RAPID THERMAL FIRING OF SCREEN PRINTED CONTACTS FOR LARGE AREA CRYSTALLINE SILICON SOLAR CELLS

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ABSTRACT

Rapid Thermal Firing (RTF), i.e. firing of screen printed contacts using Rapid Thermal Processing (RTP), is a promising alternative compared to infrared heated conveyor belt furnaces concerning a reduction in process time. In addition, due to flexible process design and in-situ temperature measurement, RTF is well suited for detailed studies and optimisation of the firing process and the contact formation. Exploiting the advantages of RTP such as high heating and cooling rates and short plateau times, we have developed an RTF process with a very short total process time of 60 s and less than 10 s above 600 °C. Applying the process to large area cells (100 cm²) fill factors > 78% have been achieved even on shallow RTP-diffused emitters with a grid shading of 7%. Contact resistivity mappings of the rapid thermal fired front contact grid confirm a laterally homogeneous contact formation.

INTRODUCTION

Screen printing of contacts is the dominating industrial applied metallisation technique for crystalline silicon solar cells. For contact formation silver pastes and aluminium or aluminium/silver pastes are used for the front and the back contacts, respectively. After printing and drying of the pastes contact firing is necessary, in order to obtain the desired electrical contact properties. In industrial scale solar cell manufacturing the contact firing is usually done in infrared (IR) heated conveyor belt furnaces.

Firing of screen printed contacts using Rapid Thermal Processing (RTP), is a promising alternative compared to IR heated conveyor belt furnaces. On the one hand RTP can lead to a reduction in process time and the thermal budget of the wafer [1]. On the other hand every single process step can be designed highly flexible with regard to thermal cycle and gas atmosphere. Combined with the possibility of an in-situ measurement of the wafer temperature this flexibility predestines RTP furnaces for detailed studies of the firing process and the contact formation of printed contacts.

The capability to fire screen printed contacts by RTP in pure Ar atmosphere has already been reported by Laugier et al. [2], resulting in moderate fill factors on multicrystalline (mc) silicon. On 4 cm² float zone (FZ) cells Doshi et al. have demonstrated that fill factor values up to 79% can be achieved on shallow RTP-diffused emitters [3]. Using a POC13 diffused 50 Ω/sq emitter fill factors up to 80.5% have been realised on 4 cm² FZ cells, as we have published earlier [4]. This result shows the potential of RTF regarding screen printed contacts on moderately doped emitters and represents the highest value reported so far for a cell with screen printed and rapid thermal fired contacts.

The aim of the present work is (i) to transfer the main ideas of RTP, i.e. low thermal budget and short process time to firing of screen printed contacts, (ii) to develop a firing process that is in principle transferable to industrial cell manufacturing and (iii) to achieve high quality contacts and high fill factor values especially on large area cells. It will be shown that Rapid Thermal Firing (RTF) is a serious alternative to conventional firing to significantly reduce process time.

RAPID THERMAL FIRING (RTF) OF SCREEN PRINTED CONTACTS

Contact firing has been carried out in a single wafer RTP furnace (SHS 10 from STEAG—RTP) shown in Fig. 1. The gold coated reactor with water cooled walls contains a quartz chamber that can be purged by N₂ and either O₂ or forming gas (FG). The silicon wafers are heated by incoherent irradiation of 25 tungsten halogen lamps of 1.5 kW each mounted in two lamp banks above and below the chamber. Wafer sizes up to 6 inch and 15x15 cm², respectively, can be processed.

Fig. 1. Schematical drawing of the used RTP furnace.

In all experiments the thermal cycle during RTF has been adjusted in a closed-loop. For each process step the temperature or a heating rate is set and the wafer temperature is measured in-situ by optical pyrometry.

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Fig. 2. Example for a RTF process showing the different process phases.

assuming the pyrometer has been calibrated. The lamp power is adjusted by a Proportional-Integral-Differential (PID) control, in order to match the measured to the set temperature. The corresponding PID parameters can be adjusted for each process step.

The thermal cycle for contact firing is exemplarily shown in Fig. 2. In principle the process consists of four different phases: In phase 1 the quartz chamber is purged with the gas atmosphere used during phase 2, in phase 2 the organic binders of the metallisation pastes are burned out. The electrical properties of the contact are formed in phase 3 and, finally, in phase 4 the quartz chamber is again purged and the wafer is submitted to natural cooling. Depending on the gas atmosphere used during RTF phases 1 and 4 can be omitted or noticeably shortened.

Fig. 3. Deviation of wafer temperature measured by means of optical pyrometry from set temperature as a function of time (left) for the developed process.

