Large Area Back-Contact Back-Junction Solar Cells with Efficiency Exceeding 21%

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Abstract — In this work high efficiency solar cells are fabricated with the use of low-cost industrially available technologies. The solar cell concept is called ZEBRA: a litho-free process in which standard 156x156 mm\textsuperscript{2} monocrystalline n-type Cz-Si are processed into high efficiency Interdigitated Back Contact (IBC) solar cells. In our first trial we obtained conversion efficiencies of more than 20% on solar cells with 239 cm\textsuperscript{2} area. With the help of a three-dimensional simulation of the device, a further improvement to more than 21.5% was demonstrated. We indentify the open-circuit voltage and the series resistance as the main losses to achieve the simulated efficiency. After an extensive optimization, targeting mainly the improvement of the fill factor, the cell results are presented in this work. The optimised solar cells show an improvement in the energy conversion efficiency of up to 21%. Furthermore, the simple metallization and the module interconnection designed for the ZEBRA cells allow for a bifacial application. Indoor and outdoor measurements on single-cell modules show an enhancement in the generated power of up to 12% at one sun front illumination conditions.

Index — photovoltaic cells, silicon.

I. INTRODUCTION

The developing of the PV market toward thinner and higher energy conversion efficiency solar cells enhances the industrial relevance of cell technologies as Back-Contact Back-Junction solar cells (BC-BJ) due to their characteristic architecture. The absence of the front metal contacts allows the sunward surface and the back-side to be independently optimized for optical and electrical performance. The drawback for having both emitter and metallization contacts on the back side of the cell requires high material quality and complicated process technology involving many masking and alignment steps which result in a higher manufacturing cost [1]. Although most research institutes already demonstrated high efficiencies on relatively small areas (4 cm\textsuperscript{2}) BC-BJ solar cell architecture [2]-[5] so far the most successful approach in mass production is used by Sunpower with cell efficiencies of over 24% on high quality n-type monocrystalline wafers [6]. This efficiency record is obtained with IBC cells where opposite charge carriers are collected by the busbars located at the opposite edge of the cell. This configuration has been applied to wafer area up to 125x125 mm\textsuperscript{2} to avoid large electrical losses due to the increase series resistance.

ISC Konstanz previously presented small area IBC solar cell [7] with efficiency up to 19.7% where an extensive screening on various fabrication condition and geometries were investigated. The progress made in improving surface passivation together with the advanced emitter structures and screen printing technology developed the so called ZEBRA concept which holds the possibility to become an industrial high efficiency solar cell for the future. The ZEBRA technology is high efficiency IBC solar cells and module fabricated using low-cost industrially available techniques. In more depth, the ZEBRA solar cells are fabricated on industry standard 156x156 mm\textsuperscript{2} monocrystalline n-type Cz-Si wafers. The first results on large area were presented by Mihailetchi et al., with demonstrated efficiencies exceeding 20% at 1 sun illumination condition [8]. In this paper we present our progress and results on IBC solar cells obtained with ZEBRA concept.

The process sequence of the ZEBRA cells was designed for industrial feasible application and the characteristic geometry adopted allowed for a bifacial characteristic which is unusual for an IBC solar cell structure, due to the large metal coverage on the back side.

II. EXPERIMENTAL DETAILS

The n-type ZEBRA solar cells process-flow uses only industrial relevant techniques. It comprises two high temperature diffusion steps performed in industrial-size quartz tube furnace with BBr\textsubscript{3} and POCl\textsubscript{3} source, to form the n\textsuperscript{+} and p\textsuperscript{+} diffused regions respectively. To achieve the best surface passivation we tested silicon dioxide in combination with silicon nitride as passivating and/or antireflection layers on both sides of the wafers. The interdigitated pattern on the back side is accomplished by laser processing and finally metal pastes are screen-printed to create the back contacts. A cross section drawing of our ZEBRA cells is show in Fig. 1.
In order to fabricate high efficiency ZEBRA cells on large area wafers we designed a three-dimensional method to interconnect the $p$ and $n$ fingers to their respective busbars. At the module level ZEBRA cells are designed to use, if needed, the industrial standard stringing methods of the conventional cells, thus avoiding the need of adopting specific equipments in production. In addition to the large ZEBRA cells, IBC cells on small area (4 cm$^2$) are also fabricated as a reference evaluation.

