TOPCon solar cells – Technology roadmap for 25.5%-efficiency industrial manufacturing

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Abstract
This paper presents an analysis and the results of extensive simulations of the efficiency limits and roadmap to 25.5% of a tunnel oxide passivated contact (TOPCon) solar cell, on the basis of an efficiency level of 25.21% (designed area, identified by ISFH) achieved through three years of continuous technical optimization on a pilot line at Longi. It is demonstrated that the key points for reaching the target of 25.5% mainly rely on optimizing the boron selective emitter, the profile of the poly-Si layer (thickness, dopant concentration and its rate of descent), the bulk properties (minority-carrier lifetime > 20ms), the metal contact recombination and metallization, the texture morphology and the anti-reflection coating.

Introduction
The tunnel oxide passivated contact (TOPCon) cell concept is well known for yielding a high-efficiency crystalline silicon solar cell, and its development is now undergoing serious momentum. For the tunnel oxide passivated contact structure, a 1.5nm SiO$_x$ layer is applied to the rear surface of an n-type silicon absorber, functioning as a high-quality chemical passivation layer, as well as having an electron tunnelling structure function. A heavily doped polysilicon (poly-Si) layer is employed over the ultrathin oxide layer as the effective carrier collection layer.

The TOPCon solar cell is one of the most promising next-generation industrial products, as it presents several advantages over the passivated emitter and rear (PERC) solar cell. First, the higher-efficiency potential of TOPCon compared with PERC has been demonstrated on a laboratory scale [1,2] as well as in a commercial manufacturing setting [3–5].

Second, the fabrication process for a TOPCon solar cell is compatible with mainstream production lines, with the addition of a few extra process steps – a tube diffusion system for the boron-doped emitter and a low-pressure chemical vapour deposition (LPCVD) or plasma-enhanced chemical vapour deposition (PECVD) for poly-Si fabrication. Meanwhile, no laser doping or opening is required in this production line (no boron selective emitter). The cost is also lower than that for heterojunction solar cells.

“For a TOPCon solar cell, the formation of the tunnelling oxide passivated contact is a critical process.”

Figure 1. Recorded efficiencies of Longi R&D cells.
Third, based on n-type Czochralski (Cz) wafers, a TOPCon solar cell is not prone to suffering from light-induced degradation (LID) [6]. The temperature coefficient of a TOPCon solar cell is lower than that of mainstream products [7].

The tunnelling oxide passivated contact concept was first proposed by the Fraunhofer Institute in 2013 [8,9]. In just a few years, there have been dramatic developments in TOPCon solar cells owing to the efforts of a number of research institutions and industrial institutions. Fig. 1 presents the recorded efficiencies and pilot line production efficiencies of Longi R&D PERC and TOPCon solar cells. From the figure, it can be seen that the recorded efficiency has exceeded 25.21%, as identified by ISFH, which is about 1% higher than that of the mainstream PERC product; moreover, the power of a 72-half-cut-cell module has reached 570W.

For a TOPCon solar cell, the formation of the tunnelling oxide passivated contact is a critical process. An optimization of the doping profile of n⁺ poly-Si can minimize the metal recombination and reduce the contact resistance. Similarly, a low doping concentration and a deep junction depth of the p⁺ emitter on the front side is beneficial with regard to electrical properties. At the same time, it has been proved that the utilization of incident light dramatically improves through the use of light-trapping strategies, including texture morphology, metallization morphology and anti-reflection film [10,11]. It is strongly believed that the fabrication of TOPCon cells in mass production is the way forward to deal with grid parity, demonstrating several advantages ranging from lower production costs and capitalized costs to higher efficiencies. Besides, specific understanding of this structure encourages continuous progress at the industry level.

In this paper, the potential roadmap to another efficiency step-up to 25.5% will be summarized in relation to experience gained in mass production and associated theoretical development.

**TOPCon solar cell development at Longi**

**Process flow for TOPCon solar cells fabricated at Longi**

For the TOPCon solar cells, phosphorus-doped 1Ω·cm Czochralski-grown (170µm, <100>) Si wafers, sliced into 166×166mm pieces, are used. Fig. 2 shows a schematic of the TOPCon solar cell and the process sequence.

After cleaning and saw damage etching, the next step to be carried out is alkaline texturing (RENA Technologies process) in order to reduce the reflection to 10%. An optimized boron emitter is then formed as follows:

1. A BBBr source is used during the light-doping process, and a sheet resistance of 200Ω/sq. is obtained to reduce the surface recombination.
2. A laser is employed to remove the borosilicate glass (BSG) in the finger region.
3. The laser damage removal process is carried out.
4. To further reduce the contact resistance and metal recombination, a BBBr heavy-doping process is conducted, resulting in a sheet resistance of around 80Ω/sq.

