

Selective tunnel oxide passivated contact on the emitter of large-size n-type TOPCon bifacial solar cells



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ABSTRACT

This paper reports the application of novel selective tunneling oxide passivated contacts (TOPCon) on the emitter of large-size n-type TOPCon bifacial solar cells. TOPCon technology is applied to the front surface of n-type TOPCon bifacial cells. The design of the front surface cell TOPCon layer was optimized, and only the SiO₂/poly Si passivation layer was applied to metal contact of the emitter in order to avoid parasitic absorption of sunlight by the polysilicon layer. The quasi-steady state photo-conductance (QSSPC) analysis focused on the front-surface conventional n-type PERT cell structure and the front-surface selective TOPCon cell structure, resulting in a saturation current density of 1400 fA/cm² for the front-surface metal contact recombination of the conventional n-type passivated emitter rear totally-diffused (PERT) cell structure and a saturation current density of 430 fA/cm² for the front-surface metal contact recombination of the selective TOPCon cell structure. The maximum conversion efficiency of bifacial solar cells with a large area of 252 cm² prepared using this technique reaches up to 23.21%. This represents an average conversion efficiency improvement of 0.21% compared to solar cells with a conventional PERT structure on the front surface and a TOPCon on the rear surface. Simulation of a cell optimized for this structure can achieve an open circuit voltage of over 720 mV, a short circuit current of 40 mA/cm², and a cell efficiency of 24%.

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1. Introduction

Currently, the n-PERT bifacial cell technology has been industrialized [1,2]. N-type bifacial cell products have gradually been recognized by the industry and the market due to the national Front Runner advanced technology certification [3,4]. The advantage of using the n-PERT technology is that it can provide a 10–30% rear side power gain. [5]. However, a bottleneck in the efficiency improvement of conventional n-PERT cell technology is the reduction of the carrier recombination losses during metal/semiconductor contact [6,7]. Therefore, the study of more advantageous TOPCon technology is an important topic for the development of a new generation of n-type bifacial cells. The polycrystalline silicon based passivation

contact structure, i.e. the tunneling oxide passivated contact concept was first proposed by the Fraunhofer Institute in Germany [8,9], with a substrate structure of ultra-thin silicon oxide (SiO_x) and a heavily doped polycrystalline silicon (poly-Si) layer for silicon solar cells providing excellent full-area passivation and carrier collection, which can significantly improve the overall performance of the device [10,11]. Due to the excellent performance of this structure and the relative simplicity of the industrial production process [12], it has become a hot topic for research on high-efficiency cells. In recent years, research for this polysilicon passivation contact technology, or termed TOPCon [8], the doped polycrystalline silicon on oxide (POLO) structure [13], n-type passivated emitter and rear poly (PERPoly) [14], has made significant progress, including polysilicon growth [15,16], oxide preparation [17,18] and device integration [19]. At the laboratory level, ISFH/Hannover has increased the maximum efficiency of polysilicon passivated contact solar cell efficiency up to 26.1% [20]. On the theoretical and simulation side, there is also an in-depth understanding of the mechanisms, including tunneling mechanisms [21], energy loss [22], surface recombination rates [23], the

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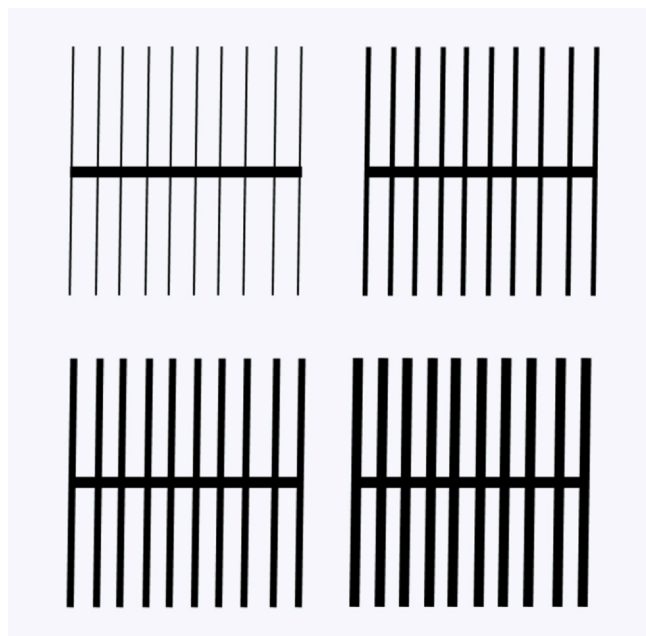


Fig. 1. Metal electrodes patterns.

effect of wafer parameters [24]. Currently, TOPCon structures are mainly used on the rear surface of solar cells, while the front surface adopts a conventional diffused junction and contacting scheme. In order to further reduce the carrier recombination rate on the cell surface and reduce the surface contact resistance, the application of TOPCon structure on the front surface of the cell is gradually being studied by the industry [25,26].

