Investigation on significant efficiency enhancement of thin crystalline silicon solar cells

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ABSTRACT. Compared with industrial thick crystalline silicon (c-Si) solar cells, thin c-Si cells have unique advantages of greater cost effectiveness and cell flexibility, representing a future technology trend. However, its present efficiency is far behind that of conventional thick c-Si solar cells. To improve the efficiency, it is necessary to consider and implement advanced designs. We report a strategy of optimizing cell designs to significantly improve the efficiency of a 20 μm-thick thin c-Si solar cell. Compared with the reference, the short-circuit current density is increased from 34.3 to 38.2 mA/cm², the open circuit voltage is boosted from 632 to 684 mV, and the fill factor presents an improvement from 76.2% to 80.8%, resulting in an absolute efficiency gain of 4.6% from 16.5% to 21.1%. The experimental results are further explained by the device simulations.

1 Introduction

Being the most important cell type of the present commercial photovoltaics (PV) market, crystalline silicon (c-Si) solar cells have dominated the global PV market with a share of 95%. At present, the mainstream industrial cell with a c-Si passivated emitter and rear cell (PERC) has a thickness of 160 to 170 μm. According to the International Technology Roadmap for Photovoltaics, the thinning of c-Si cells is an irreversible technology trend for next-generation PV to deliver greater cost effectiveness; this is because the silicon material alone occupies as high as 55% to 60% of the cell cost and as high as ~40% of the module cost. The thin solar cells have some unique advantages. For example, compared with thick c-Si solar cells, the thinner silicon wafer for solar cells has the potential to achieve a higher open circuit voltage ($V_{oc}$) due to the lower bulk recombination arising from its smaller volume and more efficient electron–hole pair extraction. The thin c-Si solar cells still have the potential to achieve high efficiency. Furthermore, thin silicon cells have flexibility, offering a wide range of applications. These potential benefits motivate the research toward the thinner c-Si solar cells.

The experimental reports in the area of thin c-Si cells with a thickness ≤ 20 μm are investigated and analyzed. It is found that, by far, the reported efficiencies are far behind that of...
the industrial thick silicon solar cells (∼24% for the PERC cells and 26.81% record efficiency for silicon cells). Regarding the laggard reason, from the point of view of PV parameters, the efficiency improvement in the previous reports is attributed to the increase of either short-circuit current density ($J_{sc}$), $V_{oc}$, or fill factor (FF) compared with the reference cells. The strategies in the reported solar cells have no ability to simultaneously improve the three PV parameters.

In this work, we theoretically and experimentally investigate the efficiency enhancement of 20 μm-thick thin c-Si solar cells using the optimized designs. Compared with the reference cell, the $J_{sc}$ value is improved from 34.3 to 38.2 mA/cm², the $V_{oc}$ value is increased from 632 to 684 mV, and the FF value is enhanced from 76.2% to 80.8%. As a result, the simultaneous improvement of the three PV parameters leads to a significant efficiency increase from 16.5% to 21.1%. The device simulations are conducted to explain the experimental results. Compared with the existing literature, this work demonstrates a strategy to significantly improve the efficiency of thin silicon solar cells.

2 Designs and Experiments

2.1 Designs
The present silicon solar cell designs are conducted using the two commercial software programs. The optical simulations for the light absorption design are implemented using the software of Sunsolve. During the optical calculations, the complex optical constants of the c-Si wafer, $\text{Al}_2\text{O}_3$, $\text{SiN}_x$, $\text{SiO}_x$, and $\text{SiO}_2$ are taken from the literature. The device simulations are conducted via the joint software of Sunsolve and Quokka. The $J_{sc}$ calculations are based on the Sunsolve software and the calculations of $V_{oc}$ and FF are conducted via Quokka 3. The set of input parameters for the present device simulations are listed in Table 1.

