How many Finger-Interruptions should we tolerate?

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Motivation

1. Innovation, like ..
   - Ultra fine line screens
   - Novel printing technique

2. Dispute in lab and production:
   When must we clean/exchange the screen?

   What would be a sensible criteria on the number of finger cuts?

   Failure catalogs often allow only a low number of finger cuts (e.g. 5, 7)

   High rejection rate

   Increased efficiency, but also …
   increased risk for finger cuts
General considerations

Power loss of a finger cut depends on
- Layout: finger length, redundancy features
- Individual position of the cut
- Position of further cuts in the neighborhood

Definition of standard PERC cell for this study
- Layout: 100 fingers, 45 µm, M2 Wafer
- $R_{\text{line}}$ 0.55 Ω/cm (0.5, 0.7, 0.9 Ω/cm)
- $R_{\text{sheet}}$ (Emitter) 90 Ω/□
- No redundancy line
- 3BB / 5BB / 18BB

IV-parameters the standard cell (5BB)
- $\eta$ = 21.4%, FF = 80.5%,
- $V_{\text{oc}}$ = 670 mV, $J_{\text{sc}}$ = 39.7 mA/cm²
Loss of cut in inner section

For a cut in an inner section (between BBs):

- No loss if cut is in the middle between BBs
- Maximum loss for cut close to one BB

Power loss of finger in symmetry element (SE) [1]

\[ \Delta P_{\text{line}}(SE) = \frac{1}{3} l^3 j_{mp}^2 d^2 R_{\text{line}} \]

Max. additional loss of one cut in inner section

\[ \Delta P_{\text{inner cut}} = \Delta P_{\text{line}}(2l) - 2 \times \Delta P_{\text{line}}(SE) \]

\[ = 6 \Delta P_{\text{line}}(SE) \]

\[ = 0.68 \text{ mW (3BB)} \]

\[ \Delta \text{eta (inner c., 3BB)} = 0.0028 \% \]

\[ \Delta \text{eta (inner c., 5BB)} = 0.00056 \% \]

Cut in outer section

- Maximum loss for cut close to BB
- Loss = Additional loss in emitter
  + loss due to increased current in finger

Power loss in semiconductor in one symmetry element [1]

\[ \Delta P_{semi} (SE) = \frac{1}{12} d^3 l j_{mp}^2 R_\square \]

Max. power loss of one cut in out section:

\[ \Delta P_{semi} (outer \ cut) = 6 \Delta P_{semi} (SE) + 2\Delta P_{line}(SE) \]

In principal (max.) loss of a cut any position could be calculated in a similar way
- However, for random positions and neighboring cuts things are getting very complicated
- And, in reality, current paths will slightly bend (emitter current not perpendicular to finger current)
Cuts in random positions

To investigate the impact of cuts in random positions we use the software Griddler 2.5 Pro [2]

We wrote a script which creates finger cuts in random positions

Output: IV parameter, voltage maps

- $\eta$ decreases gradually with the number of cuts, such as FF
- $V_{oc}$ and $J_{sc}$ remain virtually unchanged
- Higher $R_{\text{line}}$ reduces the FF severely, but the shape of the curves similar;
- However, for higher $R_{\text{line}}$ the decrease gets slightly steeper
Loss per cut, 3BB cell

- Within the first 50 cuts, only losses < 0,005%

- First cuts with eta loss > 0,008% start ~70 cuts -> these correspond to cuts neighboring existing cuts in the outer sections

- Cuts with eta loss > 0,018% correspond to cluster with at least three neighboring cuts
Impact of BB number

- A higher number of BBs reduces impact of cuts drastically
- Lower loss per cut and smaller risk for severe cuts
- For 5 BB more than 50 cuts are needed for decrease of $\Delta \text{FF} > 0.1\%$
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<table>
<thead>
<tr>
<th>#BB</th>
<th>Δ η / 100 cut</th>
<th>#cuts for ΔFF = 0.1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 BB</td>
<td>-0.18 %abs</td>
<td>14 cuts</td>
</tr>
<tr>
<td>5 BB</td>
<td>-0.048 %abs</td>
<td>60 cuts</td>
</tr>
<tr>
<td>18 BB</td>
<td>-0.0040 %abs</td>
<td>&gt;500 cuts</td>
</tr>
</tbody>
</table>

Rline = 0.55 Ohm/cm
Validation experiment

Experiment
- 150 CZ- PERC precursors from industrial production line,
- We deliberately introduced 50/100 cuts into a printing screen by screen filler
- Combined this screen with print of 3BB / 5BB / 0BB resulting in ~15 per group
Validation Experiment: IV Data

Experiment: ~15 solar cells per group with deliberately introduced finger cuts
Simulation: cuts at similar positions as in screen, variation of $R_{\text{line}}$ from 0.5Ω/cm to 0.9 Ω/cm

$\Rightarrow$ Experiment and Simulation match reasonable well
Validation Experiment

- Data plotted normalized to simulated value at 0 cuts
- Simulation and experiment match well, however statistical error is significant
H.A.L.M. provided an analysis of 220,000 PERC cells:
(#cuts / Mean(eta_loss) / frequency)

- #cuts were derived from EL picture by an algorithm
- Eta Loss < 0.01% for 1-5 cuts, eta loss ~0.05% for 7-12 cuts
- However, very low count >5 cuts (<0.5% of all cell have >5 cuts)

Data and simulation do not match well! -> Further effects?
Hypothesis:

- This line probably operates with rejection criteria of 5 cuts
- Before number of cuts increases gradually towards 5 cuts, operators take action (e.g. cleaning or exchange of screen)

-> The few cells with >5 cuts originate from another mechanism than clogging of screen. E.g. they might be the first prints after a stop, or after screen cleaning procedure

-> most likely these cell suffer on further problems, e.g. a reduced cross section

Increased line conductivity could easily explain eta loss in observed range!
Further, H.A.L.M. provided an analysis of ~300,000 mc-Si 5BB Al-BSF cells:

\[ \frac{\text{#cuts}}{\text{Mean(eta_loss)}}/\text{frequency} \]

- This data set features brought distribution with maximum at 15 cuts

Data show a slight increase of $\eta$ with number of cuts!

- must also arise from another effect, e.g. a reduction of line width
- however, data compatibly with low loss by cuts
Conclusions

- Finger cuts are detrimental, but the losses produced by random cuts are very small
- A higher number of BBs reduces impact of cuts drastically
  • For 5BB about 50 cuts are needed for $\Delta FF = 0.1\%$
  • For 18BB more than 500 of cuts are needed for $\Delta FF = 0.1\%$
- Single digit rejection criteria (e.g. < 7 cuts) are not justified by physics.
  For 5BB cells, it would be prudent to allow at least 50 cuts.
- Reduced finger cross section has a bigger impact -> better to monitor paste laydown or $R_{\text{line}}$
- No reliability problems due to finger cuts are known to us
- A relaxed criteria on the number of finger cuts would allow for:
  • Lesser cleaning and lower consumption of screens -> higher productivity
  • More headroom for further reduction of line width -> potential for higher efficiency

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<th>Exp $\Delta \eta$ (100 cuts)</th>
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<td>3 BB</td>
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<td>-0.048 %</td>
<td>-0.046 %</td>
</tr>
<tr>
<td>18 BB</td>
<td>-4.0 E-06 %</td>
<td>~ 0</td>
</tr>
</tbody>
</table>

Have “Mut zur Lücke”!
(Dare the gap)
Acknowledgements

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