This paper presents a prospective n-PERT bifacial c-Si solar cell structure based on a bifacial high-efficiency cell structure with a tunneling oxide passivation on the front surface metal contact electrode only and a full TOPCon structure on the rear surface. The characterized structure was fabricated using these optimum parameters and a recombination current density of 430 fA/cm^2 was obtained at the front surface metal emitter. Process optimization experiments and characterization of the front surface passivated structure were carried out to develop a feasible process and a maximum conversion efficiency of 23.21% was achieved for a bifacial solar cell with a large area of 252 cm^2 .

2. Experiments and simulations

Solar-grade n-type Czochralski (CZ) c-Si wafers ($158.75 \times 158.75 \text{ cm}^2$) with $\langle 100 \rangle$ crystal orientation, $1 \Omega\text{-cm}$ resistivity, and $170 \mu\text{m}$ thickness

were used to fabricate metal contact passivating testing samples and solar cells. The samples and cells preparation process are shown as Fig. 3.

2.1. Sample preparation for metal contact recombination

2.1.1. Metal contact recombination testing for n-PERT structure cell

After saw damage etching and KOH solution alkaline texture, an industrial thermal diffusion tube furnace was used to form boron doped $p^+/n/p^+$ structure. The borosilicate glass (BSG) was cleaned by HF solution. Both surfaces were passivated by AlO_x and SiN_x layers. Then the metallization was realized by printing and firing. The metal electrodes patterns are shown in Fig. 1. The metal coverages are 8.61%, 15.26%, 21.81% and 28.41% respectively. The testing sample sketch map is shown in Fig. 2(a). Before testing, the metal electrodes were removed by acid solution without damaging the passivation of emitter [27].

2.1.2. Metal contact recombination testing for selective TOPCon structure on front surface of solar cell

After saw damage etching and KOH solution alkaline texture, SiO_2 and poly-si layers were grown on both surfaces using low-pressure chemical vapor deposition (LPCVD) system. The poly-si layers were boron doped to form $p^+/n/p^+$ structure by thermal diffusion tube furnace and the BSG was cleaned by HF solution. Then SiN_x layers were deposited by PECVD system. Metallization was completed in the same way as mentioned above and the sample sketch map is shown in Fig. 2(b). Before testing, the metal electrodes were also removed by acid solution without damaging other locations.

2.2. Cell fabrication

2.2.1. Fabrication of bifacial solar cell with front conventional n-PERT structure and rear TOPCon structure

Fig. 3 experiment A shows the process flow and Fig. 4(a) shows n-PERT with rear TOPCon Solar cell construction diagram. The wafers were etched by KOH solution to remove the saw damage, and followed by alkaline texturing on both sides of the wafer resulting in a random pyramids surface. All samples were then subject to standard RCA clean and short dip in HF before boron diffusion in an industrial tube furnace to form the emitter with sheet resistance of $150 \Omega/\square$.

HF/ HNO_3 acid solution was used to remove wrap-around p^+ doping on rear surface and edge isolation in an inline single-side etching machine. However, the front BSG was retained as a protective layer for subsequent treatment. After a short HF dip, a $\sim 1.5 \text{ nm}$ interfacial SiO_2 and a 150 nm undoped poly-si layer were deposited via a LPCVD. The interfacial oxide was thermal grown in situ before the deposition of a poly-si capping layer using SiH_4 as the source gas.

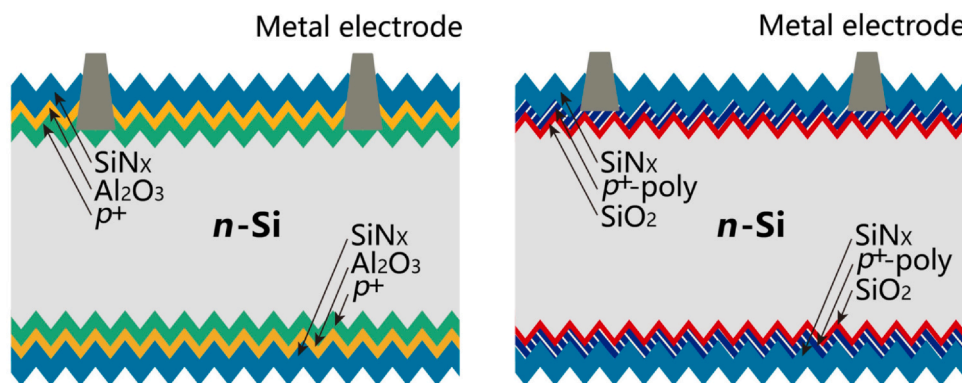


Fig. 2. Metal contact recombination J_0 test structure (a) n-PERT (b) selective TOPCon.