![Figure 2. (a) Schematic of the TOPCon solar cell, and (b) the process sequence.](image-url)
After the formation of the emitter, the BSG is removed and polished by means of a wet-chemical step on the rear side. Next, an ultrathin tunnel-SiO$_x$ layer (~1.5nm) is formed by thermal oxidation, then in situ doped n$^+$ polysilicon (~130nm) is deposited by LPCVD. In the next step, the wrap-around of the poly-Si is removed, followed by crystallization in a tube furnace and the cleaning process.

After crystallization and cleaning, a 6nm passivation layer is deposited on the front side as the passivation layer, followed by the anti-reflection layer coating. On the rear side, a hydrogenated SiN$_x$ layer is employed for further passivation by PECVD. At the metallization stage, silver/aluminium contacts are screen printed on the front side, and silver contacts on the rear, with subsequent firing in a belt furnace. After firing, a hydrogenation process is performed.

**TOPCon technology development at Longi**

**Optimized doping profile**

The properties of the emitter, including the doping density and the distribution of boron, significantly influence the optical and electrical properties of the solar cell [12]. For example, a heavily doped emitter can decrease the contact resistance; nevertheless, the solar cell suffers from recombination, as is the case for deeper doping profiles.

The optimized boron emitter is formed in several stages; the fabrication process of a boron emitter is shown in Fig. 3(a). The selective emitter structure could reduce the emitter saturation current density $J_{0e}$; the average $J_{0e}$ value of this type of structure is 9fA/cm$^2$. Meanwhile, 40µm-wide heavy doping can dramatically reduce the contact resistance to less than 1.5mΩ·cm$^2$, which is accompanied by a lower $J_{0metal}$ less than 300fA/cm$^2$. Fig. 3(b) shows the electrochemical capacitance voltage (ECV) profile for light doping and heavy doping.

**Optimized metallization scheme**

Shading losses play an important role in efficiency losses. In order to reduce the efficiency loss resulting from the metallization shading, a new advanced metallization scheme was developed. The average width and height of the optimized metallization area was 23µm and 13µm, respectively, with an optimum finger width of 20µm.

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Fig. 4 shows the geometry of the advanced fingers. The electrical properties of the TOPCon solar cell can be significantly improved by optimizing the metallization; for example, the efficiency can be increased by 0.2%. Table 1 lists the improvements in the electrical parameters, namely efficiency ($\eta$), open-circuit voltage ($V_{oc}$), short-circuit current ($I_{sc}$) and fill factor ($FF$). Apart from the gain in efficiency, the cost of the fingers can also decrease by 35%, which is very important for reaching grid parity.

Optimized silicon wafer
A series of experiments were carried out concerning the resistivity and lifetime of silicon wafers. Fig. 5 presents the experimental efficiency results as a function of resistivity and lifetime, revealing that an acceptable resistivity of ~1Ω·cm seems to be the most promising, whereas a higher or lower resistivity would be disadvantageous. The improvement in efficiency also comes with a longer lifetime of the silicon wafer (minority-carrier lifetime > 20ms). An optimization of the bulk properties confirmed a 0.2% improvement in efficiency.

Optimized cell efficiency
The optimized cells were sent to ISFH for third-party certification. The best performing cell fabricated according to the above-mentioned optimization strategies yielded an efficiency of 25.21% (designed area). The $I$–$V$ curves and parameters are shown in Fig. 6, with $V_{oc} = 721.6\,\text{mV}$, $I_{sc} = 10117\,\text{mA}$ and $FF = 83.9\%$.

Figure 3. (a) Fabrication process for a boron selective emitter. (b) ECV profile for light doping and heavy doping.

Figure 4. The resulting finger geometry for the advanced metallization scheme.
Table 1. Improvements ($\Delta$) in the electrical properties as a result of the advanced metallization scheme.

<table>
<thead>
<tr>
<th>Advanced metallization</th>
<th>$\eta$ [%]</th>
<th>$V_{oc}$ [mV]</th>
<th>$I_{sc}$ [mA]</th>
<th>$FF$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta$</td>
<td>0.2</td>
<td>23</td>
<td>41</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Figure 5. Experimental efficiency results as a function of (a) resistivity, and (b) lifetime.
Road map to 25.5%

Power loss analysis
A detailed loss analysis was carried out by means of a Quokka 3 simulation to understand the loss mechanisms and to identify options for improving cell performance [13]. The input parameters used in the simulation were based on experimental measurements taken from the 25.21% TOPCon solar cells.

Fig. 7 shows the power loss of the 25.21% TOPCon solar cell. The main losses include shading, front non-contacted recombination and front-surface transmission, equating to almost 67% of the total in the energy loss analysis. Nevertheless, the bulk properties (19.8%) and front contacted recombination (8.8%) should not be ignored for high-efficiency TOPCon solar cells.

The path to achieving 25.5%

Optimized light management
As an indirect semiconductor, crystalline silicon exhibits poor absorption. Optimized light management can effectively facilitate the usage of incident light. The pyramid structure was therefore optimized on the front surface to improve the light trapping.

