

18.5% EFFICIENT FIRST-GENERATION MIS INVERSION-LAYER SILICON SOLAR CELLS

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ABSTRACT

In this paper, recent progress in the development of high-efficiency metal-insulator-semiconductor inversion-layer (MIS-IL) silicon solar cells at ISFH is presented. We fabricated MIS-IL solar cells showing independently confirmed energy conversion efficiencies of up to 18.5%. This represents the highest value reported to date for MIS-IL silicon cells. The increase in cell efficiency has been possible by improvements along several lines: (i) reduced perimeter recombination losses, (ii) a reduced contact resistance of the MIS front grid, and (iii) reduced rear surface recombination losses. The cells are characterised in detail and design modifications for further improvements towards 20% efficiency are presented.

INTRODUCTION

Metal-insulator-semiconductor inversion-layer (MIS-IL) silicon solar cells are a promising alternative to conventional diffused *p-n* junction Si solar cells. Their low-temperature fabrication process is simple and cost effective. Furthermore, MIS-IL solar cells have already been produced in an industrial pilot production and are successfully operating in PV power plants [1,2]. Despite of being fabricated in a simple process consisting of only seven steps, the efficiency of these conventional (classified by us as 'first-generation') cells reaches 15.7% on $2 \times 2 \text{ cm}^2$ FZ silicon (ISFH) and 15.3% on $10 \times 10 \text{ cm}^2$ CZ silicon (ASE, Alzenau) [3]. Detailed two-dimensional (2D) numerical modelling and experimental investigations have been performed in order to analyse and subsequently eliminate the device limiting factors of these first-generation inversion-layer silicon solar cells [4,5,6].

In this work we focus on the improvements of first-generation MIS-IL cells along the following lines: (i) reduction of the perimeter recombination losses, (ii) reduction of the losses associated with the contact resistance of the MIS front grid, and (iii) reduction of the rear surface recombination losses. These improvements allowed to increase the independently confirmed efficiency of MIS-IL silicon solar cells to 18.5%.

CELL DESIGN

Standard process

An industrially feasible process for the fabrication of MIS-IL cells was developed in the 1980s by R. Hezel's group at the University of Erlangen [7,8]. This MIS-IL cell processing sequence is characterised as follows:

1. Chemical cleaning (optional: texturing of the Si wafer with random pyramids before the cleaning)
2. Rear surface: vacuum evaporation of Al
3. Preparation of a tunnel oxide at 500°C
4. Front surface: vacuum evaporation of Al through a metal mask (finger spacing $280 \mu\text{m}$)
5. Al etch (removal of excess Al along the grid lines)
6. Caesium dip (for increased positive charge densities along the Si surface)
7. Deposition of a low-temperature PECVD silicon nitride film onto the entire front surface at 250°C

Fig. 1 depicts a schematic representation of a MIS-IL cell fabricated with the standard process described above. The optional surface texture consisting of random pyramids has been omitted in the drawing for the sake of clearness.

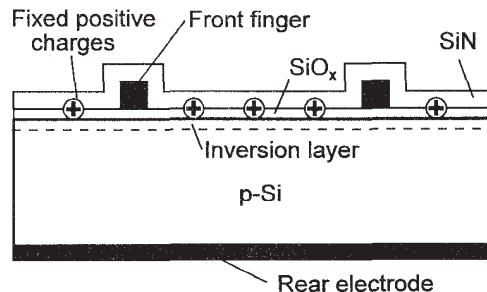


Fig. 1. Schematic diagram of a standard first-generation MIS-IL silicon solar cell. The surface texture with random pyramids is not shown.

Design modifications

In order to investigate the influence of individual high-efficiency features on the above-mentioned standard MIS-IL cells, their fabrication process has been modified. These modifications include the following features:

- A) Definition of the active cell area by an oxide window
- B) Implementation of Cs underneath the MIS front grid
- C) Implementation of a rear surface with point contacts and oxide passivation

Figure 2 shows a modified MIS-IL cell incorporating the features A, B, and C. For our studies we prepared five different sets of MIS-IL solar cells on 0.5- Ω cm p-type FZ silicon. In order to consider the impact of processing related variations, each set consisted of four identically processed solar cells. The first set incorporates none of the high-efficiency features. Set two uses feature A, set three uses feature B, and set four uses feature C. Finally, set five exploits features A, B, and C. Since inversion-layer emitters are sensitive to variations of the front surface roughness, the texturing of the wafers has been omitted in these optimisation experiments.