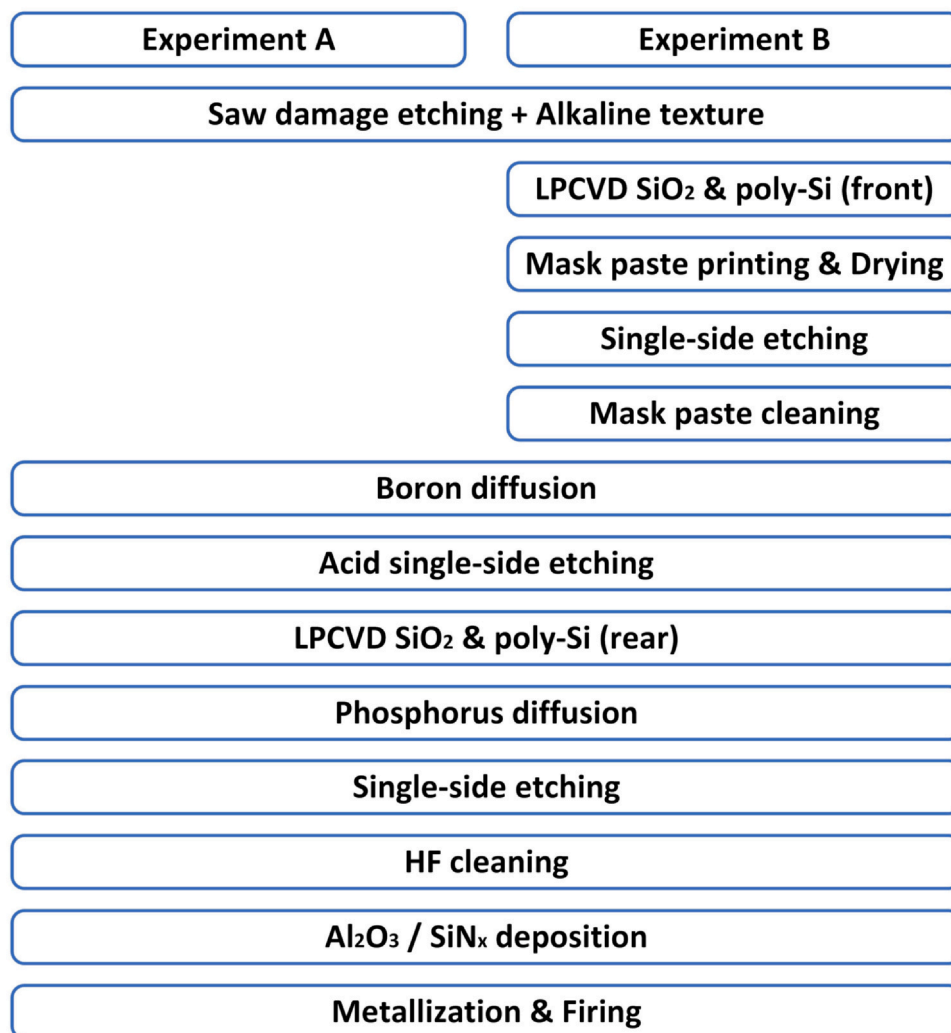


Fig. 3. Process flow diagram for each solar cell group.

The rear surface of the samples were then doped using phosphorus oxychloride (POCl₃) in a thermal tube furnace (Tempress/Amtech) resulting in an average sheet resistance of 40 Ω/□.

A single-side etching (SSE) was used to remove the wrap around n⁺ poly-si area without damaging the boron emitter. After wet chemical cleaning, the BSG and phosphosilicate glass (PSG) were

stripped thoroughly. The front boron emitter of the samples was passivated by 5 nm AlO_x and 75 nm SiN_x, while, the rear surface of the samples was covered by SiN_x layer with 60 nm using commercial inline PECVD reactor. Finally, the metal contacts with “H-pattern” were printed on both sides of the cells using an industrial screen-printing line and sintered in a fast-firing belt furnace.

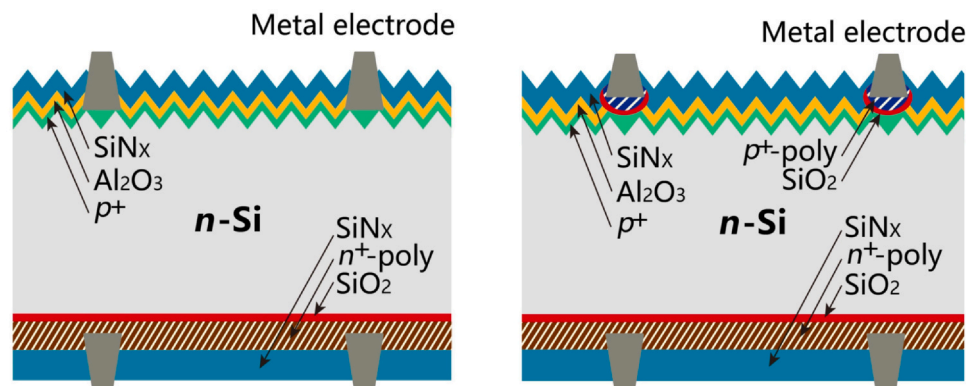


Fig. 4. Solar cell construction diagram.

