ACCURATE MEASUREMENT OF BUSBARLESS SILICON SOLAR CELLS

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8th Metallization Workshop
Constance, May 14, 2019
Measurement of Busbarless Silicon Solar Cells

Motivation

- Busbarless solar cells become more and more important
- Measurement of current-voltage (I-U) characteristics of busbarless cells
  - Contacting of grid fingers only
  - Different setups for measurement developed \([2-6]\)
- **Challenging**: Realization of 4-wire connection
  
  "*Voltages and currents shall be measured [...] using independent leads from the terminals*" \([7]\)
  
  → Separate, electrically isolated current and voltage contacts on fingers necessary

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Measurement of Busbarless Silicon Solar Cells

Motivation

- At CalLab PV Cells measurement unit constructed based on Pasan’s Grid TOUCH unit [1]
- Conducting wires spanned over front side perpendicularly to grid finger orientation
  (1) Front contact to solar cell
  (2) Pressing of solar cell onto rear contact (additional vacuum suction)
- Realization of active solar cell cooling

Measurement of Busbarless Silicon Solar Cells

Motivation

- Separate, electrically isolated current ($I$) and voltage ($U$) wires

  - **Ideal 4-wire sensing:**
    Distance $d_{ItoU} = 0$ between $I$ and $U$ wires

  - **Sensing in reality:**
    Distance $d_{ItoU} \neq 0$ between $I$ and $U$ wires due to constructional restrictions

→ **Aim of this work:** Evaluation of "non-ideal" distance between $I$ and $U$ wires
Experimental Investigation of Non-Ideal Sensing
Current-Voltage Measurement of Busbarless Solar Cells

- *I-U* measurement of busbarless solar cells with different front grid resistivity $R_{\text{grid}}$

<table>
<thead>
<tr>
<th>Front grid paste</th>
<th>$R_{\text{grid}}$ [mΩ/cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-temperature, conventional</td>
<td>6</td>
</tr>
<tr>
<td>Low-temperature, conventional</td>
<td>20-40</td>
</tr>
<tr>
<td>Low-temperature, advanced</td>
<td>&gt;200</td>
</tr>
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</table>

- Finger resistivity several orders of magnitudes higher than busbar resistivity

![Graph showing measured fill factor for busbarless solar cells with varying front grid resistivity.](image)

- Standard configuration
- Front grid paste: 2.6 mm
- Front grid resistivity: 40 mΩ/cm (6 mΩ), 225 mΩ/cm (225 mΩ)
- Measured fill factor [%]
- Number of adjacent current wires disconnected: 0, 2, 4, 80, 81, 82, 83, 84, 85, 86
Experimental Investigation of Non-Ideal Sensing
Current-Voltage Measurement of Busbarless Solar Cells

- \(I-U\) measurement of busbarless solar cells with different front grid resistivity \(R_{grid}\)

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- Finger resistivity several orders of magnitudes higher than busbar resistivity

Front grid resistivity

- 40 mΩ/cm
- 225 mΩ/cm

Front grid paste

- High-temperature, conventional
- Low-temperature, conventional
- Low-temperature, advanced

Measured efficiency [%]

<table>
<thead>
<tr>
<th>Number of adjacent current wires disconnected</th>
<th>Measured fill factor [%]</th>
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<tbody>
<tr>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>81</td>
</tr>
<tr>
<td>4</td>
<td>82</td>
</tr>
<tr>
<td>8</td>
<td>83</td>
</tr>
<tr>
<td>12</td>
<td>84</td>
</tr>
<tr>
<td>16</td>
<td>85</td>
</tr>
<tr>
<td>20</td>
<td>86</td>
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</table>

Standard configuration

- 2.6 mm

Front grid paste

- High-temperature, conventional
- Low-temperature, conventional
- Low-temperature, advanced

Measured efficiency [%]
I-U measurement of busbarless solar cells with different front grid resistivity $R_{\text{grid}}$

- Disconnection of $I$ wires next to $U$ wires
- Increase in distance $d_{I-U}$ between $I$ and $U$ wires
Experimental Investigation of Non-Ideal Sensing
Current-Voltage Measurement of Busbarless Solar Cells

Possible expectation:
- Reducing number of current contacts leads to decrease in FF and η