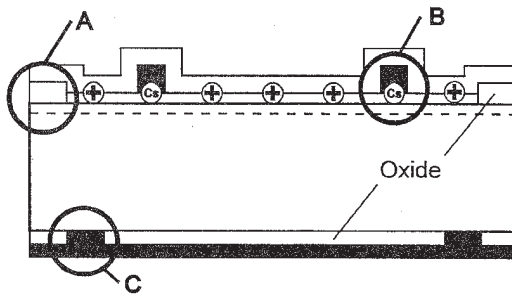


Fig. 2. Schematic diagram of the modified MIS-IL cells: A) oxide window, defining the active cell area, B) implementation of Cs underneath the MIS front grid and C) rear electrode with point contacts and oxide passivation.

RESULTS AND DISCUSSION

Impact of design modifications on cell parameters

Fig. 3 shows the effect of the high-efficiency features A to C on the 1-sun energy conversion efficiency of non-textured MIS-IL silicon solar cells. The values shown are the average of four identically processed cells. As can be seen from Fig. 3, the incorporation of a single feature improved the cell efficiency between 0.2% absolute for feature A and 0.9% absolute for feature C. If the features A-C are implemented into a single solar cell, the efficiency improves by 2.0% absolute (13.5% relative, see right bar in Fig. 3).

For a more detailed analysis of the impact of the different features on the cell parameters their relative deviations with respect to the reference cells incorporating none of the features A, B, or C are shown in Fig. 4.

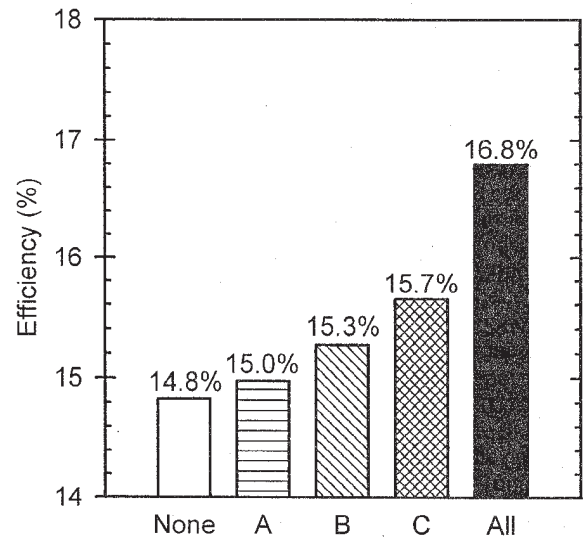


Fig. 3. Measured impact of different high-efficiency features on the 1-sun energy conversion efficiency of non-textured MIS-IL solar cells on 0.5 Ω cm p-type FZ silicon (AM1.5G, 100 mW/cm², 25°C, aperture area $\sim$ 4 cm²). The values shown are the average of four identically processed cells.

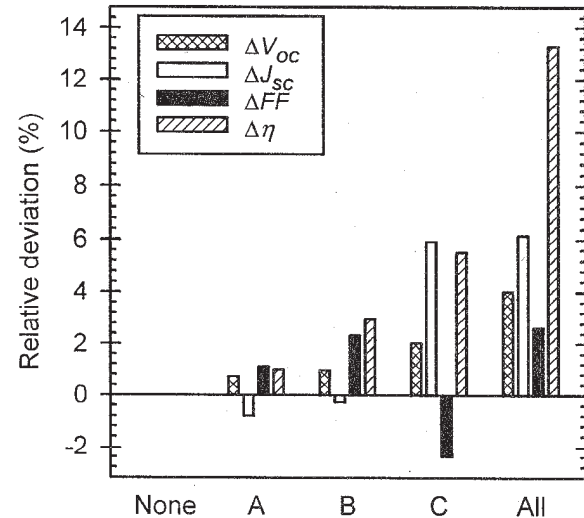


Fig. 4. Measured relative deviations of the averaged solar cell parameters with respect to reference cells incorporating none of the features A, B, or C.

Table I. Measured impact of different high-efficiency features on the 1-sun performance of non-textured first-generation MIS-IL solar cells. The values given are the average of four identically processed cells.