III. RESULTS AND DISCUSSION

Table I presents the results achieved after optimization in our development on small IBC and large ZEBRA cells. A conversion efficiency of 20.2% was obtained on small area and 20% on 238 cm$^2$ in October 2011. Figure 2 shows the internal quantum efficiency (IQE) and the total reflection for the best ZEBRA cell before and after the module encapsulation. The high IQE value (up to 99%) indicates a good carrier collection overall the cell including the area above the base region where the electrical shadow occurs [8]. In one cell module, the IQE is strongly reduced at short wavelengths due to the absorption in the EVA while at long wavelength the agreement with the IQE of the cell is good. For those cells a short-circuit current density ($J_{sc}$) of 41 mA/cm$^2$ was measured which is close to the maximum current that can be extracted from the IBC cells processed in this manner. Nevertheless it was clear from IQE analysis that a further improvement could be obtain with better front surface passivation and an optimized internal reflection. Sun-Voc measurements under open-circuit condition showed pseudo-fill factors ($p$-FF) of more than 82% for the small and the large cells indicating that the primary losses in FF were not caused by shunting of the cells. Since the solar cells were fabricated in the same experiment, the 3% absolute drop in fill factor (FF) for the large cell was attributed to addition series resistance (caused by line resistance, busbar, and losses at the cell edge). At the time of these measurements calculation shown that reducing the contact resistance alone would increase the FF by at least 1.5% abs.

A. Further Improvement

In order to prove the potential of the ZEBRA cell we recently run an extensive optimization of the metallization process with the target to minimize the losses in the FF. Visual camera alignment for laser etching mask was use to obtain a better alignment with the metallized screen printing fingers. We achieved a mismatch lower than 20µm which avoid any possible shunting between opposite polarity areas. Moreover several metal pastes from different suppliers were tested in a defined procedure which allowed identifying the better firing temperature ranges where both contact resistance and line resistance for emitter and BSF are minimized. The latest results obtained on large area ZEBRA cells are presented in Table II. The average fill factor of 78.7% with standard deviation of 0.3% demonstrates a successful reduction of the series resistance of the cells. The Voc value of 644 mV did not improve due to the better metallization. The best cell shows an efficiency up to 21% which shrinks the gap with the potential simulated efficiency. The Voc value of 644 mV may be limited due to recombination losses at the contacts or non optimal passivation scheme for both emitter and BSF area. Improving

### Table I

<table>
<thead>
<tr>
<th>Cell area [cm$^2$]</th>
<th>$J_{sc}$ [mA/cm$^2$]</th>
<th>Voc [mV]</th>
<th>FF [%]</th>
<th>$p$-FF [%]</th>
<th>$\eta$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>41.4</td>
<td>630</td>
<td>77.6</td>
<td>82.3</td>
<td>20.2</td>
</tr>
<tr>
<td>239</td>
<td>41.0</td>
<td>644</td>
<td>75.7</td>
<td>82.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>

### Table II

<table>
<thead>
<tr>
<th></th>
<th>$J_{sc}$ [mA/cm$^2$]</th>
<th>Voc [mV]</th>
<th>FF [%]</th>
<th>$p$-FF [%]</th>
<th>$\eta$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average±St.Dev</td>
<td>40.4±0.3</td>
<td>644±2</td>
<td>78.7±0.3</td>
<td>-</td>
<td>20.5±0.2</td>
</tr>
<tr>
<td>Best cell</td>
<td>41.2</td>
<td>646</td>
<td>79.1</td>
<td>82.2</td>
<td>21.0</td>
</tr>
</tbody>
</table>
Voc requires a deeper understanding of the present limitations in the device. By measuring the implied Voc on the fabricated cells after firing step (no metal applied) we obtain value between 660 to 680 mV at 1sun illumination which is far above from the Voc of the cells. This indicates on one hand the good passivation of the front and back surfaces (as seen also in Fig. 2) and on the other hand it highlights the detrimental effect of the screen printing and firing through metallization. It has been shown that during the firing process metal from the paste penetrates into the diffused region to an extent that depends, for example, on the paste composition, firing temperature, etc.