Measurement:
- Strong increase in measured FF and η to artificially high values
- Increase the larger, the higher $R_{\text{grid}}$
- No effect on $I_{\text{sc}}$ and $V_{\text{oc}}$
- Position of $I$ and $U$ wires with very strong impact

→ Overestimation of FF and η by non-ideal sensing
Why does FF and $\eta$ depend so severely on distance between $I$ and $U$ wires?
Theoretical Investigation of Non-Ideal Sensing
Analytical Calculations

- Analytical calculations of $I-U$ curves\textsuperscript{[1,2]}
  - Based on two-diode model approach for PERC-like solar cell
  - Series resistance of finger grid not yet considered in two-diode model
  - Current flow perpendicular to fingers only assumed
- Increasing current between current wires
  - Voltage distribution in finger due to finite finger conductivity
  - Iterative calculation of voltage and current distribution

Theoretical Investigation of Non-Ideal Sensing
Calculation of Ideal Sensing

Ideal 4-wire sensing:
- Voltage and current contact at same position
- Contact arrangement similar to module interconnection

Reference configuration

Theoretical Investigation of Non-Ideal Sensing
Calculation of Ideal Sensing

Ideal 4-wire sensing:

- Voltage at voltage contact externally defined by voltage source
- Voltage distribution in finger exemplarily for one voltage close to mpp
- Measured voltage at contact similar, but higher voltage between contacts
Theoretical Investigation of Non-Ideal Sensing
Calculation of Ideal Sensing

Ideal 4-wire sensing:
- Current distribution in finger
  ➞ Lower current density between current contacts
- Measured current density is average over distribution
  ➞ Measured current density reduced

<table>
<thead>
<tr>
<th>Distance from current wire [mm]</th>
<th>Current density [mA/cm²]</th>
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<tbody>
<tr>
<td>0</td>
<td>38.4</td>
</tr>
<tr>
<td>1</td>
<td>38.2</td>
</tr>
<tr>
<td>2</td>
<td>38.0</td>
</tr>
<tr>
<td>3</td>
<td>37.8</td>
</tr>
<tr>
<td>4</td>
<td>37.6</td>
</tr>
<tr>
<td>5</td>
<td>37.6</td>
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\[ R_{\text{grid}} = 225 \text{ m}\Omega/cm \]
\[ N_{\text{wires}} = 30 \]
\[ U_{\text{meas}} = 573.8 \text{ mV} \]

\[ j_{\text{ideal}}^{\text{meas}} = 37.67 \text{ mA/cm}^2 \]
\[ j_{\text{no grid}}^{\text{meas}} = 37.88 \text{ mA/cm}^2 \]
Theoretical Investigation of Non-Ideal Sensing
Calculation of Ideal Sensing

Ideal 4-wire sensing:
- Calculation done for entire voltage range of forward \(I-U\) curve
Theoretical Investigation of Non-Ideal Sensing
Calculation of Ideal Sensing

Ideal 4-wire sensing:

- Calculation done for entire voltage range of forward $I-U$ curve

$\rightarrow$ Grid resistance leads to “distributed series resistance”\([1,2]\)

<table>
<thead>
<tr>
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<th>FF [%] advanced paste</th>
<th>Grid neglected</th>
<th>Ideal sensing</th>
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<tr>
<td>Grid neglected</td>
<td>80.48</td>
<td></td>
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Grid resistance leads to “distributed series resistance”\([1,2]\)

\[ N_{\text{wires}} = 30 \]
\[ R_{\text{grid}} = 225 \text{ m}\Omega/cm \]

Grid neglected
Ideal sensing

Theoretical Investigation of Non-Ideal Sensing
Calculation of Ideal Sensing

Ideal 4-wire sensing:

- Calculation done for entire voltage range of forward I-U curve
- Grid resistance leads to “distributed series resistance” [1,2]

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<td>80.05</td>
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→ For ideal sensing reduction of FF compared to grid-free case

Theoretical Investigation of Non-Ideal Sensing
Calculation of Non-Ideal Sensing

Non-ideal 4-wire sensing:
- Voltage and current contact at different positions
Theoretical Investigation of Non-Ideal Sensing
Calculation of Non-Ideal Sensing

Non-ideal 4-wire sensing:

- Voltage and current contact at different positions
- Voltage distribution different from ideal 4-wire sensing
- Voltage in finger locally reduced compared to ideal sensing
Theoretical Investigation of Non-Ideal Sensing
Calculation of Non-Ideal Sensing

Non-ideal 4-wire sensing:
- Current density distribution different from ideal 4-wire sensing
- Current density in finger locally increased

![Graph showing current density distribution comparison between ideal and non-ideal 4-wire sensing. The graph plots current density [mA/cm$^2$] against distance from current wire [mm]. Ideal voltage sensing at 37.8 mV and non-ideal voltage sensing at 573.8 mV are indicated.]