2.2.2. Fabrication of bifacial solar cell with front selective and rear total TOPCon structure

The wafers also went through the same saw damage removal, texturing, RCA clean and HF dip steps as described before. Then on the front side of the wafers a ~1.5 nm interfacial SiO₂ and a 150 nm undoped poly-si layer were deposited via a low pressure chemical vapor deposition system. The selective structure on front surface need to be fabricated. The patterned anti-acid paste layer was masked and dried by a screen-printing tool and belt furnace, followed by the usage of an HF/HNO₃ acid solution in an inline single-side etching machine to remove the parts of the front surface poly-si layer that are not covered by the anti-acid paste. Then the anti-acid paste was removed in a KOH/H₂O₂ solution. After that, the front side p⁺ emitter was formed in a tube furnace. An HF/HNO₃ acid solution in an inline single-side etching machine was used to remove wrap-around BSG and SiO₂/poly-Si on the rear surface thoroughly, in the meantime, the rear surface of the wafer was polished in order to get a better passivation by subsequent thin films growing. The front BSG was retained as a protective layer for the following steps. Then on the rear surface of the wafers were deposited an ~1.5 nm interfacial SiO₂ and a 150 nm undoped poly-Si layer, and diffused back surface field by using POCL₃ with sheet resistance of 40 Ω/□. Next, the wrap-around PSG and poly-si layer on front surface were removed via single-side etching, and the BSG on front surface and PSG on rear surface were stripped thoroughly by HF cleaning. The subsequent steps, including AlO_x and SiN_x layers deposition, as well as metallization are the same with the upper cells. The cell fabrication process flow and Solar cell construction diagram mentioned above are shown in Fig. 3 experiment B and Fig. 4(b).

2.3. Characterization

The injection-dependent carrier lifetime characteristics were extracted by a QSSPC lifetime tester (WCT-120, Sinton Instruments). The electrical performance of solar cells was characterized by a current-voltage (J-V) measurement system (VS-6821S, Vision). External quantum efficiency (EQE) and Reflectivity were measured by IQE-Scan of GP Solar.

2.4. Simulation parameters

In order to study the efficiency potential of the front surface selective TOPCon structure, this paper uses the 3D simulation software Quokka [28]. Quokka is a simulation software that enables fast multi-dimensional simulation of silicon-based solar cells from 1D to 3D, simplifying the carrier transport model and increasing the speed of calculation without significant loss of accuracy. Table 1 shows all the simulation input parameters for the front surface selective TOPCon structure with a cell thickness of 170 μm, a wafer resistivity of 1 Ω cm and a lifetime of 3000 us.

Table 1
Quokka simulation parameters.

Simulation Parameters	Units	Value-PRET	Value-Front SE-TOPCon
bulk resistance	Ω cm	1	1
bulk lifetime	us	3000	3000
emitter Rsheet	Ω/sq	120	120
emitter J _{0E} -passivated	fA/cm ⁻²	8	8
emitter J _{0E} -contacted	fA/cm ⁻²	1400	430–50
emitter contact opening	um	40	40
BSF Rsheet	Ω/sq	20	20
BSF J _{0E} -passivated	fA/cm ⁻²	5	5
BSF J _{0E} -contacted	fA/cm ⁻²	50	50
BSF contact opening	um	40	40

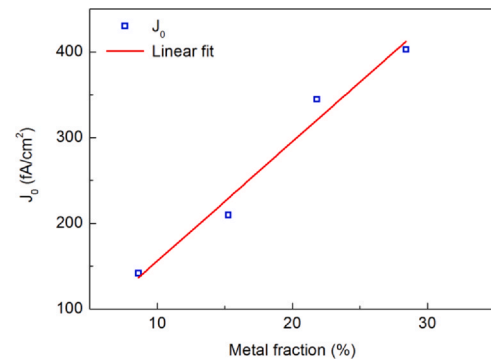


Fig. 5. Measured total saturation current $J_{0, \text{tot}}$ for symmetrical n-type PERT structure samples at different metallization ratios f .

3. Results and discussions

3.1. Characterization and analysis

3.1.1. Characterization of metal contact recombination on the front surface of n-type PERT structured cells

To quantify the effect of screen-printed fire-through metallization on the recombination current density of the front surface of n-type PERT structured cells, the above test structures with four kinds of metal fractions shown in Fig. 1 were measured by QSSPC tester with the light flashing on one side without metallization to avoid any shading effect. Furthermore, Fig. 5 shows the measured total $J_{0, \text{tot}}$ from the front surface of n-type PERT structured cells test structures as a function of metal fraction on one side. The total measured $J_{0, \text{tot}}$ of the test structures with four kinds of metal fractions (f) on one side can be expressed as

$$J_{0, \text{tot}} = J_{0, \text{pass, rear}} + (1 - f)J_{0, \text{pass, front}} + fJ_{0, \text{cont}} = (J_{0, \text{count}} - J_{0, \text{pass}})f + 2J_{0, \text{pass}} \quad (1)$$

Where $J_{0, \text{cont}}$ and $J_{0, \text{pass}}$ metal are the full area J_0 values for the metallized and un-metallized n-type PERT structured cells. The proportional value of the sample metallization is f , the saturation

