MgF2 were deposited and optically characterized by ellipsometric and optical measurements by means of a Sentech SE850 ellipsometer and a PerkinElmer Lambda 950 spectrophotometer with integrated sphere, respectively. The ellipsometric measurements were recorded at three different angles of incidence (50°, 60°, and 70°). To model the dielectric function, multiple fitting models are used. To improve the model accuracy, both the ellipsometric as well as the transmission and reflection data were simultaneously fitted. The ITO film was modelled with the optical data from Holman,25 except for the n-data, where we could use our own
measurements. The optical data for c-Si and poly-Si layers were taken from Schinke and Baker-Finch, which were validated in Messmer et al. All other data, including C60, perovskite, and a-Si layers, were taken from PV lighthouse. Free-carrier absorption (FCA) is accounted for in all layers.

Figure 2b shows the comparison between the experimental data (dotted lines) and the optical simulation data (solid lines). The simulation data show the arithmetic average from three single simulations with varied perovskite thickness around 350 ± 25 nm. This is based on the layer thickness of approximately 350 nm determined by SEM cross-sectional images of the experimental device and accounts for the perovskite’s rough surface, which was analyzed by AFM measurements. The green lines in Figure 2b show the reflection (subtracted from 1) of the whole tandem device of Figure 2a. The averaged simulation data match the experimental reflection very well. For wavelengths above 1 μm, the simulated reflection is slightly smaller than the experimental data.

### Table 1: Optical simulation parameters

| Quantity | Value |
|----------|-------|
| Sentaurus TCAD Total | Q-2019.12 |
| Global | 298.15 K |
| Spectrum | AM1.5 g, 1 sun (from previous work) |
| Crystalline silicon | |
| Thickness | 180 μm |
| Resistivity | 1 Ω cm (n- and p-type) |
| Complex refraction data | Schinke et al. extended with FCA model of Baker-Finch |
| Layer stack | |
| Perovskite top cell | 92 nm MgF2, Fraunhofer IST |
| | 75 nm ITO, n: IST, k: Holman et al. |
| | 25 nm SnOx, Fraunhofer IST |
| | 10 nm C60 |
| | 480 nm perovskite |
| | 11 nm PTAA, Fraunhofer IST |
| Interconnection layers | 20 nm ReCO (ITO), IST |
| | SiT, Schinke et al. extended with FCA model of Baker-Finch (same for all poly-Si layers) |
| P(E)RC | |
| Rear | 70 nm AlOx, SiNx (bifacial) or Phong model (for monofacial) |
| Front n-TOPCon | 30 nm poly-Si(n) |
| | 1.4 nm oxide |
| Rear p-TOPCon | 1.4 nm oxide |
| | 100 nm poly-Si(p) |
| | 70 nm SiNx |
| SHJ | |
| Front | ReCO: 8 nm a-Si(n), 8 nm a-Si(p) |
| | SiT: 20 nm μ-Si(p/n), 8 nm a-Si(i) |
| Rear | 8 nm a-Si(i) |
| | 15 nm a-Si(p) |
| | 70 nm ITO (highly doped for bifacial, lowly doped for monofacial, IST) |

### Table 2: Electrical simulation parameters

| Quantity | Value |
|----------|-------|
| Quokka3 | 1.2.7 |
| Crystalline silicon bulk | |
| Resistivity | 1 Ω cm |
| Thickness | 180 μm |
| Lifetimes | τp-type = 1 ms, τn-type = 12 ms |
| P(E)RC | |
| Front emitter | j0 = 76 fA/cm² (on textured) |
| | Collection efficiency = 16% |
| Al finger width | 100 μm (with point contacts) |
| Full rear BSF | j0 = 10 fA/cm² (non-contacted) |
| | j0,met = 400 fA/cm² (contacted) |
| Front n-TOPCon | j0 = 5 fA/cm² (on planar) |
| Rear p-TOPCon | |
| Thickness of poly-Si(p) | 100 nm |
| Sheet resistance | Calculated for N0 = 1.5 × 10²⁰ cm⁻³ with mobility μ = 25 cm²/Vs. |
| Recombination | j0 = 5 fA/cm² (non-contacted) |
| | j0,met = 20 fA/cm² (contacted) |
| Ag finger (bifacial device) | Width: 30 μm |
| | Pitch: 1.600 μm (low Ag costs) |
| SHJ | |
| Recombination | j0,front = 0.5 fA/cm² (on planar) |
| | j0,rear = 0.5 fA/cm² |
| Thickness of rear TCO | 70 nm |
| TCO sheet resistance | Calculated with mobility μ = 50 cm²/Vs and N0 = 2 × 10²⁰ cm⁻³ for bifacial and N0 = 1 × 10²⁰ cm⁻³ for monofacial rear side |
| Si/a-Si(p)/TCO contact resistivity | 240 mΩ·cm² |
| Ag finger (bifacial device) | Width: 35 μm |
| | Pitch: 1.600 μm (low Ag costs) |
| Area factor (used for j0) | Textured/planar = √3 (see Baker-Finch and McIntosh) |
| Front metallization ratio | 2% (see Kamino et al.) |
due to slightly better light trapping properties of the simulated cell. The dotted blue line shows the measured external quantum efficiency of the perovskite cell EQE (Pero) from Schulze et al.\textsuperscript{33} in comparison with the simulated absorbed photon density within the perovskite A gen (Pero) shown as solid blue line. The complex refractive index for perovskite from Manzoor et al.\textsuperscript{33} was adapted in order to match the low energy onset of the perovskite’s EQE, which was determined by Schulze et al.\textsuperscript{33} to be 1.68 eV. One can see that the simulated A gen (Pero) describes the EQE (Pero) quite well within the measurement uncertainties. However, please note that as a purely optical simulation, A gen does not include electrical losses, which are included in the measured EQE (Pero); still A gen (Pero) is slightly smaller than EQE (Pero). Therefore, we conclude that the parasitic losses in the top cell layers for short wavelengths are probably slightly overestimated in our simulation, since especially the characterization of optical losses within the top ITO is challenging. On the other hand, we deduce that recombination losses within the perovskite are rather small. Since A gen (Pero) is describing the EQE (Pero) quite well, we assume in the following that the short-circuit current density of the perovskite $j_{sc,Pero}$ is equal to the generated photo current density $j_{ph,Pero}$ in the perovskite absorber.