$R_{grid} = 225\, m\Omega/cm$
$N_{wires} = 30$
$U_{meas} = 573.8\, mV$
Theoretical Investigation of Non-Ideal Sensing
Calculation of Non-Ideal Sensing

Non-ideal 4-wire sensing:

- Current density distribution different from ideal 4-wire sensing
  → Current density in finger locally increased

- Measured current density is average over distribution
  → Measured current density overrated compared to ideal 4-wire sensing

![Graph showing current density vs. distance from current wire]

- $R_{\text{grid}} = 225 \, \text{m}\Omega/cm$
- $N_{\text{wires}} = 30$
- $U_{\text{meas}} = 573.8 \, \text{mV}$

Current density distribution

$\mathbf{j}_{\text{meas}} = 37.98 \, \text{mA/cm}^2$

$\mathbf{j}_{\text{ideal}} = 37.67 \, \text{mA/cm}^2$

Distance from current wire [mm]
Theoretical Investigation of Non-Ideal Sensing
Calculation of Non-Ideal Sensing

Non-ideal 4-wire sensing:

- Calculation done for entire voltage range of forward I-U curve
Theoretical Investigation of Non-Ideal Sensing
Calculation of Non-Ideal Sensing

Non-ideal 4-wire sensing:
- Calculation done for entire voltage range of forward $I-U$ curve

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<td>80.69</td>
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<td>0.64</td>
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Grid neglected
Ideal sensing                     
Non-ideal sensing
$N_{\text{wires}} = 30$
$R_{\text{grid}} = 225 \, \text{m\Omega/cm}$

Current density [mA/cm$^2$]
Voltage [mV]

$N_{\text{wires}} = 30$
$R_{\text{grid}} = 225 \, \text{m\Omega/cm}$
Theoretical Investigation of Non-Ideal Sensing
Calculation of Non-Ideal Sensing

Non-ideal 4-wire sensing:

- Calculation done for entire voltage range of forward I-U curve

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<td>Non-ideal sensing</td>
<td>80.69</td>
<td>80.52</td>
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<tr>
<td>FF overestimation</td>
<td>0.64</td>
<td>0.11</td>
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Theoretical Investigation of Non-Ideal Sensing
Calculation of Non-Ideal Sensing

Non-ideal 4-wire sensing:
- Calculation done for entire voltage range of forward I-U curve

<table>
<thead>
<tr>
<th></th>
<th>η [%] advanced paste</th>
<th>η [%] conventional paste</th>
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<tr>
<td>Ideal sensing</td>
<td>21.62</td>
<td>21.72</td>
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<tr>
<td>Non-ideal sensing</td>
<td>21.79</td>
<td>21.75</td>
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<tr>
<td>η overestimation</td>
<td>0.17</td>
<td>0.03</td>
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Current density [mA/cm$^2$]
Voltage [mV]
Theoretical Investigation of Non-Ideal Sensing

Calculation of Non-Ideal Sensing

Non-ideal 4-wire sensing:

- Calculation done for entire voltage range of forward I-U curve

For conventional metallization:
Non-ideal sensing uncritical

For advanced metallization:
Significant overestimation of FF and η

- Overestimation increases Cell-to-Module (CTM) loss
- Included in uncertainty budget as systematic uncertainty of FF, η and $P_{mpp}$
How can the measurement unit be improved?
Theoretical Investigation of Non-Ideal Sensing Approaches for Improving Contacting Unit

(1) Approaching voltage to current wire

- Calculation of ΔFF for variation of voltage sense position
Theoretical Investigation of Non-Ideal Sensing Approaches for Improving Contacting Unit