Fig. 8(a) shows scanning electron microscopy (SEM) images of the optimized pyramid texture, while Fig. 8(b) gives the reflectance for the textured structure. From this result, it can be seen that the reflection...
"By optimizing the anti-reflection film through coating it with MgF₂, the transmission of incident light is higher than the baseline."

decreases throughout all wavelengths, indicating a more effective utilization of incident light. Apart from the morphology, coating films having a low refractive index further optimize the usage of sunlight, simultaneously resulting in excellent passivating properties on the front side. MgF₂ has the advantages of high thermal stability, low optical constant n, durability, and negligible absorption in the wavelength range of interest, thus making the material a good candidate for anti-reflection purposes [14]. By optimizing the anti-reflection film through coating it with MgF₂, the transmission of incident light is higher than the baseline, and a 0.2mA/cm² improvement in J_sc is realized.

Extra-fine metallization
A better doping profile of the emitter can reduce the recombination at the front side. To address the issue of decreased FF resulting from increased sheet resistance, an advanced metallization scheme B was developed. Table 2 presents the parameters for different metallization schemes. To minimize the recombination of the emitter, the sheet resistance was increased from 200Ω/sq to 300Ω/sq. A higher sheet resistance, however, can also lead to larger current transport losses towards the front side. Consequently, narrower fingers of width 18µm and smaller finger distances were used to mitigate the FF and I_sc losses. With the use of a narrower finger scheme, along with an appropriate emitter, a better carrier collection with reduced FF and I_sc losses can be obtained.

Optimized polysilicon
Parasitic absorption losses in the poly-Si on the rear side were considered one of the important optical losses. In order to reduce the optical loss resulting from the poly-Si, the thickness and the deposition conditions of the poly-Si should be optimized [15].

Table 3 presents the relevant parameters for two different poly-Si schemes, in which the phosphorus doping concentration is kept constant (higher than 7.0E+20cm⁻³). When the poly-Si film thickness is reduced from 130nm in scheme A to 90nm in scheme B, the photogenerated current can increase by 0.15mA/cm². In addition, an optimization of the poly-Si fabrication process, for example reducing the polysilicon deposition temperature and pressure, can further decrease the parasitic absorption losses on the rear side.

Conclusions
After several years of development work on processes and techniques, TOPCon solar cells with an efficiency in 25.21% have been achieved. Simulations based on a characterization database have been carried out to demonstrate the main limits of current solar cells. The key points for obtaining a 25.5% efficiency relate to bulk properties, emitter optimization and optical loss minimization.
1. Bulk properties should initially be considered for creating high-efficiency TOPCon solar cells. For silicon wafers, an appropriate resistivity of ~1Ω and a longer lifetime (minority-carrier lifetime > 20ms) is necessary.

2. Optimization of the boron selective emitter can dramatically decrease the contact resistance, and also reduce the recombination loss at the front surface. It is necessary to maintain a balance between contact resistance and recombination.

“The key points for obtaining a 25.5% efficiency relate to bulk properties, emitter optimization and optical loss minimization."

**Table 2. Parameters for the different metallization schemes.**

<table>
<thead>
<tr>
<th>Metallization</th>
<th>Efficiency [%]</th>
<th>Front side</th>
<th>Rear side</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{\text{sheet, light doping}}$ [Ω/sq.]</td>
<td>$J_{\text{shunt}}$ [fA/cm$^2$]</td>
<td>$W_{\text{fingers}}$ [µm]</td>
</tr>
<tr>
<td>Scheme A</td>
<td>25.2</td>
<td>200</td>
<td>9</td>
</tr>
<tr>
<td>Scheme B</td>
<td>25.5</td>
<td>300</td>
<td>7</td>
</tr>
</tbody>
</table>

**Table 3. Parameters for different poly-Si schemes.**

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Efficiency [%]</th>
<th>Thickness [nm]</th>
<th>$R_{\text{sheet, poly-Si}}$ [Ω/sq.]</th>
<th>$J_{\text{shunt, poly-Si}}$ [fA/cm$^2$]</th>
<th>$J_{\text{shunt, metal}}$ [fA/cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly-Si A</td>
<td>25.2</td>
<td>130</td>
<td>60</td>
<td>1.5</td>
<td>15</td>
</tr>
<tr>
<td>Poly-Si B</td>
<td>25.5</td>
<td>90</td>
<td>60</td>
<td>1.5</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 8. (a) Scanning electron microscopy (SEM) images of the optimized pyramid texture. (b) Reflectance for different texture structures. (c) Structure of the coating film on the front surface. (d) Transmission curves for different anti-reflection films.
Optical losses must be treated in respect of the front-surface morphology and anti-reflection films, as well as optimizing the metallization. An optimized pyramid structure, an MgF$_2$ coating film and extra-fine fingers should be employed in TOPCon solar cells.

References

About the Authors
Xinxing Xu graduated with a Bachelor of Science degree in applied physics from Southeast University of Nanjing, China. He works at Longi as a director engineer, and was responsible for improvements in TOPCon cell efficiency. He has over 11 years’ experience in the PV industry.

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