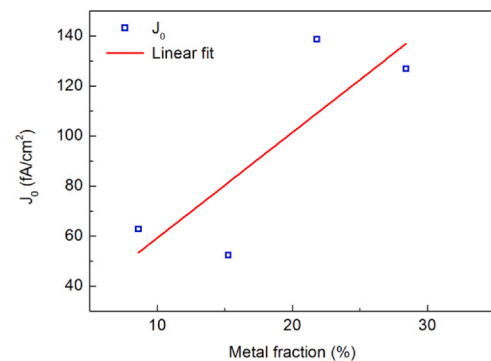


Fig. 6. Measured total saturation current $J_{0, \text{tot}}$ for symmetric SiO_x/n⁺-poly-Si/SiN_x H samples at different metallization ratios f .

Table 2
Effect of different structures of front surface sio₂/poly-si layers on solar cell parameters.

Group		V _{oc} /mV	J _{sc} /mA cm ⁻²	FF/%	E _{ff} %
A	Average	695.65	39.91	82.33	22.86
	Max	696.46	39.98	82.27	22.91
B	Average	706.38	39.73	82.21	23.07
	Max	707.54	39.91	82.18	23.21

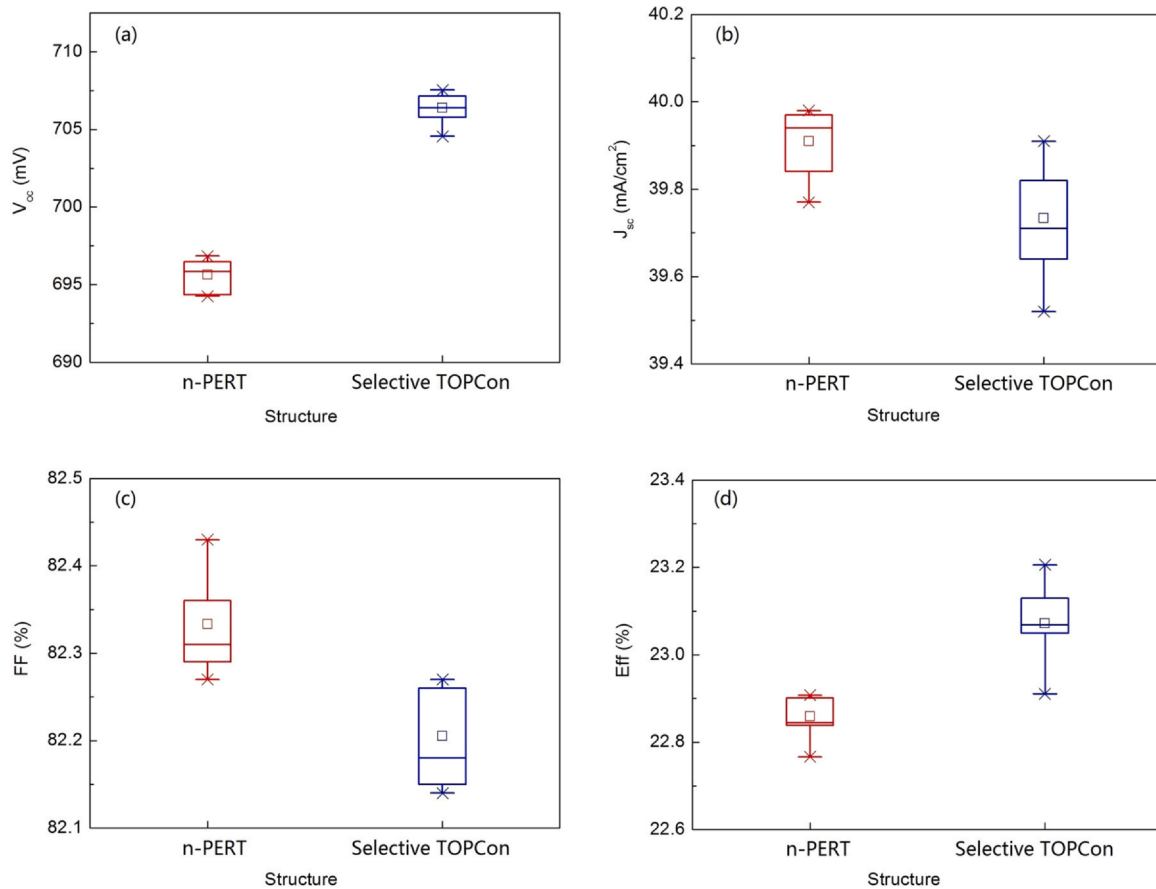


Fig. 7. J-V results data for both groups.

current density in the metallized area is $J_{0, \text{cont}}$ and the total saturation current density $J_{0, \text{tot}}$ is equal to the sum of the front passivation $(1 - f) \times J_{0, \text{pass, front}}$, the rear $J_{0, \text{pass, rear}}$, and $f \times J_{0, \text{cont}}$. Assuming the same front and rear passivation effect of $J_{0, \text{pass}}$ for the non-metallic contact part, it follows from Eq. (1) that the ratio of $J_{0, \text{tot}}$ to f is equal to $f \times J_{0, \text{cont}}$ minus $J_{0, \text{pass}}$ and the intercept with the y-axis is equal to $2 \times J_{0, \text{pass}}$.