In order to receive reproducible solar cell results, it turned out to be absolutely necessary to control the thermal cycle well. This can be achieved by a precise design of each process step and by carefully optimising the PID parameters especially in process phase 3. Phase 3 shows the temperature deviation of the measured and the set temperature during burn out and firing for a well controlled process with high heating and cooling rates. The deviation during the first seconds of the heating ramp is caused by the inertia of the lamps due to the high heating rate. The second deviation during cooling down is due to the solidification of the Al-Si-eutectic of the printed back contact. However, these deviations have no negative influence on the solar cell results, as they are situated in less critical parts of the process. In fact, around the firing peak the deviation can be kept well below 5 °C, thus permitting an excellent reproducibility of the developed RTF process.

OPTIMISATION OF RTF PROCESS PARAMETERS

The optimisation of the RTF process parameters have been carried out on multicrystalline (Baysix) 5x5 cm² wafers. The wafers have been processed according to a simplified process sequence, including a POCl₃ diffused emitter with a sheet resistance of 35 Ω/sq, an evaporated Al back contact and without antireflective coating or texturing. During RTF an Al back surface field is formed.

Regarding the determination of electrical properties of the front contact a test structure has been used, including a 2x2 cm² solar cell, structures for contact resistivity measurements according to Meier and Schröder [5] and a structure for resistivity measurements of the fired silver paste. After RTF the different structures have been separated by laser cutting from the front side followed by an FG anneal at 400 °C.

The first step of optimisation was to select the most promising silver paste. For this purpose commercially available and laboratory pastes have been investigated. Requirements have been: Low contact resistivity, low resistivity of the printed and fired paste, good printability and adhesion. Once the right silver paste has been chosen, the burn out temperature and burn out time have been matched to the contained organic binders.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T_{up}$</td>
<td>30-90 K/s</td>
</tr>
<tr>
<td>$T_{peak}$</td>
<td>730-790 °C</td>
</tr>
<tr>
<td>$t_{peak}$</td>
<td>1-10 s</td>
</tr>
<tr>
<td>$T_{down}$</td>
<td>10-40 K/s</td>
</tr>
<tr>
<td>B</td>
<td>0-1</td>
</tr>
<tr>
<td>$\alpha V$</td>
<td>10-15 slm</td>
</tr>
<tr>
<td>$c(O_2)$</td>
<td>0-20 %</td>
</tr>
</tbody>
</table>

In a second step of optimisation we have focused on the actual firing (phase 3 in Fig. 2), as it is the most crucial process part with regard to the cell performance. Phase 3 can be completely described by means of seven process parameters that are itemised in Table 1. In order to describe the lamp power of the two lamp banks in the RTP reactor, it is convenient to define an irradiation ratio B, which is the ratio of the lamp power on the back side of the cell compared to the total lamp power during RTF. Thus, for $B = 0$ the wafer is heated only from the front side, for $B = 1$ only from the rear side. Starting from these seven parameters we have extracted the significant ones by varying all parameters in the listed intervals (see Table 1) using Design of Experiment (DOE) techniques, in particular two-factorial experimental designs [6]. It turned out that five parameters have a significant effect on the IV-characteristics: $\Delta T_{up}$, $T_{peak}$, $t_{peak}$, $c(O_2)$ and B. Based on these parameters a further optimisation has been carried out.
APPLICATION OF THE RAPID THERMAL FIRING PROCESS TO LARGE AREA CELLS

To answer the question, whether RTF is suited for contact firing in case of large area cells, we have processed 10x10 cm² solar cells according to a simple industrially relevant process scheme that is based completely on screen printing.

Cell technology

Multicrystalline (Baysix, 340 μm thick, 0.6-1 Ω-cm) and Czochralski (290 μm thick, 1 Ω-cm) boron doped silicon wafers have been used for cell fabrication. Fig. 4 shows the technology steps for cell manufacturing. After saw damage etch using a single-stage hot KOH etching solution, wafers have been cleaned in a HNO₃/HF etch. Note that the Cz wafers are not texturized with random pyramids.

For emitter formation the Soltech paste P 101 has been homogeneously screen printed as a phosphorous dopant on the front side of the wafer. For most of the wafers the emitter diffusion has been carried out in an infrared heated RTC conveyor belt furnace (CBF) at 915 °C resulting in a sheet resistance of 35 Ω/sq. Additionally some Cz wafers have been diffused in an RTP furnace at 950 °C with a resulting emitter sheet resistance of ~20 Ω/sq. After emitter formation the residues of the phosphorous paste has been removed in HF.

For solar cell metallisation a commercially available aluminium paste and the selected silver pastes have been screen printed on the back and the front side, respectively. The contacts have been co-fired using the developed RTF process. In order to obtain good fill factors the peak temperature as well as the plateau time had to be slightly adapted to the emitter profiles.

In order to further exploit the advantages of RTF, we have reduced the process time down to 60 s including burn out and firing. This has been achieved by an increase of the cooling rate in phase 3 and a shortening of the burn out (see Fig. 2). The actual firing (phase 3) does not require more than 18 s including a very short 1 s plateau at peak temperature. The wafer temperature is less than 10 s above 600 °C, featuring the low thermal budget of the process. It is important to note that no degradation of the illuminated solar cell characteristic has been observed due to process time reduction. This is shown exemplarily in Fig. 5 for the shortening of phase 3 due to an increase of the cooling rate.