(1) Approaching voltage to current wire
- Calculation of ΔFF for variation of voltage sense position
Theoretical Investigation of Non-Ideal Sensing Approaches for Improving Contacting Unit

(1) Approaching voltage to current wire

- ΔFF decreases with square of distance from middle position

![Graph showing the relationship between voltage sense position and difference in non-ideal to ideal FF percentage.](image)
Theoretical Investigation of Non-Ideal Sensing Approaches for Improving Contacting Unit

(1) Approaching voltage to current wire

- ΔFF decreases with square of distance from middle position

![Graph showing the relationship between voltage sense position and difference non-ideal to ideal FF.](image)

- Theoretical Investigation of Non-Ideal Sensing Approaches for Improving Contacting Unit

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Theoretical Investigation of Non-Ideal Sensing Approaches for Improving Contacting Unit

(1) Approaching voltage to current wire

- ΔFF decreases with square of distance from middle position

![Graph showing the relationship between voltage sense position, grid resistance, and difference in FF.](image-url)
Theoretical Investigation of Non-Ideal Sensing Approaches for Improving Contacting Unit

(1) Approaching voltage to current wire

- ΔFF decreases with square of distance from middle position
- ΔFF increases for increase of front grid resistivity

![Graph showing the difference between non-ideal and ideal FF as a function of grid resistivity and voltage sense position.](image-url)
Theoretical Investigation of Non-Ideal Sensing Approaches for Improving Contacting Unit

(1) Approaching voltage to current wire

- $\Delta FF$ decreases with square of distance from middle position
- $\Delta FF$ increases for increase of front grid resistivity

Improvement of measurement unit

- Strong reduction of distance between $I$ and $U$ wires necessary
- $\Delta FF > 0.2\%_{\text{rel}}$ for minimal distance (= wire diameter)

$\rightarrow$ Approach not effective
Theoretical Investigation of Non-Ideal Sensing Approaches for Improving Contacting Unit

(2) Approaching of current wires

- Calculation of difference $\Delta FF$ between ideal and non-ideal voltage sensing
Theoretical Investigation of Non-Ideal Sensing Approaches for Improving Contacting Unit

(2) Approaching of current wires

- Calculation of difference $\Delta FF$ between ideal and non-ideal voltage sensing

![Graph showing the relationship between grid resistance and difference in FF percentage]
Theoretical Investigation of Non-Ideal Sensing Approaches for Improving Contacting Unit

(2) Approaching of current wires

- $\Delta FF$ decreases strongly with distance between current wires

![Graph showing the difference non-ideal to ideal FF as a function of the distance between current wires.](image-url)
Theoretical Investigation of Non-Ideal Sensing Approaches for Improving Contacting Unit

(2) Approaching of current wires
- $\Delta FF$ decreases strongly with distance between current wires
Theoretical Investigation of Non-Ideal Sensing Approaches for Improving Contacting Unit

(2) Approaching of current wires

- \( \Delta \text{FF} \) decreases strongly with distance between current wires
- \( \Delta \text{FF} \) increases for increase of front grid resistivity
Theoretical Investigation of Non-Ideal Sensing Approaches for Improving Contacting Unit

(2) Approaching of current wires
- $\Delta FF$ decreases strongly with distance between current wires
- $\Delta FF$ increases for increase of front grid resistivity

Improvement of measurement unit
- Already small reduction of distance with significant effect
- $\Delta FF < 0.1\%_{\text{rel}}$ for moderate distance of 2 mm

Approach promising, but implies asymmetric arrangement of wires
Summary

- Accurate measurement of busbarless solar cells in 4-wire connection challenging
  - Resistivity of fingers much higher than resistivity of busbars
- Investigation of influence of distance between $U$ and $I$ wires by experiments and calculations
  - Voltage distribution in front finger can affect measured fill factor and efficiency
  - Conventional metallization: Non-ideal sensing uncritical
  - Advanced metallization: Significant overrating of FF and $\eta$ for non-ideal sensing
- Approaches for improvement of contacting unit
  - Reduction of distance between voltage and current wires not effective
  - Reduction of distance between current wires promising

Same principle applies for contacting of rear grid of busbarless bifacial solar cells
Thank you very much for your attention!

Fraunhofer Institute for Solar Energy Systems ISE

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