The measured EQE of the silicon bottom cell (dotted red) and the simulated generated photon density A gen (Si) (solid red) show good agreement, except for wavelengths above 1 \( \mu \)m, where the lower escape reflection of the simulated cell leads to a higher absorption in the silicon compared with the experimental cell. Consequently, we can approve that the simulation model correctly describes the recently published optical data for perovskite-silicon tandem solar cells with a SHJ silicon bottom cell.

After validating the optical model, we apply some adaptions since the experimental test structure is not current-matched ($j_{ph,Pero} = 17.7 \text{ mA/cm}^2$, $j_{ph,\text{Si}} = 19.3 \text{ mA/cm}^2$). The following realistic adaptions were applied, which are also currently planned for upcoming experiments:

1. The thickness of the ITO recombination layer is reduced from 70 to 20 nm, as already done for other tandem devices.\textsuperscript{39}
2. The thickness of the perovskite is increased from 350 to 480 nm, which increases the $j_{ph,Pero}$.
3. The silicon absorber thickness is decreased from 250 to 180 \( \mu \)m, which is industry standard.
4. Since current-matching cannot be reached by thickness variations alone, the bandgap of the perovskite absorber was lowered from 1.68 to 1.66 eV (see also previous studies\textsuperscript{33,40,41}).

When applying these adaptions, this reference Pero-ReCO-SHJ tandem device with planar front side and textured SHJ bottom cell is ideally current-matched with $j_{sc,Pero} = j_{sc,\text{Si}} = 19.40 \text{ mA/cm}^2$.

### 2.3 Electrical model

To investigate the different silicon bottom cell architectures of Section 2.1, we perform the optical simulation according to Section 2.2 for each tandem concept, including the two different interconnection layers, the variation of textured and planar front side, as well as the monofacial and bifacial cases. Subsequently, we use the optical generation profiles as an input for the electrical simulation of the silicon bottom cell executed by Quokka\textsuperscript{3,18,42}, which is a profound tool.
explicitly developed for solar cell simulation. A detailed electrical modelling of the perovskite top cell is not included in this paper and will be the subject of future work.

Parameters for the simulation of the silicon bottom cell are mostly based on recent publications, as listed in detail in Table 2. All bottom cells feature a 180-μm-thick, 1-Ω-cm p-type (n-type) c-Si wafer with a minority carrier lifetime of 1 ms (12 ms). Further parameters will be discussed in the following:

1. For the P[E]RC bottom cell, the data for the shallow phosphorus front emitter were taken from internal measurements at Fraunhofer ISE featuring a surface recombination parameter described by $J_0 = 76 \text{ fA/cm}^2$ for the textured front side and an emitter collection efficiency of 16.3% due to the high doping which accounts for field-effect passivation towards the unpassivated interface between silicon and ReCO or SiT interlayer. For planar devices, $J_0,\text{eff}$ is reduced by a typical area factor of $\sqrt{3}$ (see Baker-Finch and McIntosh). The rear side is the same for all P[E]RC variations featuring an AlOx/SiNx passivation with $J_0,\text{PERC,rear,pass} = 10 \text{ fA/cm}^2$, and local Al-BSF point contacts with $J_0,\text{PERC,rear,Al-BSF} = 400 \text{ fA/cm}^2$.

2. The front side of TOPerc features an n-TOPCon passivation with $J_0 = 5 \text{ fA/cm}^2$ on the planar front side (factor $\sqrt{3}$ higher on textured front side$\text{ }^{32}$). The rear side is the same as P[E]RC.