In Fig. 5, a $J_{0, \text{cont}}$ of 1400 fA/cm² can be obtained, giving a $J_{0, \text{pass}}$ of 8 fA/cm². The metal coverage on the front surface of our PERT solar cells is about 3%, so the total $J_{0, \text{tot}}$ on the front surface of the cell is estimated to be 49.76(1400 × 3% + 8 × (1–3%)) fA/cm² [27].

3.1.2. Metal contact recombination characterization of n-type front surface selective TOPCon structured cells

The calculation procedure is the same as for the n-PERT cell front surface analysis. In Fig. 6, a $J_{0, \text{cont}}$ of 430 fA/cm² can be obtained and giving a $J_{0, \text{pass}}$ of 8 fA/cm². The metallization coverage for the n-type front surface selective TOPCon is the same as for the n-PERT cell, both at 3%. The total J_0 for the front surface of the cell is estimated at 20.66(430 × 3% + 8 × (1–3%)) fA/cm². It can be clearly concluded that metallization reduces the passivation effect on the front surface. And there is room for improvement: developing a silver paste which is more suitable for SiO_x/n⁺- poly-Si /SiN_x:H structures or using alternative metallization methods could further improve the passivation of such front structures. Based on the front surface J_0 of the two different frontal structures it can be concluded that the use of the SiO_x/n⁺- poly-Si /SiN_x:H structure in the metallized part can effectively reduce the front surface recombination and some research significance [29,30].

3.2. Analysis of solar cell performance

3.2.1. Comparison of solar cell I-V characteristics

Two groups of sample cells were prepared according to the process described above for the comparison of electrical parameters. Sample A was a conventional TOPCon cell structure, while sample B was based on sample A with SiO₂/poly-si (p⁺) passivation technology applied under the front surface metal electrode. Samples were used and the cells were tested J-V under standard test conditions (Irradiance 1000 W/m² and cell temperature 25 °C) after the two sample cells were prepared. The following comparison results were obtained, as shown in Table 2. Where V_{oc} is the open circuit voltage, J_{sc} is the short circuit current density, FF is the fill factor and E_{ff} is the cell conversion efficiency.

According to the comparison results of each parameter in Fig. 7, it is obvious that the open circuit voltage V_{oc} in Group B is significantly improved. As the Group B sample cells have a SiO₂/poly-si (p⁺) passivation layer applied under the front surface metal electrode, the metal recombination in the metal electrode is significantly reduced, effectively improving the shortcomings of the frontal recombination and enhancing the passivation effect on the front surface.

According to the comparison results, the open circuit voltage V_{oc} of Group B cells has a significant advantage over Group A, increasing from 695.65 mV to 706.38 mV, while maintaining a high short circuit current density, the fill factor is basically the same, and the average cell conversion efficiency is 23.07%, with a maximum of 23.21%, which is an increase of cell conversion efficiency compared to the A samples of conventional TOPCon cell structure. This represents an average conversion efficiency improvement of 0.21% compared to a

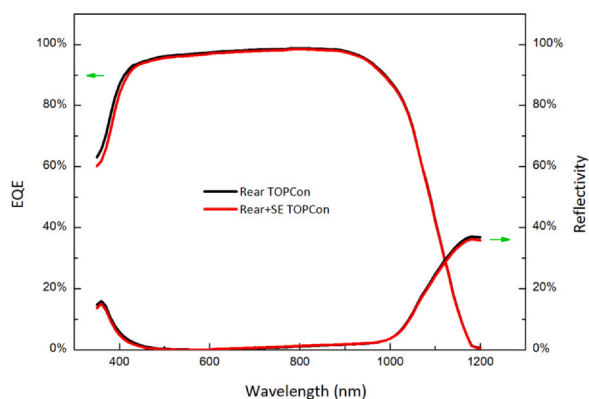


Fig. 8. Corresponding curves of the spectra of the two groups of experimentally prepared solar cells.

conventional PERT structure on the front surface and a TOPCon on the rear surface.

3.2.2. Spectral response test analysis of solar cell

Fig. 8 shows the results of the external quantum efficiency (EQE) versus reflectance (Ref) curves for the corresponding sample cells. The results show that the EQE of the two different structures are basically the same, while the EQE and Ref of sample B are slightly reduced due to the introduction of the poly-si (p^+) layer, which slightly absorbs sunlight at certain wavelengths. However, because the B sample only added the poly-si (p^+) layer under metal electrode, the light-receiving parts beyond the metal electrode remained the same structure as the A sample, effectively avoiding the light absorption problem of the front surface carrier transport layer, making the overall optical properties of the two samples similar, and the short-circuit current density of the B sample cell was not significantly reduced compared to that of the A sample.