2.2 Experiments
For industrial thick silicon solar cells, silicon wafer is obtained from the silicon ingot cutting. An industrial thick silicon solar cell (e.g., PERC cell) fabrication procedure is shown in Fig. 1(a): (i) the industrial thick silicon wafer (typically 160 to 170 μm for PERC) is textured using

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<tr>
<th>Table 1</th>
<th>Input parameters for the present device simulations on the three PV parameters.</th>
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<tbody>
<tr>
<td><strong>Input parameters for $J_{sc}$ calculation via Sunsolve</strong></td>
<td></td>
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<tr>
<td>Cell size: 3 cm × 3 cm; Si thickness: 20 μm</td>
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<tr>
<td>Cell front side: upright pyramidal Si texture: random, angle of 54 deg, height of 1.5 μm; front grid layout: 21 fingers (effective width of 30 μm each and the spacing of 1500 μm), a bus bar of 650 μm in effective width</td>
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<tr>
<td>Cell rear side: line contact pattern (line width of 75 μm and the pitch of 1000 μm)</td>
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<tr>
<td><strong>Input parameters for $V_{oc}$ and FF calculations via Quokka 3</strong></td>
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<tr>
<td>Bulk resistivity: 0.75 Ω·cm</td>
<td></td>
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<tr>
<td>Emitter region: $J_{01} = 28$ fA/cm²; $J_{02} = 0$ (treated as ideal); $R_s$: 126 Ω/sq</td>
<td></td>
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<tr>
<td>SE region*: width of 200 μm; average depth of 0.65 μm; non-contacted $J_0 = 120$ fA/cm²; contacted $J_0 = 500$ fA/cm²; $R_s$: 58 Ω/sq</td>
<td></td>
</tr>
<tr>
<td>Cell rear*: local rear $R_s$: 55 Ω/sq; local contacted $J_0$: 400 fA/cm²; full rear non-contacted effective recombination $S$: 10 cm/s</td>
<td></td>
</tr>
<tr>
<td>External series resistance: 0.5 Ω·cm²</td>
<td></td>
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<tr>
<td>Shunt resistance: 2 × 10⁶ Ω·cm²</td>
<td></td>
</tr>
<tr>
<td>Front contact resistivity: 2.5 to 3 mΩ·cm²</td>
<td></td>
</tr>
<tr>
<td>Rear contact resistivity: 3 mΩ·cm²</td>
<td></td>
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</table>

Note: SE is the selective emitter, $J_{01}$ is the recombination parameter of the diffusion region, $J_{oc}$ is the recombination parameter of the depletion region, and $J_0$ is the recombination parameter.

*The values refer to Ref. 23.
wet-chemical alkaline to achieve random pyramids for a lower surface reflectance. (ii) POCl₃ is used as a precursor gas to form the n⁺ emitter by the diffusion method. The front selective emitter (SE) is conducted under the front contacts using local laser doping. (iii) After that, the phosphor silicate glass and the protective coating are removed by hydrofluoric (HF) acid etching. (iv) The thermal oxidation method is used to form a SiO₂ layer. (iv) The rear double-layer passivation of thin aluminum oxide (Al₂O₃)∕SiNₓ is conducted by the atomic layer deposition (ALD) method and plasma-enhanced chemical vapor deposition (PECVD) method, respectively. (v) Front SiNₓ is deposited by PECVD to form an anti-reflective coating. Laser ablation of the line pattern is used to create localized contacts. (vi) Finally, screen printing and co-firing techniques are used for front and rear metallization for electrodes.

By contrast, the layer transfer (LT) method is a promising technique to acquire thin monocrystalline silicon by three typical steps: (i) HF acid is used electrochemically to etch pores into a thick silicon wafer for a porous silicon. (ii) This porous silicon wafer is used as a substrate to epitaxially grow a monocrystalline silicon layer. (iii) The epitaxial thin silicon layer is lifted off from the porous silicon substrate. In this work, 20 μm-thick thin crystalline silicon solar cells are investigated. Here the 20 μm-thick silicon cell, which is based on our technical accumulation, is chosen. The thin silicon solar cell fabrication procedure is shown in Fig. 1(b): (i) 20 μm-thick thin monocrystalline silicon wafer (p-type, doping concentration: 2.0 × 10¹⁶/cm³) is obtained by the LT method. (ii) Multiple thin film layers of Al₂O₃∕SiNₓ∕SiOₓ are deposited at the front surface of the epitaxial silicon (i.e., the rear of solar cell) with the 8 nm-Al₂O₃ thin film prepared using ALD. 135 nm-SiNₓ and 250 nm-SiOₓ thin films are deposited by PECVD. (iii) The rear opening of the cell is conducted using laser drilling. The p⁺ local back surface field is conducted using a 532 nm-wavelength laser. The sheet resistance is 56 ± 8 Ω/sq. The rear line pattern has a line width of 80 ± 15 μm and a pitch of 1000 ± 150 μm. The metal aluminum (Al) is used for metallization at the rear of the cell. (iv) The above silicon is attached on a flexible stainless-steel
substrate by a conductive metal bonding, and then the thin silicon is lifted off from the porous Si substrate. (v) The residual porous Si is removed by a KOH solution, and then front silicon texturing (pyramidal shape) is done by an NaOH solution. (vi) The ion planting method is used to form an \( n^+ \) emitter with a doping concentration of \( 1.0 \times 10^{18} \text{cm}^{-3} \). (vii) Multiple thin film deposition of the SiO\(_2\)/SiN\(_x\)/SiO\(_x\) is done via PECVD at the front of the cell, with the low-temperature deposited 10 nm-thick SiO\(_2\) thin film for surface passivation. The double layers of 60 nm-thick SiN\(_x\)/40 nm-thick SiO\(_x\) thin film are for surface anti-reflection. (viii) The front SE is conducted using local laser doping with a width of 200 \( \mu \text{m} \) and a sheet resistance of 55 \( \Omega/\text{sq} \). The front metal contacts adopt Cu/Ni plating. For the present cell, more detailed parameters such as the front metal contact are given in Table 1. The cross-sectional schematic of the present 20 \( \mu \text{m} \)-thick thin c-Si solar cell is shown in Fig. 2(a).