Feature	V_{OC} [mV]	J_{SC} [mA/cm ²]	FF [%]	η [%]	$R_{s,dark}$ [Ω cm ²]	$R_{s,light}$ [Ω cm ²]	R_{shunt} [k Ω cm ²]
None	613 $\pm$ 8	31.5 $\pm$ 0.4	76.8 $\pm$ 0.7	14.8 $\pm$ 0.5	0.77 $\pm$ 0.10	1.05 $\pm$ 0.20	10 $\pm$ 4
A	617 $\pm$ 3	31.2 $\pm$ 0.4	77.7 $\pm$ 1.2	15.0 $\pm$ 0.3	0.68 $\pm$ 0.12	1.00 $\pm$ 0.20	698 $\pm$ 134
B	619 $\pm$ 4	31.4 $\pm$ 0.1	78.6 $\pm$ 0.6	15.3 $\pm$ 0.4	0.45 $\pm$ 0.03	0.63 $\pm$ 0.02	11 $\pm$ 4
C	625 $\pm$ 3	33.3 $\pm$ 0.2	75.0 $\pm$ 1.5	15.7 $\pm$ 0.3	0.88 $\pm$ 0.02	1.25 $\pm$ 0.10	10 $\pm$ 5
All	638 $\pm$ 7	33.4 $\pm$ 0.2	78.9 $\pm$ 0.2	16.8 $\pm$ 0.2	0.68 $\pm$ 0.05	0.94 $\pm$ 0.08	902 $\pm$ 297

Feature C, the point-contacted rear electrode, has the strongest impact on the efficiency improvement of the MIS-IL solar cells. Due to the reduction of the rear surface recombination velocity from about 2×10^4 cm/s for the full-area ohmic back contact [9] to below 100 cm/s for the point-contacted electrode [10], the cell efficiency improves by 0.9% (i.e. relatively by 6%). This efficiency increase can largely be attributed to an improvement of the short-circuit current density J_{SC} by almost 2 mA/cm² (i. e. relative by 6%), see Fig. 4 and Table I. The second important feature is the Cs-treatment underneath the MIS front grid (feature B). From an evaluation of the series resistance $R_{s,light}$ of the cell under 1-sun illumination at the maximum power point it can be seen that the Cs-treatment significantly reduces $R_{s,light}$ from 1.05 to 0.63 Ω cm², see Table I. This leads to a significant improvement of the fill factor approaching 79%, an excellent value for MIS-IL solar cells. The definition of the active cell area by an oxide window, feature A, has the smallest impact on the cell efficiency. The corresponding reduction of the perimeter recombination increases the cell efficiency by 0.2%. This efficiency increase can largely be attributed to an improvement of the fill factor by 1.2% relative, see Fig. 4.

Results for textured cells

In order to improve the efficiency beyond the best value (16.8%) of Table I, additional batches of cells incorporating all features discussed above were fabricated with (i) a textured front surface ('random pyramids'), (ii) a double-layer AR coating (PECVD silicon oxide onto the SiN film), and (iii) a front grid with a reduced finger width (8 μ m instead of 14 μ m). Table II shows the 1-sun parameters of the best first-generation MIS-IL cells fabricated prior to this work in comparison to the best cells fabricated in this work. Our best MIS-IL silicon solar cells reach an independently confirmed efficiency of 18.5%. This increase in cell efficiency by 2.8% absolute compared to textured first-generation MIS-IL solar cells fabricated with the standard process is largely due to the increase in J_{SC} of 3.7 mA/cm². Fill factor and V_{OC} could also be improved by 3% relative, see Table II.

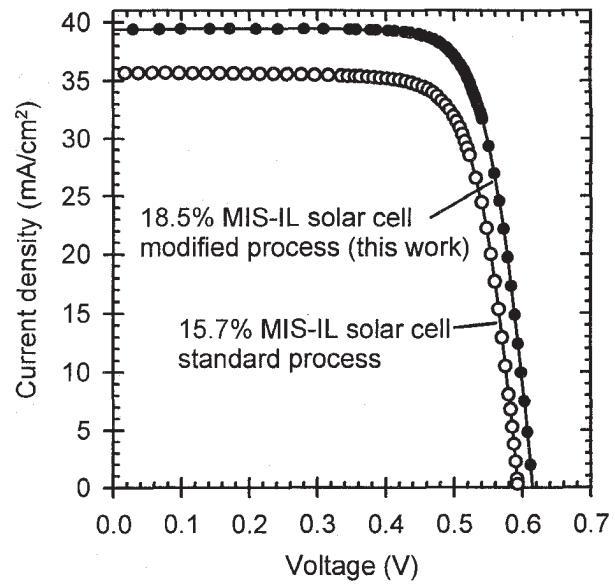


Fig. 5. Measured 1-sun I-V curves of the 15.7% and the 18.5% efficient first-generation MIS-IL solar cells (aperture area ~ 4 cm²) of Table II.