3.3. Simulation and optimization

The Quokka 3 simulation tool for solar cells of different structure was used on the basis of the conductive boundary approach [31]. In this simulation, the metal electrode passivation contact was defined using the recombination parameter J_0 estimated by the QSSPC measurement of symmetrically processed lifetime samples. This paper analyses the detailed gain in the open circuit voltage of the cell brought about by the reduction in the metal contact recombination through the test data obtained in the experiment from Figs. 5 and 6, and imported into Quokka simulation software. The simulation results shown in Fig. 9(a, b) revealed significant

improvements in V_{oc} and the fill factor (FF) using the selective emitter cell structure which has high influence on the cell efficiency [32]. The metal recombination value is reduced from 430 fA/cm^2 to 200 fA/cm^2 , V_{oc} can be increased from 711 mV to 715 mV , the cell efficiency value can be relatively increased by 0.1% . If the metal recombination value can be reduced to 50 fA/cm^2 [27,30], then V_{oc} can reach 719 mV and the cell efficiency can be increased to 23.81% . From the experimental results in Table 2, it can be concluded that the application of selective TOPCon structure on the front surface of the cell has a very obvious effect on the mean value of the average open-circuit voltage of the cell with a relative increase of 10.73 mV , and mainly comes from the reduction of the metal contact recombination on the front surface. At present, the experimentally measured metal contact recombination current density value for the selective TOPCon structure is 430 fA/cm^2 , which is a significant decrease compared to the 1400 fA/cm^2 of the conventional PERT on the front surface, but its absolute value is still high, which is strongly related to the fact that the metallization process has not yet reached its optimum state. The new metal pastes with different chemical composition are needed to match the selective TOPCon structured cells in order to obtain lower metal contact recombination current density values, thus making the advantages of the selective TOPCon cells more obvious.

In order to further investigate the efficiency enhancement path of selective TOPCon cells, simulations were performed to investigate the effects of silicon substrate minority carrier lifetime and bulk resistivity on the cell parameters, and the simulation results are shown in Fig. 10(a-d). J_{sc} increases with increasing the bulk resistivity and the minority carrier lifetime. FF decreases with the increasing bulk resistivity, and this trend is stronger when the bulk minority carrier lifetime is low. E_{ff} is the result of the balance of the cell parameters, and there is no doubt with a higher bulk minority carrier lifetime, the cell parameters are higher. While for the bulk resistivity, it can be concluded that the cell efficiency is higher at low resistivity when the bulk minority carrier lifetime is low ($<2000 \mu\text{s}$). As the bulk minority carrier lifetime continues to increase, the cell efficiency peaks at a wafer resistivity of $0.8 \Omega\text{cm}$ with the minority carrier lifetime increases. For example, a silicon substrate with 0.5 ohm/sqr gives the highest cell efficiency of 23.72% for a 2 ms minority carrier lifetime, while a silicon substrate with 0.8 ohm/sqr gives the highest cell efficiency of 24.03% for a 5 ms minority carrier lifetime [28].

4. Conclusions

This paper focuses on the optimized design of the front surface TOPCon layer. To effectively reduce contact resistance and improve device performance, the rear surface of the solar cell uses a TOPCon layer structure, while on the front surface, to avoid parasitic

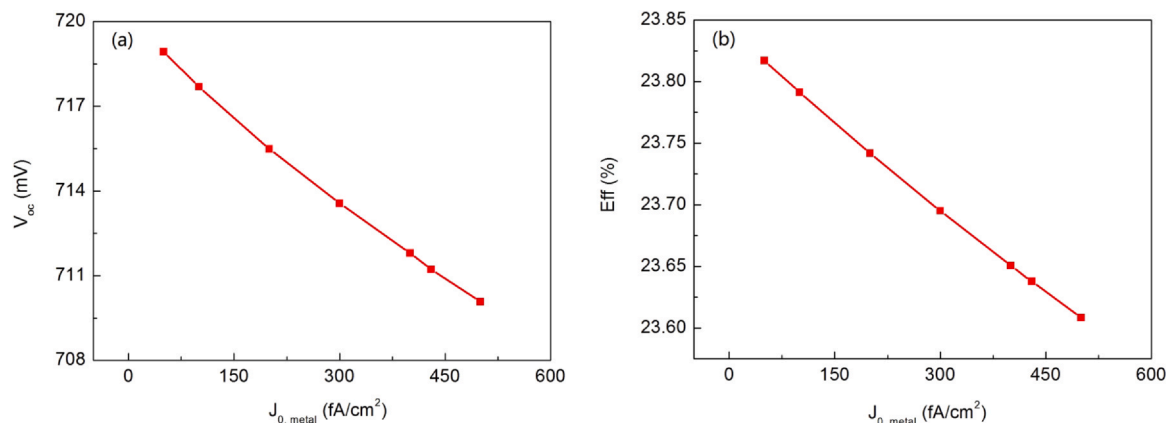


Fig. 9. The recombination current density of two kinds of cell structure effect on V_{oc} (a) and E_{ff} (b).