To better understand this effect we used Silvaco, a TCAD three-dimensional device software simulator, to compute the performance of our IBC cells. The experimental data for doping profiles, device geometry, and material properties were used as input parameters. A set of simulations was performed in which metal contacts on the base and emitter penetrate into the diffused regions assuming the maximum recombination velocity ($S_{metal}=10^7$ cm/s) under the metal area and a much lower S under the passivated regions (determined by fitting the experimental IQE). The results are plotted in Fig. 3. For no metal penetration the simulation correctly predicts the implied $V_{OC}$ limit of the cell. However, as the metal penetrates into the diffused region a sharp decrease in $V_{OC}$ of the cell is observed, culminating with cell shunting when the emitter junction is reached. No change in the calculated $J_{SC}$ and FF is observed until the shunting occurs, which is also confirmed experimentally (data not shown). The inset of Fig. 3 shows the additional variation in $V_{OC}$ should the metal fingers widths vary from the present experimental condition. This simulation highlights the need of better metal pastes with more superficial contact formation. By reducing the detrimental effect of the metallization on $V_{OC}$ (see Fig. 3) corroborated with a lower contact resistance (FF=79%) the present solar cell process could reach efficiencies in excess of 21.5%.

### A. Bifacial Characteristic

We also investigate the potential of the ZEBRA cells for driving down the costs for the solar energy conversion by increasing the amount of power generated by each solar panel (kWh/kWpeak) due to its bifacial characteristic. For this purpose we build a customized flasher-setup which allows us to monitor and quantify the power of the cell measured in bifacial mode at different illumination intensities from the back side, while the front side is kept at 1 sun intensity. In Fig. 4, the enhanced power of one cell module by varying the rear side light intensity is reported. For a typically albedo condition total power (front plus back) can reach up to 12% boosting significantly the energy output and consequently driving down the energy payback time for the ZEBRA cells. In order to evaluate the total gain in power we performed outdoor measurement of one-cell-module assembled in standard condition over a ground reflectivity about 70%. A calibrated module was used to monitor the light intensity over the day. The Fig. 5 shows that the albedo contribution over a daylight illumination is higher at lower light intensity condition (afternoon and morning time). Illumination intensity of 1 sun is reached at the noon time when the direct light is predominant. In this condition the albedo contribution is at the minimum of 15%. This increases the total amount of power generated by each solar panel widening the peak distribution of power collected during the day. This is shown in Fig. 6 where the relative increased of power output for a ZEBRA mini-module with black and transparent backside is presented. The integration of the power over all daylight time shows a gain about 12% for the bifacial module compared with a monofacial characteristic.

### IV. CONCLUSION

As a part of the cost reduction strategy, ISC Konstanz developed solar cells with high-efficiency back-contact back
understanding the formation architecture. The latest improvements, results of an extensive optimization of the ZEBRA technology were reported. The best efficiency of 21.0% was achieved with an industrial viable process flow on 156x156 mm\(^2\) n-type monocrystalline Cz-Si wafers reaching, to our knowledge, the efficiency record for IBC solar cells architecture. The differences between implied Voc and final cell Voc were also discussed. The open circuit voltage before and after the improved metallization was limited to a maximum value of 644 mV. As a consequence this study underlines the importance of developing an advanced cell structure with tailored doping profile in order to control the recombination under both metal areas and passivated regions. Moreover, the bifacial feature of the ZEBRA one cell module was also investigated performing indoor and outdoor measurements. The total power output measured over a day reveals a gain of 12% for the bifacial module, demonstrating the potential for the ZEBRA concept to drive down the cost of the solar energy conversion by increasing the amount of power generated by each solar panel.

REFERENCES