3. The front side of TOPCon$^2$ is the same as for TOPerc, whereas the rear side is described by 100 nm of p-TOPCon with a poly-Si doping of $1.5 \times 10^{20} \text{ cm}^{-3}$. The etched rear side is the same for all TOPCon$^2$ variations and is described with $J_0 = 5 \text{ fA/cm}^2$ for the non-contacted areas, and $J_0 = 20 \text{ fA/cm}^2$ for the Ag fire-through paste contacted areas. In the bifacial case, the poly-Si(p) has to account for the lateral conductance, especially when using n-type c-Si bulk material.

4. For the SHJ bottom cell, the a-Si(i) passivation is described by $J_0 = 5 \text{ fA/cm}^2$ for the planar front side (factor $\sqrt{3}$ higher on textured front side$\text{ }^{32}$). The textured rear side is the same for all SHJ and features an a-Si(i) passivation of $J_0 = 5 \text{ fA/cm}^2$ for both contacted and passivated areas. In the bifacial case, a moderately doped 70-nm-thick ITO is needed for lateral transport, whereas in the monofacial case, a lowly doped ITO is sufficient and provides better optical properties. The rear finger pitch for the bifacial cell of both TOPCon$^2$ and SHJ bottom cell was optimized to lower the Ag consumption in order to minimize costs without significantly losing in cell efficiency.

As described in Section 2.2, the Pero-ReCO-SHJ(p) tandem cell with planar front side has been ideally current-matched via thickness and bandgap adaptions, so that $j_{sc,matched} = j_{sc,Pero} = j_{sc,SHJ}$. For all other cases, the short-circuit current of the tandem device has been current-matched by $j_{sc,matched} = 0.5 \cdot (j_{sc,Pero} + j_{sc,SHJ})$ for reasons of simplicity and to ensure a fair comparison between the concepts. This is a good approximation as long as the difference $j_{sc,Pero} - j_{sc,SHJ}$ is small which is the case for all our tandem devices (see Figure A1). The corrected current mismatch lies in the range of $-0.35$ to $0.45 \text{ mA/cm}^2$, which could be easily performed by bandgap adaptions of the perovskite absorber and/or different absorber thicknesses.

### 2.4 Cost evaluation model

In order to determine a suitable, low-cost, and industry viable bottom cell for perovskite–silicon tandem devices, a cost analysis is required that complements the results of the optical and electrical device simulations for each of the tandem cell designs shown in Figure 1. Advanced bottom-up cost calculations were performed using the SCost modelling approach, which is aligned with the SEMI standards E3544 and E10.45. The calculations for all concepts were performed for a green field production facility located in Eastern Europe with an annual production capacity of 5 GWp (with 72 cells per module with an area of 2.08 m$^2$, refer Table 3).

The processing costs were calculated based on data for industrial crystalline silicon solar cell and module manufacturing equipment including stepwise equipment CAPEX (with a depreciation of 7 years), throughput, downtime and yield assumptions, labor requirements, maintenance costs, as well as facility area costs. In addition, we accounted for overhead costs with a total of 7.5 €/module for selling, general, and administrative expenses (SG&A) as well as for research and development (R&D) for each corporate unit (represented by cell and module production). To account for cost of capital, we assumed cost of debt and equity capital on all assets and working capital as presented in Table 3 resulting in weighted average cost of capital (WACC) of 5.0%. Thus, the all-in cell and all-in module costs can be equated to a potential sustainable selling price of the manufacturer. Equipment parameters as well as material consumption and prices have been assessed through via direct communication with equipment manufacturers and material suppliers as well as data from literature. All costs are given in €2020, and further details on the process flow of each Pero-Si tandem concept can be found in Figures A2 and A3.

### 3 EFFICIENCY AND COST EVALUATION

This section shows the results of the cell efficiency and cost evaluation for the perovskite–silicon tandem solar cell devices based on the different bottom cell concepts introduced in Section 2.1 and the optical model of Section 2.2. In the first subsection we analyze the optical generation current densities and losses, followed by the results of the electrical cell parameters of each concept. The third subsection will show the estimated costs for each cell concept based on an elaborated cost calculation. The final section will conclude with a techno-economic assessment on tandem devices.

#### 3.1 Analysis of optical losses

The optical model described in Section 2 allows for a detailed analysis of the optical current densities within each tandem concept. Figure 3...
shows the optical gains and losses of the whole Pero-Si tandem device for each silicon bottom cell and interconnection concept in the case of the bifacial device with textured front side, monofacially illuminated with 1 sun and AM1.5 g from the front side. At the bottom, we can see the generated current densities in the perovskite and silicon absorber as a dark blue and red bar, respectively. The optical losses are shown cumulatively on top of the generated current densities in Figure 3, except for the Pero-P[E]RC concept, which see that the 0.1 mA/cm² of FCA absorption in the lightly doped 20 nm ITO (shown in purple) is slightly smaller than the 0.2 mA/cm² FCA absorption of the highly doped 30 nm poly-Si (p) (shown in yellow). The sum of the generated current densities of the top and bottom cell is \( j_{\text{gen,sum}} = 40.7 \text{ mA/cm}^2 \) (which in the electrical simulation will lead to short-circuit current \( j_{\text{sc}} \), which is restricted to half of \( j_{\text{gen,sum}} \)).