### 2.3 Characterizations

The photovoltaic \( J-V \) response of the present designed cells is characterized using a class AAA solar simulator (Oriel Sol 3A™ class AAA, model 94023A) with a Keithley source meter under standard test conditions (i.e., air-mass 1.5 global illumination with a light intensity of 1000 W/m\(^2\) at a temperature of 25°C). Before the \( J-V \) measurements for the present cells, the calibration is conducted. The wavelength-dependent reflectance of the solar cells is measured using a spectrophotometer (Perkin Elmer Lambda 950) equipped with an integrating sphere. The external quantum efficiency (EQE) of the solar cells is measured (PV measurements QEX10 spectral response measurement system). The saturation current density \( J_0 \) of the cells is obtained from the quasi-steady-state photoconductance tester (Sinton Instrument, WCT-120) using a symmetrical sample structure. The sheet resistances are measured by the four-point probes (Four Dimensions Inc., 280I series).

### 3 Results and Discussion

Figure 2(a) shows a cross-sectional schematic of the present 20 \( \mu \text{m} \)-thick thin c-Si solar cell, with the front double-layer SiN\(_x\)/SiO\(_2\) and rear SiO\(_2\)/SiN\(_x\) designed and included to enhance the light absorption in short wavelengths and longer wavelengths, respectively, to improve the value of \( J_{sc} \). The front SiO\(_2\)- and rear-Al\(_2\)O\(_3\) layers are used to improve \( V_{oc} \) due to the better passivation. The role of the front SE is to improve \( V_{oc} \) and FF. This SE design strategy is also commonly used in the present industrial PERC solar cells. In this work, the optical simulations are conducted using the software Sunsolve. The calculated wavelength-dependent light absorption and reflection of the present solar cell is shown in Fig. 2(b), where the calculations also include three other cell structures for comparison and absorption understanding. Noted that, in the present optical calculations, the front metal contacts are not included. This factor is considered in the device simulation section.
It is seen in Fig. 2(b) that, compared with the planar c-Si cell with a typical front 75 nm-thick single-layer SiN_x film, the front pyramidal texture can increase the light absorption in both short and long wavelengths as shown in the aluminum back surface field (Al-BSF) cell. Here the shape of the silicon surface texture is pyramids with a random distribution, which can simulate the real experimental situation well. To continue to improve the light absorption, the standard PERC architecture is used. It is found in Fig. 2(b) that, when the rear SiN_x/Al_2O_3 is applied, the cell absorption at longer wavelengths is significantly enhanced from 850 to 1100 nm, whereas the absorption remains unchanged at the wavelengths of 300 to 850 nm. The present aim is to achieve a higher absorption; therefore, the rear design of SiO_x/SiN_x/Al_2O_3 is applied. The calculation results show a clear absorption enhancement at longer wavelengths of 800 to 1100 nm. To maximize the total absorption, the front double-layer antireflection coating of SiN_x/SiO_x is designed to replace traditional single-layer SiN_x. It is seen that the light absorption is enhanced at short wavelengths of 300 to 480 nm. As a result, the 20 μm-thick thin c-Si cell with the present optical designs shows excellent light absorption, with the optimal thickness parameters being 250 nm-SiO_x/135 nm-SiN_x/8 nm-Al_2O_3 at the rear side and 10 nm-SiO_2/60 nm-SiN_x/40 nm-SiO_x at the front side.

