A study of the “short-circuit” effect during the fast firing process

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8th Metallization & Interconnection Workshop, Konstanz, May 13, 2019
Motivation

- Lightly doped Si surfaces $\rightarrow$ higher Voc $\rightarrow$ higher Eta

- Current status

<table>
<thead>
<tr>
<th></th>
<th>Screen-printed and firing-through Ag contacts [1,2,3]</th>
<th>Evaporated Al contacts (PVD) [4]</th>
</tr>
</thead>
<tbody>
<tr>
<td>sheet resistance</td>
<td>100 $\Omega$/sq</td>
<td>170 $\Omega$/sq</td>
</tr>
<tr>
<td>surface concentration</td>
<td>$8 \times 10^{19}$ $\text{cm}^{-3}$</td>
<td>$1.8 \times 10^{19}$ $\text{cm}^{-3}$</td>
</tr>
<tr>
<td>$J_{0,\text{pass}}$</td>
<td>75 fA/cm$^2$</td>
<td>11 fA/cm$^2$</td>
</tr>
<tr>
<td>$\rho_c$ (contact resistance)</td>
<td>2 m$\Omega$·cm$^2$</td>
<td>1 m$\Omega$·cm$^2$</td>
</tr>
</tbody>
</table>

$\rightarrow$ Need better understanding of contact formation

Formation of Ag contacts: Kim’s model [5, 6]

- Reaction 1 (open-circuit state): the reduced Ag atoms precipitate into Ag crystallites

- Reaction 2 (short-circuit state): no reduction of Ag$^+$ ions

- To trigger short-circuit state: local Ag contacts that are formed earlier than others

\[
\begin{align*}
4Ag^+_{(in\ glass)} + 2O^2-_{(in\ glass)} + Si_{(solid)} & \rightarrow 4Ag_{(in\ glass)} + SiO_2_{(in\ glass)} \\
Si_{(solid)} + 4xAg_{(solid)} + (1-x)O_2_{(gas)} & \rightarrow Si^{4+} + 4xAg^+_{(in\ glass)} + 2(1-x)O_2^{-2}_{(in\ glass)}
\end{align*}
\]

Formation of Ag contacts: fast firing and temperature gradient

- To trigger short-circuit state: local Ag contacts that are formed earlier than others
  - temperature gradient exists over the cell surface (a likely case)
  - Ag crystallites formed in part A, which may occur earlier than in part B, become the short-circuiting sites that influence the contact formation in part B

Belt fire furnace, heating zone (e.g. 3 m)
Formation of Ag contacts: influence from busbars

- Reaction (short-circuit state): **no reduction** of Ag\(^+\) ions [5, 6]
- To trigger short-circuit state: local Ag contacts that are formed earlier than others
- Mitigate this effect by omitting the busbars?

\[
Si_{(solid)} + 4xAg_{(solid)} + (1 - x)O_2_{(gas)} \rightarrow Si^{4+} + 4xAg^{+}_{(in\ glass)} + 2(1 - x)O^{-2}_{(in\ glass)}
\]

Experiment 1: solar cell

- Mitigate this effect by omitting the busbars (BBs)?
  - 6-inch n-type PERT rear junction solar cells [7]

### Experiment 1: solar cell IV and $\rho_c$

<table>
<thead>
<tr>
<th>Ag Paste</th>
<th>Firing</th>
<th>Jsc (mA/cm²)</th>
<th>Voc (mV)</th>
<th>FF (%)</th>
<th>Eta (%)</th>
<th>$\rho_{cAg}$ (mΩ·cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>paste A</td>
<td>with BB</td>
<td>39.7 ± 0.2</td>
<td>686 ± 1</td>
<td>75.9 ± 1.4</td>
<td>20.7 ± 0.4</td>
<td>12.2 ± 8.7</td>
</tr>
<tr>
<td></td>
<td>without BB</td>
<td>39.7 ± 0.1</td>
<td>688 ± 1</td>
<td>80.2 ± 0.1</td>
<td>21.9 ± 0.1</td>
<td>2.4 ± 0.8</td>
</tr>
<tr>
<td>paste B</td>
<td>with BB</td>
<td>39.7 ± 0.1</td>
<td>680 ± 1</td>
<td>52.2 ± 4.9</td>
<td>14.1 ± 1.3</td>
<td>76.1 ± 34.4</td>
</tr>
<tr>
<td></td>
<td>without BB</td>
<td>39.6 ± 0.1</td>
<td>682 ± 1</td>
<td>80.1 ± 0.3</td>
<td>21.6 ± 0.1</td>
<td>1.9 ± 1.0</td>
</tr>
</tbody>
</table>

5BBs, 100 fingers
~10 cells each group

$\rho_{cAg}$: contact resistance of the Ag grid; for each group (two cells, totally 36 measurement points)
Experiment 1: solar cell
PL/EL image

PL

EL, 2.5A

Paste A

fire without BB

Eta = 21.9 %

fire with BB

Eta = 21.0 %
Experiment 2: contact resistance

- Is it an effect that is valid in specific pastes?

- Test with another five Ag pastes on cell precursors

5BBs, 78 fingers
~36 measurement points for each group

- Doping concentration (cm$^{-3}$) vs. Depth (µm)

- Doping concentration (cm$^{-3}$) for boron and phosphorus pastes:
  - Boron 150 Ω/sq
  - Phosphorus 150 Ω/sq
Experiment 2: contact resistance

- Is it an effect that is valid in specific pastes?
  - Test with another five Ag pastes on cell precursors

5BBs, 78 fingers
~36 measurement points for each group
Experiment 2: contact resistance

- Is this effect valid for the p+ surface as well?
  - test on the p+ surface of the cell precursor

- Similar trend was observed for
  - different firing recipes
  - different surface morphologies and doping profiles [8]
  - p-type cells [8, 9]
  - passivated contact [9]

5BBs, 78 fingers
~36 measurement points for each group

- 

Other related experiments

Literature review: current injection between Ag and Si [10]

Summary

Observation in the lab:
- Firing without BBs leads to a decrease of $\rho_c$ for all seven tested Ag pastes (from four suppliers)

→ perhaps a general effect for all screen-printed and firing-through Ag pastes, instead of an effect valid for specific pastes

- The decrease of $\rho_c$ also hold in solar cells, leading to better Eta

A possible theory to explain:
- Short-circuit effect [5, 6]

\[ Si_{(solid)} + 4xAg_{(solid)} + (1 - x)O_2_{(gas)} \rightarrow Si^{4+} + 4xAg^+_{(in\ glass)} + 2(1 - x)O^{2-}_{(in\ glass)} \]

figure taken from [5]