1. For the Pero-P[E]RC tandem device, the main optical loss related to the bottom cell concept is the FCA in the heavily d-Si doped emitter (1.0 mA/cm², shown in light red), which is needed to reduce recombination at the unpassivated metal-like c-Si surface. If we compare the ReCO-P[E]RC to the SiT-P[E]RC concept, we see that the 0.1 mA/cm² of FCA absorption in the lowly doped 20 nm ITO (shown in purple) is slightly smaller than the 0.2 mA/cm² FCA absorption of the highly doped 30 nm poly-Si (p) (shown in yellow). The sum of the generated current densities of the top and bottom cell is \( j_{\text{gen,sum}} = 40.7 \text{ mA/cm}^2 \) (which in the electrical simulation will lead to short-circuit current \( j_{\text{sc}} \), which is restricted to half of \( j_{\text{gen,sum}} \)).

2. The Pero-TOPerc device replaces the front phosphorus emitter by a full-area passivating n-TOPCon. The decrease of FCA in the phosphorus emitter is partly counterbalanced by FCA losses in the 30 nm of poly-Si(n). With \( j_{\text{gen,sum}} = 40.9 \text{ mA/cm}^2 \), the sum of the generated current densities is only slightly higher (+0.2 mA/cm²) for Pero-TOPerc with respect to Pero-P[E]RC.

3. The Pero-TOPCon² structure is shown for both p- and n-type c-Si bulk material. Comparing TOPCon² to TOPerc, we see that the rear poly-Si(p) accounts for additional 0.5 mA/cm² of parasitic losses (dark green), which lower the sum of the generated current densities in Pero/Si by 0.2 mA/cm² to \( j_{\text{gen,sum}} = 40.7 \text{ mA/cm}^2 \). The choice of the bulk material only very slightly affects the FCA in the c-Si bulk.

4. For Pero-SHJ, there are almost no FCA losses in the a-Si layers due to better red response; however, this is counterbalanced by the moderately doped TCO at the rear side, which is needed for lateral current transport and accounts for FCA losses around ~0.8 mA/cm². Therefore, the sum of the generated current densities is similarly high as Pero-TOPCon² (\( j_{\text{gen,sum}} = 40.7 \text{ mA/cm}^2 \)).

For tandem devices featuring a planar front side (not shown), the sum of the generated optical currents of all tandem architectures is lowered to \( j_{\text{gen,sum}} = 38.5-39.1 \text{ mA/cm}^2 \), mainly due to the increase in reflection losses to 4.0 mA/cm² (for ReCO) and 3.5 mA/cm² (for SiT). This difference in reflection losses arises from the worse refractive index matching of the TCO with respect to poly-Si and is much more pronounced in the case of planar front side. Due to shorter optical paths, the parasitic losses in all top layers are slightly decreased for planar devices by around 20%.

### 3.2 Electrical analysis of the bottom cells

Subsequently, the data from our optical model are used as input for the calculation of the electrical parameters of each of the different silicon bottom cell architectures in Figure 1.

Figure 4a shows the short-circuit current density \( j_{\text{sc,matched}} \) of the tandem device according to Section 2.3. Please note that we assumed an effective shadowing of 2% due to the front metallization grid, which is in line with Kamino et al.27 The black diamonds show the \( j_{\text{sc,matched}} \) for the textured bifacial devices for both TCO recombination layer (ReCO, open diamonds) and silicon tunneling junction (SiT, small closed diamonds). One can see that \( j_{\text{sc,matched}} \) follows the trends of the generated current density in Figure 3, except for the Pero-P[E]RC...
structure, where the highly doped phosphorus emitter lowers the $j_{sc,matched}$ by another 0.3 mA/cm² due to recombination in the n’+ emitter. The red diamonds in Figure 4a show the $j_{sc,matched}$ of the textured monofacial devices for both ReCO (open diamonds) and SiT (small closed diamonds). Monofacial devices yield higher $j_{sc,matched}$ compared with bifacial devices (which are only illuminated from the front side here) due to better light-trapping of the full metal rear side. This is shown for the P[E]RC and TOPerc bottom structure, as well as
for the SHJ bottom cell, where the monofacial device currently holds the current world record in tandem efficiencies. The monofacial Pero-SHJ benefits even more with respect to the bifacial case, since the rear TCO is not needed for lateral conductivity and therefore can be lower doped which causes less FCA. We also investigated planar front surfaces that are mostly used due to the challenging growth of the perovskite cell on textured wafers. The green boxes in Figure 4a show $j_{sc}$ of the planar front devices, for both the monofacial (light green) and bifacial (dark green) cases, as well as for ReCO (open boxes) and SiT (small closed boxes). Compared with the textured devices, one can see a shift towards lower $j_{sc,matched}$ for all bottom cell structures by ~1 mA/cm² due to higher reflection losses, but still the same trends comparing the different bottom cell structures. However, one can see that for these planar devices, the choice of the SiT interconnection (closed dots) is beneficial compared with using ReCO (open rectangles) due to better matching of the refractive index of the top layer stack leading to better light trapping for the device that features SiT interconnection.