As is shown in Fig. 3(a), the left image shows the photo of the semi-finished cell without front passivation or metal contacts, where the left-top corner was intentionally destroyed to show a bare steel substrate. The photo of the completed thin c-Si cell is shown in the right of Fig. 3(a), where the size is 3 cm x 3 cm. Figure 3(b) show a cross-sectional SEM image of the present cell, where the textured Si front surface consists of randomly distributed pyramids with an average height of 1.5 μm. An image of a fabricated thin silicon solar cell showing the bending feature refers to Fig. 3(c).

The measured current density–voltage (J−V) response characteristics of the two solar cells are shown in Fig. 4(a), where the inset is a typical cell given in a previous report as the reference. The measured PV results of the reference cell and the present cell are listed in Table 2. Here the reference cell that we fabricated has the same size as the target cell of 3 cm x 3 cm. It is seen in Table 2 that, compared with the reference cell, the J_sc value is increased by 3.9 mA/cm^2 from 34.3 to 38.2 mA/cm^2. The J_sc improvement is further investigated by the comparison of the EQE. The measured wavelength-dependent reflection and EQE are shown in Fig. 4(b). It is seen that, compared with the reference cell, the EQE of the target cell shows significant enhancements in the short-wavelength range of 300 to 450 nm and in the longer wavelength range of 750 to 1200 nm, respectively. This work focuses on the improvement of the efficiency of the thin silicon solar cell by optimizing the optical and electrical designs. Regarding the investigation on the changes of the efficiency and reflectivity to the bending radius, it is not conducted in this work because of the limitation in our present experimental facilities. It may be considered in future work. It is found in Table 2 that the V_oc is remarkably increased by a net value of 52 mV from 632 to 684 mV. Meanwhile, the FF is improved by 4.6% from 76.2% to 80.8%. As a result,
the simultaneous improvement of the three PV parameters leads to a significant efficiency increase from 16.5% to 21.1% with an absolute efficiency gain of 4.6%.

Compared with previous reports,5–9 the main difference is that the present cell shows a simultaneous increment of the three PV parameters. This improvement is attributed to the present cell design strategy. The device simulations are conducted to explain the measured PV results by jointly using the software Sunsolve and Quokka 3. From the simulated results of the equivalent photon current densities, the loss analysis is conducted, and the results are shown in Table 3. It is found in Table 3 that the photocurrent density lost to the environment is 6.44 mA/cm², which takes up 13.90% of the total. The calculated photocurrent density from the total cell absorption is 39.76 mA/cm², and the produced effective $J_{sc}$ value is 38.31 mA/cm², which occupies 82.71% of the total incident photon current density of 46.32 mA/cm². The calculated $J_{sc}$ value of 38.3 mA/cm² is only slightly higher by 0.1 mA/cm² than the measured 38.2 mA/cm² with good agreement.

In addition, the second obvious difference between this work and the previous reports is the high $V_{oc}$ value achieved here. It is noted that, in the existing literature, the average $V_{oc}$ is in the rage of 620 to 630 mV, and the highest $V_{oc}$ is 642 mV with thin c-Si solar cells adopting the structure of a single-layer front SiNx and rear SiO2 layer as shown in the set of Fig. 4(a). By contrast, the $V_{oc}$ value of the present cell is up to 684 mV, resulting in a net $V_{oc}$ improvement of 42 mV compared with the value of 642 mV. The $V_{oc}$ and FF of the present cell are simulated using the software Quokka 3. The set of input parameters for the present $V_{oc}$ and FF calculations