Table II. Measured 1-sun parameters of the best textured first-generation MIS-IL cells fabricated at ISFH on 0.5- Ω cm *p*-type FZ silicon, (AM1.5G, 100 mW/cm², 25°C, aperture area ~ 4 cm², all values independently confirmed by Fraunhofer-ISE).

Cell type	First-generation MIS-IL solar cell standard process	First generation MIS-IL solar cell modified process (this work)	
	14 μ m	14 μ m	8 μ m
J_{SC} [mA/cm ²]	35.6	37.7	39.3
V_{OC} [mV]	595	621	615
FF [%]	74.4	77.4	76.7
η [%]	15.7	18.1	18.5

In order to analyse the efficiency potential of MIS-IL cells, we performed two-dimensional numerical simulations with the semiconductor device simulation program DESSIS [6,11]. The cell efficiency was calculated as a function of the front and the rear recombination velocity parameters $S_{0,front}$ and $S_{0,rear}$. The corresponding results are shown in Fig. 6, whereby S_0 is defined as $S_0 = \sigma v_{th} N_t$. In agreement with the experimental results of the previous section, a reduction of the rear surface recombination velocity leads to a significant improvement of the cell efficiency (transition from 1 to 2 in Fig. 6).

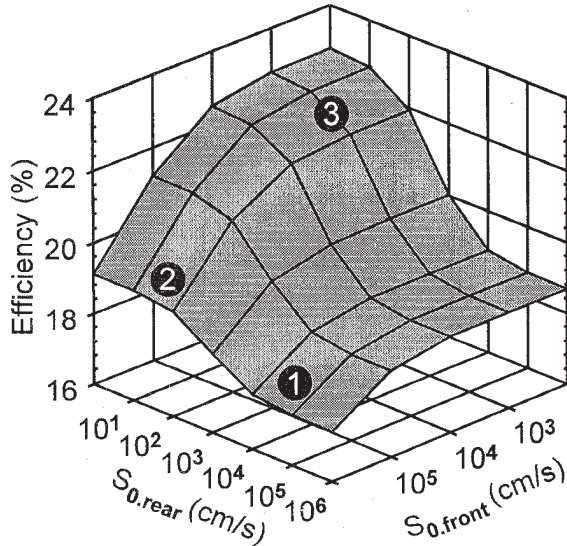


Fig. 6. Calculated efficiency of a MIS-IL silicon solar cell as a function of the front and rear surface recombination velocity parameters $S_{0,front}$ and $S_{0,rear}$ (0.5- Ω cm p -type FZ silicon, Auger-limited bulk lifetime, thickness 350 μ m, J_{SC} adjusted to 39 mA/cm²).

Furthermore, it is evident from Fig. 6 that an improvement of the front surface passivation of the non-metallised emitter areas, i.e. a reduction of the front surface recombination velocity, can further increase the cell efficiency (transition from 2 to 3). This can technologically be realised by increasing the SiN deposition temperature from 250°C to 400°C. So-called truncated-pyramid cells have already demonstrated a significant improvement of the open-circuit voltage due to the superior surface passivation properties of 400°C silicon nitride films [12]. Further improvements can be obtained by applying mechanically structured surfaces consisting e.g. of parallel groves [13]. Considering the results discussed in this work, this should enable us to reach energy conversion efficiencies above 20% by applying the inherently simple technology of MIS inversion-layer silicon solar cells.

In this study, improved metal-insulator-semiconductor inversion-layer silicon solar cells are presented with independently confirmed 1-sun efficiencies of 18.5%. This value is the highest ever reported for this cell type. The improvement can clearly be attributed to three major effects: reduced perimeter recombination losses, a reduced contact resistance of the MIS front grid, and reduced rear surface recombination losses. It has been shown that the latter had the strongest impact on the improvement of the solar cell efficiency. For further improvements towards 20% efficient MIS-IL silicon solar cells, novel cell structures incorporating passivation schemes that are able to reduce the front surface recombination are under investigation at ISFH.

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