The open-circuit voltage $V_{oc}$ of each silicon bottom cell concept is shown in Figure 4b. The $V_{oc}$ is dominated by the passivation of the c-Si wafer surface and the bulk recombination of the p-type and n-type wafer. Furthermore, please note that the bottom cell $V_{oc}$ is around 15–20 mV lower than it would be for a standalone silicon cell, since the short-circuit current $j_{sc}$ is only about half as high. In Figure 4b, we can see that for the P[E]RC bottom cell, we get a $V_{oc,P[ER]C} = 664$ mV for the textured front side and a slightly higher $V_{oc,P[ER]C} = 670$ mV for the planar front side due to less front surface area. $V_{oc}$ is only moderate due to the unpassivated front surface and the Auger recombination in the highly doped emitter. For TOPerc, the front recombination is substantially lowered since the phosphorus emitter can be omitted and the c-Si wafer is well-passivated by TOPCon. This leads to a higher $V_{oc}$ of 688 mV. For the TOPCon² structure, the replacement of the local Al-BSF with a full area rear p-TOPCon leads to an open-circuit voltage of 700 mV. The TOPCon²(n) structure reaches 707 mV due to higher bulk lifetime of the n-type c-Si bulk. With 725 mV, the SHJ bottom cell yields the highest $V_{oc}$ due to the even better passivation quality of amorphous silicon a-Si(1). The planar devices all have slightly higher $V_{oc}$ compared with textured devices due to lower surface area and therefore a lower $J_{0,eff}$. $V_{oc}$

Figure 4c shows the fill factor FF of each silicon bottom cell concept. One can see that the FF increase from structure 1 to 4 is mainly correlated to the increase in $V_{oc}$. The switch from p- to n-type c-Si additionally increases the FF by ~0.6%. For the SHJ bottom cell, one can see that the FF is slightly lower for the bifacial devices (black and dark green symbols) compared with monofacial devices. This is due to lateral transport losses in the rear TCO (rear side pitch is optimized for all bifacial bottom cells in terms of minimizing the metallization costs while keeping the lateral transport losses low). Please note that the absolute number in FF is quite high since it refers only to the bottom cell and does not include resistive losses from the top cell and front metallization.

Finally, Figure 4d shows the estimated tandem efficiency for all Pero-Si tandem devices. For this, the $V_{mpp,Pero}$ for the perovskite top cell is estimated from Schulze et al., measurements on comparable perovskite structures. Schulze et al. demonstrated that the recently measured $V_{mpp,Pero}$ of 880 mV has potential to increase by another 100 mV. If we take into account the slightly lower bandgap of our simulation with respect to Schulze et al., we get $V_{mpp,Pero} = 960$ mV, which we use to calculate the estimated tandem power output according to $P_{tandem} = j_{mpp} (V_{mpp,Si} + V_{mpp,Pero})$. One can see that for the textured, bifacial devices (black diamonds), the estimated tandem efficiency $\eta$ is 29.0% for Pero-P[E]RC, whereas it is 30.0% and 30.1% for the Pero-TOPerc and Pero-TOPCon², respectively. The highest tandem efficiency is reached by the Pero-SHJ concept with 30.7%. Again, for Pero-P[E]RC, Pero-TOPerc and the Pero-SHJ, the textured monofacial (red) and planar devices (light and dark green) are shown, which are mainly dominated by the differences in $j_{sc}$. The planar devices (green and dark green) yield an efficiency which is ~1.5% lower with respect to the textured tandem devices. Please note that the bifacial devices in Figure 4 are illuminated from the front side only and will benefit in current and efficiency for additional bifacial illumination from the rear side (not considered here).

3.3 Cell and module production cost analysis

Figure 5a shows the results of the all-in cell costs for the bottom cell and interconnection concepts alongside the bifacial mono-PERC (p) single junction as a reference (Figure 5a, left). The bottom bar for all structures corresponds to the price of either the p- or n-type wafer shown in gray. Subsequent cost categories such as the equipment, facilities, labor, utilities, process consumables, waste disposal, as well as SG&A, R&D, and Cost of Capital are shown as a sum of the all production steps for each cell production route and technology dependent on the silicon bottom-cell production process.