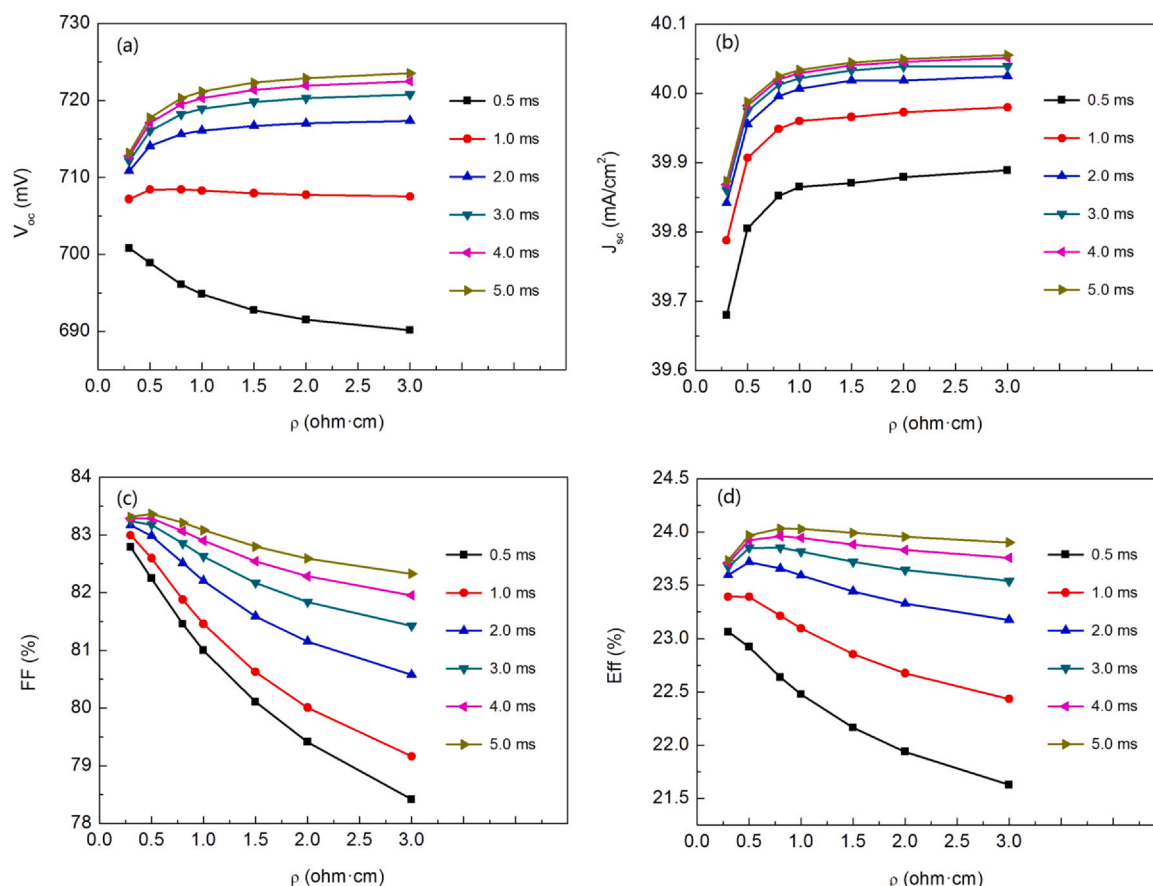


Fig. 10. The volume resistivity and minority carrier lifetime of wafer effect on V_{oc} (a), J_{sc} (b), FF (c) and E_{ff} (d).

absorption of sunlight by the polysilicon layer, only the TOPCon layer is applied to metal contact. The QSSPC analysis focuses on the conventional n-type PERT cell structure on the front surface and the characterization of the front surface selective TOPCon cell structure, the saturation current density value for the front surface cell metal contact recombination is 1400 fA/cm² for the conventional n-type PERT cell structure and 430 fA/cm² with a selective TOPCon cell characterization structure. Process optimization experiments and characterization tests were carried out on the front surface passivated structure to develop a feasible process and to produce a bifacial solar cell with a large area of 252 cm² with an average conversion efficiency of 23.07%. This represents an average conversion efficiency improvement of 0.21% compared to a conventional PERT structure on the front surface and a TOPCon on the rear surface. Using Quokka simulation software, the optimized cell can reach an open-circuit voltage of 721 mV, a short-circuit current of 40 mA/cm² and a cell efficiency of 24%.

CRediT authorship contribution statement

Bo Yu: Conceptualization, Methodology, Software. **Long Pang, Keming Liu, Dongsheng Zhang, Cuigu Wu, Ying Liu, Junyu Chen:** Data curation, Writing - original draft. **Wanbing Lu, Ridong Cong:** Visualization, Investigation. **Jinchao Shi:** Supervision. **Feng Li, Hongfang Wang:** Software, Validation. **Wei Yu:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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