Fig. 5. Conversion efficiency before SiNx deposition for two different cooling rates in process phase 3.

Following the metallisation step, the mc–Si wafers have passed a hydrogen passivation in a remote plasma. Finally, an antireflective coating of 78 nm thick PECVD–SiNx has been deposited on the front side and edge isolation has been carried out using a Nd:YAG laser.

Characteristics of the front contact grid

For the front contact grid we have used a conventional H-pattern, with a printed finger width of ~130 μm and an average finger height of ~7 μm after RTF. These values correspond to a typical finger geometry in industrial solar cell production [7]. The resulting grid shading adds up to 7% (9% with cell interconnectors).

In order to detect lateral temperature inhomogeneities that can occur due to RTP, the contact resistance of the screen printed front grid has been examined using the Specific Contact Resistance Analysis by Mapping of Potential (SRAMP) technique [8]. The solar cell is short-circuited and current is generated by light. This causes potential gradients on the surface of the solar cell and particularly a potential jump at the edge of each contact finger. Under specific assumptions the potential jump is proportional to the contact resistivity of the metal semiconductor contact. By mapping the potential over the entire cell area, contact resistivity variations can be detected.

As can be seen in Fig. 6 the contact resistance is quite homogeneous over the entire cell area. No RTP-specific edge effect occurs. Only the left edge of the cell shows somewhat higher values, which can be explained by similar inhomogeneities of the emitter sheet resistance. At first sight this result seems to be surprising, since no guard ring has been used during RTF, which is usually necessary to achieve a sufficient lateral temperature homogeneity in RTP. However, the result is plausible, as the firing peak of the developed process is very short. It can be deduced from these results that the lateral temperature profile over the whole cell is sufficiently homogeneous for contact firing.
CONCLUSIONS AND OUTLOOK

A thorough optimisation of the Rapid Thermal Firing (RTF) process for screen printed contacts has been carried out by means of Design of Experiment (DOE) techniques, resulting in a very short total process time of 60 s. Applying the RTF process to screen printed contacts on 10x10 cm² cells, fill factors above 78 % have been realised with a grid shading of 7 %. Contact resistance scans show quite homogeneous front contact properties. No RTF-specific edge effects due to temperature inhomogeneities during RTF could be detected. Using a simple and industrially relevant solar cell process based on screen printing, in-line diffusion, RTF and SiN-ARC, solar cell efficiencies as high as 15.6 % on Cz-Si and 13.7 % on mc-Si have been achieved. It can be stated that RTF opens up a sincere alternative for contact firing also for large area cells. Recent developments of high throughput RTF systems, i.e. in-line RTF furnaces, will enable the implementation of RTF in industrial silicon solar cell manufacturing in the near future.

ACKNOWLEDGEMENTS

The author would like to thank S. Peters for helpful discussions, E. Schäffer for cell measurements and A. van der Heide, ECN, for the contact resistivity mappings. We further thank ASE for providing us with diffused mc-Si wafers. The author D. Huljic is supported by the scholarship program of the Deutsche Bundesstiftung Umwelt, Germany, and a scholarship of the Albert-Ludwigs-University Freiburg, Germany. D. Biro is financially supported by the Stadtwerke Karlsruhe, Germany.

REFERENCES


Table 2. Solar cell results on multicrystalline and Czochralski 10x10 cm² silicon wafers.

<table>
<thead>
<tr>
<th>process</th>
<th>area [cm²]</th>
<th>V_oc [mV]</th>
<th>I_sc [mA/cm²]</th>
<th>FF [%]</th>
<th>η [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Cz</td>
<td>97.2</td>
<td>611.3</td>
<td>32.71</td>
<td>77.9</td>
<td>15.6</td>
</tr>
<tr>
<td>mc</td>
<td>97.2</td>
<td>597.8</td>
<td>29.69</td>
<td>77.4</td>
<td>13.7</td>
</tr>
<tr>
<td>B Cz</td>
<td>96</td>
<td>605.3</td>
<td>30.35</td>
<td>78.2</td>
<td>14.4</td>
</tr>
</tbody>
</table>

A fill factor > 78 % has been achieved even on shallow RTP-diffused emitters (process B). The slightly higher fill factor reflects in fact the lower sheet resistance compared to the CBF diffused cells. Using the same phosphorous dopant for both types of diffusions the low sheet resistance of Rs = 0.3-0.4 Ω·cm² and sufficiently good parallel resistance values Rp ~ 1.5·10⁴ Ω·cm² has been derived from dark IV-characteristics. Note that no firing through process has been applied, enabling somewhat higher parallel resistance values. The high fill factors achieved reflect also the good lateral homogeneity of the screen printed contact (see Fig. 6).