First of all, for the P[E]RC bottom cell one yields lower costs of 48.4 €/ct (and 47.5 €/ct) for the ReCO (and SiT) interconnection with respect to the 56.6 €/ct for the PERC single junction reference. However, this difference is mainly due to the missing front metallization of the bottom cells, and only serves as a reference value.

When we compare the all-in cell costs for different bottom cell concepts (Figure 5a, first focusing on the ReCO interconnection), we can see that TOPerc yields the lowest cost of 47.8 €/ct (and 47.5 €/ct) for the ReCO (and SiT) interconnection with respect to the 56.6 €/ct for the PERC single junction reference. However, this difference is mainly due to the missing front metallization of the bottom cells, and only serves as a reference value.

When we compare the all-in cell costs for different bottom cell concepts (Figure 5a, first focusing on the ReCO interconnection), we can see that TOPerc yields the lowest cost of 47.8 €/ct. The TOPerc process is slightly cheaper than for P[E]RC mainly because there is no POCl₃ diffusion step needed for TOPerc (see process flows in Figure A2). The additional 30 nm of a-Si(n) layer deposition for TOP-erc is done by a PECVD tool that has lower costs compared with the diffusion furnace. However, the P[E]RC process flow is more established, which is why we included an uncertainty on the TOPCon process of 20%, while for the P[E]RC process, we only assumed 10% of uncertainty (see error bars in Figure 5a).

The TOPCon² bottom cell yields noticeably higher costs with 54.5 €/ct (for the ReCO concept). This is due to the switch from
p- to n-type silicon wafer and increase in process consumables (yellow bar) due to the rear silver metal grid instead of the aluminum rear side for the PERC technology (we assumed half the Ag consumption as compared with a TOPCon single junction). For the process flow of TOPCon, we assumed an uncertainty of 20%.

The SHJ bottom cell yields even higher costs with 61.2 €ct/piece (for ReCO). This is mainly due to higher process consumable cost (Figure 5a, yellow bar) as well as higher equipment cost for the SHJ concept (Figure 5a, dark blue). The higher cost for the process consumables arises from the additional silver consumption on the rear, where we assumed that the low temperature silver paste processing leads to slightly thicker finger widths (35 μm for SHJ compared with 30 μm for TOPCon2). Here, we also assumed half the Ag consumption as compared with a SHJ single junction since current transport losses are smaller in a tandem device. Moreover, also the 70 nm of rear ITO as TCO layer additionally contribute to the process consumable cost.

When comparing the ReCO to the SiT interconnection, the all-in cell costs are found to be slightly higher for ReCO (~1 €ct/piece). This is mainly due to the additional process step and relative higher specific equipment CAPEX for ITO deposition by a PVD (physical vapor deposition) tool as compared with SiT concept that uses a PECVD tool for the silicon tunnel junction or TOPCon layer formation. However, there is one exception, namely, the SiT-SHJ, where the silicon tunneling junction is formed by μc-Si leading to costs that are slightly higher than for ReCO-SHJ. This is a direct result of the ReCO interconnection needing one production step (PECVD a-Si layer) less as compared with the process flow of the SiT interconnection that reduces the overall all-in cell production cost of the bottom cell. It is important to note, that for the SiT-SHJ process, we have assumed similar processing parameters as for a-Si deposition by a PECVD tool for the μc-Si deposition. However, to our knowledge, there is not yet a tool available for μc-Si deposition on silicon wafer substrates. Here, an industrial PECVD tube furnace was used with a silicon deposition rate of 10 nm/min.

If ITO is replaced by the lower-cost material AZO in the top cell layer, the ReCO layer and, for SHJ, on the rear side, the all-in cell costs are expected to drop by 0.60 €ct/pc, 0.17 €ct/pc and, 0.60 €ct/pc, respectively (not shown), assuming that AZO yields similar optical and electrical properties as ITO. Consequently, the largest drop of all-in cell costs would be expected for the ReCO-SHJ with 1.37 €ct/piece.

Figure 5b shows the all-in module costs per watt peak (Wp) including the wafer and silicon bottom cell costs (shown in gray and dark green, respectively) as well as the perovskite top cell and module production costs (shown in light green and blue, respectively). The share of costs from the perovskite top cell includes the front cell metallization and overhead costs and corresponds to a value of ~$12/ft² for the perovskite top cell. The assumed perovskite costs are on the lower side of what is published but still in line with previous results from other authors. Since the perovskite production is not readily available yet, we assumed an uncertainty of the perovskite costs of 30%, which is incorporated additionally to the uncertainties for the silicon bottom cell manufacturing. Including the module production costs (shown in blue), this results in ~$38/ft² for the perovskite single-junction module production. More details on the cost model and the assumptions for perovskite manufacturing can be found in the literature.