<table>
<thead>
<tr>
<th>Cell type</th>
<th>$J_{sc}$ (mA/cm²)</th>
<th>$V_{oc}$ (mV)</th>
<th>FF (%)</th>
<th>Efficiency (η) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference cell (measurement)</td>
<td>34.3</td>
<td>632</td>
<td>76.2</td>
<td>16.5</td>
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<tr>
<td>Present cell (measurement)</td>
<td>38.2</td>
<td>684</td>
<td>80.8</td>
<td>21.1</td>
</tr>
<tr>
<td>Present cell (simulation)</td>
<td>38.3</td>
<td>687</td>
<td>81.1</td>
<td>21.3</td>
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<th>Measured PV parameters of the reference cell and the present cell. The simulated results for the champion cell are shown for comparison and analysis.</th>
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<td>Cell type</td>
<td>$J_{sc}$ (mA/cm²)</td>
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<tr>
<th>Table 3</th>
<th>Calculated equivalent photon current densities of the present cell for loss analysis.</th>
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<tr>
<td>Incident</td>
<td>Lost front</td>
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<tr>
<td>Mean (mA/cm²)</td>
<td>46.32</td>
</tr>
<tr>
<td>Fraction of $J_{sc}$ (%)</td>
<td>100</td>
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</tbody>
</table>
are listed in Table 1. It is seen that the experimental estimated recombination current density \( J_0 \), an indicator for surface passivation quality) value and sheet resistance \( R_s \) values are 28 ± 5 fA/cm² and 126 ± 6 Ω/sq for the emitter region, respectively. To check the validity, we compare the measured values to the experimental report of the \( J_0 \) value as a function of \( R_s \) using surface passivation of SiO₂ (≈10 nm) / SiNx to an n⁺ emitter. It is found that, when the sheet resistance is 124 Ω/sq, the reported \( J_0 \) value is 13 to 16 fA/cm². Note that the above \( J_0 \) values in this literature are for a planar emitter. If applying to an emitter with a random textured surface, the \( J_0 \) value should increase approximately by a fraction of the increased surface area. For our case of random pyramidal texture with the height of 1.5 μm, the calculated surface increase fraction is around 1.73. This means that the \( J_0 \) value should be 22 to 28 fA/cm² at a sheet resistance of 124 Ω/sq for the present textured emitters. During the present \( V_{oc} \) simulations, the values of \( J_0 \) and sheet resistance at the other regions refer to the experimental reports for a PERC cell due to the approximation. Finally, the simulated \( J – V \) response curve is plotted in Fig. 5. The calculated PV parameters are listed in both the inset of Fig. 5 and Table 2. It is found in Table 2 that the simulated \( V_{oc} \) value is 687 mV, which is higher in 3 mV than the measured 684 mV. More analysis is conducted here. If input parameters of the others remain unchanged, we adopt a \( J_0 \) value of 168 fA/cm² (the case for an emitter with single-layer SiNx passivation) to make the \( V_{oc} \) calculation for comparison. The calculated \( V_{oc} \) value is 664 mV. If the rear of the present cell is changed to that of an Al-BSF cell with a typical \( J_0 \) value of 517 fA/cm² (from Ref. 25), the simulated \( V_{oc} \) value is 633 mV. These comparison results indicate that a lower \( J_0 \) value is the key to improving \( V_{oc} \). From this result, it is found that a lower \( J_0 \) value is achieved using 10 nm-thick SiO₂ thin film passivation between front silicon and SiNx and adopting an 8 nm-Al₂O₃ thin layer at the rear. In terms of FF, it is found that the calculated FF value is 81.1%, which is 0.3% higher than the experimental value. As a result, the simulated efficiency for the present cell is 21.3%, which is 0.2% higher than the measured 21.1%, demonstrating a good consistency. To our knowledge, this work achieves the highest efficiency in the field of the thin silicon solar cells with a thickness \( \leq 20 \) μm. These results also support that the present strategy is feasible to significantly improve the efficiency of thin c-Si solar cells.

4 Conclusions
The thin c-Si solar cells represent a future technology direction that has the potential to offer not only more cost effectiveness from silicon material saving but also cell flexibility. The reported efficiencies in the existing literature lag behind that of the conventional thick c-Si solar cells. This work analyzed the reason for this and thereby presented a cell design with optical and electrical optimization. The front and rear coating design increased the light absorption in both the short- and long-wavelength ranges. The fabricated 20 μm-thick thin c-Si solar cell showed a simultaneous improvement in the three PV parameters over the reference cell: the \( J_{sc} \) increased from

<table>
<thead>
<tr>
<th>( J_0 ) (mA/cm²)</th>
<th>( V_{oc} ) (mV)</th>
<th>FF</th>
<th>η</th>
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34.3 to 38.2 mA/cm², the $V_{oc}$ increased from 632 to 684 mV, and the FF improved from 76.2% to 80.8%. As a result, these improvements led to a significant absolute efficiency increase from 16.5% to 21.1% with a net gain of 4.6%. The measured results are further understood from device simulations showing good consistency. This work has demonstrated a feasible strategy to significantly improve the efficiency of thin c-Si solar cells.

Acknowledgment
The authors declare no conflicts of interest.

References

Biographies of the authors are not available.