It can be clearly seen that the cost difference between the bottom cell concepts is significantly reduced when including the effect of the increased tandem cell efficiency at the module level. For this, we assumed glass–glass modules using the same module interconnection...
as for standard silicon module manufacturing, that is, soldering a solar ribbon over the five bus bars of the cells. All tandem concepts show all-in module costs in the range of 19.4 €/Wp to 20.9 €/Wp, with the Pero-TOPerc structure exhibiting the lowest value, followed by the Pero-P(E)RC and Pero-TOPCon² concept, and the Pero-SHJ tandem concept. One can see that all tandem concepts have the potential to be cost competitive compared with the PERC single junction reference (left side). In particular, one can see that the additional production costs per Wp for the perovskite top cell (4.7 €/Wp to 4.9 €/Wp) are offset on module level due to the higher module output power of the tandem devices with respect to the single junction PERC.

3.4 | LCOE evaluation

Extending the analysis to the calculation of Levelized Cost of Electricity (LCOE) for new plants, we use the net present value method to arrive at the ratio of the discounted lifecycle costs over the discounted lifetime energy generation of the plant. The discount rate is calculated based on a WACC (weighted average capital cost) of 4.0%, and the lifecycle costs include the module manufacturing cost, balance of system (BOS) cost, and operating and maintenance cost over the system lifetime. The lifetime energy generation strongly depends on the local irradiation as well as the annual system degradation rate at the plant installation location. The LCOE calculation is performed for the bifacial and textured front tandem devices (black diamonds in Figure 4d) with a fixed installation at an optimum tilt angle located in Southern Europe with an annual global horizontal irradiation (GHI) of 1,700 kWh/m²a. Besides the system size (1 MWp vs. 5 kWp), the utility case differs from the residential case in terms of significantly lower BOS cost (refer to Table 4). All other parameters such as the lifetime, annual degradation rate (2% in first year and 0.5%/year from year 2 onwards), and capital costs are considered to be the same (refer inset of figures).

Figure 6a,b shows the nominal LCOE (without adjusting for inflation) for the standard mono-PERC module and the four Pero-Si tandem concepts as a function of the cell efficiency for the utility and residential case. The calculated efficiency potential taken from Figure 4 is shown as dots for all four perovskite-silicon tandem modules. We can see the potential to achieve lower LCOE values in comparison with the standard mono-PERC module (gray dashed line and gray dot for a 22.5% efficient PERC cell) for both the utility (Figure 6a) and the residential case (Figure 6b). In particular, Figure 6b highlights the potential to achieve even lower LCOE values for the tandem devices in the case of market segments with higher balance-of-system (BOS) cost (i.e., residential) where higher efficiency devices can bring down area-related BOS costs.

| TABLE 4 | Balance of system costs |
|---------|------------------------|
| Cost category | Utility case | Residential case |
| Inverter costs | 4.0 €/Wp | 13.0 €/Wp |
| Area proportional BOS costs | 43 €/m² | 125.0 €/m² |
| Power proportional BOS costs | 9.0 €/Wp | 13.5 €/Wp |
| Soft BOS costs | 4.1 €/Wp | 28.8 €/Wp |
| Annual costs | 1.0% | 2.0% |

**FIGURE 6** Levelized cost of electricity (LCOE) as a function of the cell efficiency (taken from Figure 4) for (a) the utility and (b) the residential sectors for monofacial illumination. The inset provides the most relevant parameters for the LCOE with degradation rate considered to be 2% in year 1 and 0.5%/year from year 2 onwards, in both cases. All shown Pero-Si tandems results have been calculated for Pero-SiT devices of Figure 1. For both applications, all tandem cell concepts promise a lower LCOE in comparison with the conventional PERC single junction case (gray dot) in the order of 11% with Pero-TOPerc yielding the lowest LCOE. Within the uncertainties of our model, all Pero-Si tandems yield a similar LCOE showing that the choice for the best silicon bottom cell is not yet decided [Colour figure can be viewed at wileyonlinelibrary.com]
It can be observed in both the utility and residential case that, under these assumptions, the Pero-TOPerc structure (green diamond) shows a slightly lower LCOE potential than other tandem concepts. However, it is important to underline that the presented LCOE potential of perovskite-silicon tandem modules depends on achieving a comparable lifetime, degradation rates, and financing conditions (i.e., bankability) for the tandem configuration to the reference PERC module (as assumed here). To highlight this, we calculated the LCOE break-even point, where the LCOE of the Pero-Si tandem device is equal to the LCOE of the conventional PERC. In terms of module lifetime, this LCOE break-even point would be reached for 21 years instead of the assumed 30 years (further details can be found in Zafoschnig et al.6). In terms of perovskite processing costs, the LCOE break-even point would be reached when assuming 3.7-times higher perovskite costs. On the one hand, this indicates that our conclusions about the LCOE reduction still hold true for a reasonable scope of our assumed parameters; however, on the other hand, it highlights the importance of especially reaching high module lifetimes and low perovskite processing costs which until now remains an open issue for the future implementation of perovskite–silicon tandem technology and thus a topic of significant interest for both the PV industry and research institutes.50

4 | CONCLUSION

We investigated four promising silicon bottom cell concepts based on the PERC, TOPCon, and SHJ technology combined with two different interconnection layers based on a TCO recombination layer (ReCO) or a silicon-based tunneling junction (SiT). All tandem concepts were investigated in terms of efficiency and cost potential when applied to a perovskite silicon tandem solar cell. For this, we elaborated a sophisticated optical simulation model which accurately describes the recently published Pero-ReCO-SHJ(p) tandem solar cell developed at Fraunhofer ISE. This allowed us to analyze the optical losses within each of the Pero-Si tandem concepts. Subsequently, the electrical simulation of the silicon bottom cells predicted the tandem efficiency potential of each cell concept which we subsequently used for a detailed cost analysis. Based on this approach and our assumptions, this yields the techno-economic potential of each Pero-Si tandem concept:

1. Pero-P[E]RC is mainly limited by the unpassivated phosphorus emitter at the front side. This results in lower $J_{SC}$ and $V_{OC}$ of the cell leading to estimated tandem efficiency of 29.0%. However, with $\sim$48 €/ct/piece, costs are expected to be low for this concept.

2. Pero-TOPerc yields a higher cell efficiency of 30.0% owing to the full-area passivating front contact combined with the good optical and electrical properties of the established PERC rear side. FCA in the n-TOPCon layer partly compensates optical gains and calls for further thickness reduction of the polycrystalline silicon (poly-Si). Replacing the phosphorus emitter and related process steps yields slightly lower costs compared with Pero-P[E]RC ($\sim$47 €/ct/piece).

3. Pero-TOPCon\(^2\) moderately increases cell efficiency compared with Pero-TOPerc (30.1%) when replacing the local Al-BSF by a full area passivating contact. However, costs with 54 €/ct/piece are higher mainly due to the silver rear fingers.

4. Pero-SHJ yields the highest efficiency with 30.7%; however, costs are further increased to $\sim$61 €/ct/piece owing to higher equipment and process consumable costs.

Both ReCO and SiT interconnection concept yield similar performances on textured surfaces, so that the focus should be on technological feasibility. When applied to a planar front side, the tandem efficiency potential of each concept is lowered by $\sim$1.5%. In this case, the SiT interconnection is expected to have an advantage over ReCO in optical properties due to better refractive index matching.

In terms of all-in cell costs, Pero-TOPerc seems to be an attractive option since it promises high efficiencies (comparable with Pero-TOPCon\(^2\) and Pero-SHJ) at a low-cost level of Pero-P[E]RC. However, we have seen that in terms of all-in module costs per $W_{m}$, with 19.4–20.9 €/ct/$W_{m}$, all tandem concepts have the potential to yield lower costs compared with a conventional 22.5% PERC cell with 21.3 €/ct/$W_{m}$ since the higher production cost for the perovskite top cell is offset by higher power output of the tandem device.

The analysis of the levelized cost of electricity (LCOE) first of all shows that in all tandem concepts have the potential to yield a significantly lower LCOE compared with the conventional PERC concept for both residential and utility installation promising an LCOE reduction of about 11%. Based on the actual cost breakdown, such a cost reduction cannot be achieved by conventional PERC cells, which show the potential of the tandem approach. Second, we see that the differences in LCOE for all tandem concepts are small and lie within the uncertainties of our model, so that to our best knowledge, the “race” for the best silicon bottom cell in terms of industrial application is still open to all the investigated bottom cell technologies, which is counter to the current trend in research where the SHJ technology is in the lead. This finding is an important message for production lanes based on the PERC and iTOPCon technology that make up the major share of production lanes today.

We therefore conclude that the attention should be directed to technological feasibility, upscaling and the production environment, as well as high module lifetimes and field performance. It will be most essential for the Pero-Si tandem technology to overcome these fundamental prerequisites in order to actually achieve lower LCOE with respect to conventional PERC stand-alone devices and other competing technologies like all-perovskite tandems.

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ORCID

Christoph Messmer https://orcid.org/0000-0003-0363-8109
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APPENDIX A.

FIGURE A1  Current mismatch $j_{sc,\text{Pero}} - j_{sc,Si}$.
The Pero-ReCO-SHJ featuring planar front (shown on the right as open rectangle in light green) was properly current matched; thus, $j_{sc,\text{Pero}} - j_{sc,Si} = 0$. All other cases show only a minor current-mismatch that is corrected in Figure 4 by $j_{sc,\text{matched}} = j_{sc,Si} + 0.5 \frac{(j_{sc,\text{Pero}} - j_{sc,Si})}{C_1}$ in order to yield ideal-current matching [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE A2  Process flow for the Pero-ReCO concepts of Figure 1 featuring a TCO recombination layer as interconnection layer [Colour figure can be viewed at wileyonlinelibrary.com]
**FIGURE A3** Process flow for the Pero-SIT concepts of Figure 1 featuring a (poly)silicon tunneling junction as interconnection layer [Colour figure can be viewed at wileyonlinelibrary.com]