ACCURATE MEASUREMENT OF BUSBARLESS SILICON SOLAR CELLS

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Fraunhofer Institute for Solar Energy Systems ISE

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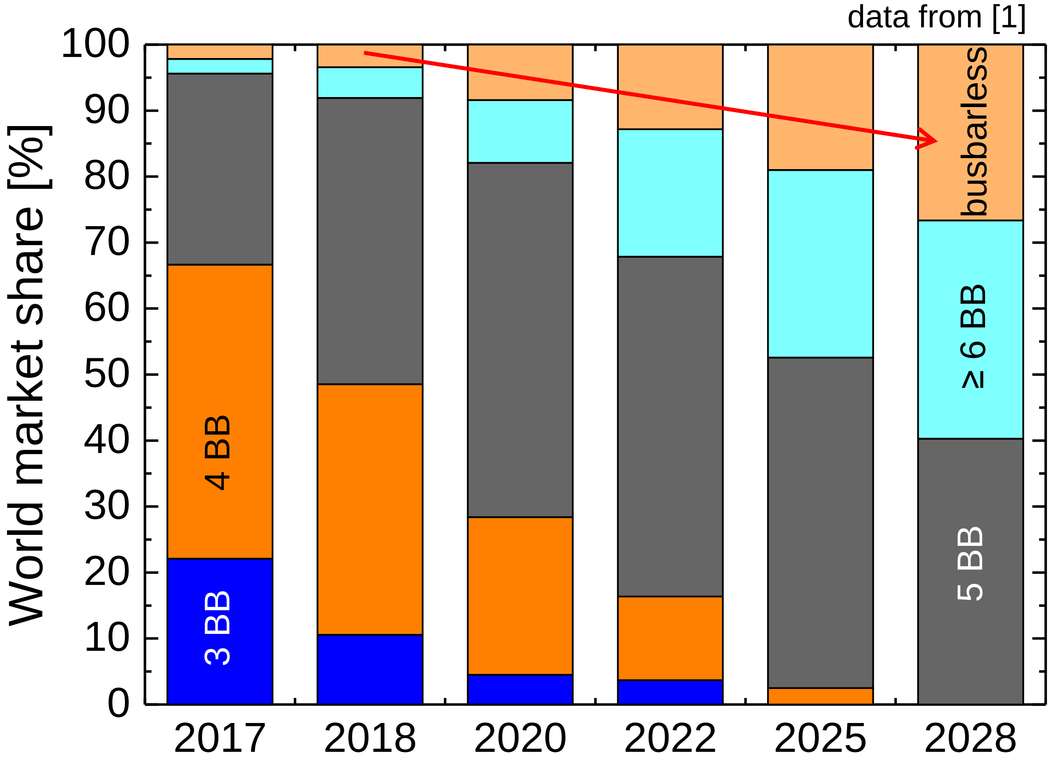
Measurement of Busbarless Silicon Solar Cells
Motivation

- 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



[1] ITRPV, Ninth Edition (2018).
[2] G. Hahn, Patent, WO2014037382A1 (2013).
[3] N. Bassi, Proc. 29th EUPVSEC, 1180 (2014).
[4] S. Dauwe, 6th Workshop on Metallization (2016).
[5] S. Raj, IEEE 7th WCPEC, 3294 (2018).
[6] M. Osborne, Press release, PV-Tech, May 30th (2018).
[7] IEC standard 60904-1.

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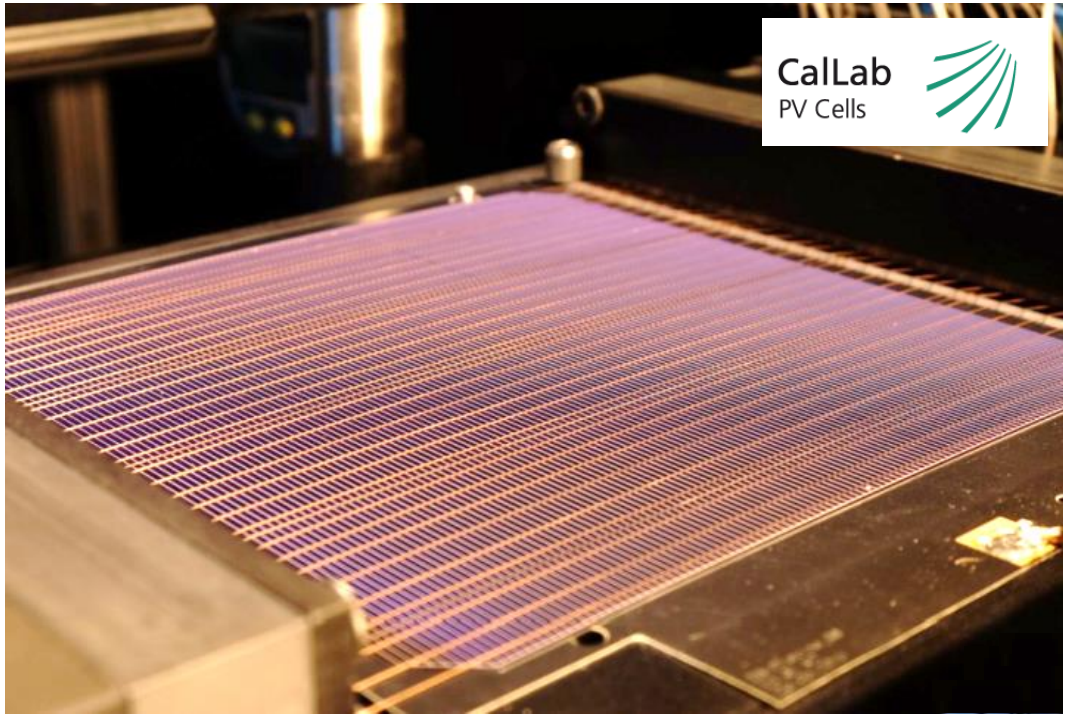
Measurement of Busbarless Silicon Solar Cells
Motivation

- At CalLab PV Cells measurement unit constructed based on Pasan's Grid$^{\text{TOUCH}}$ 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

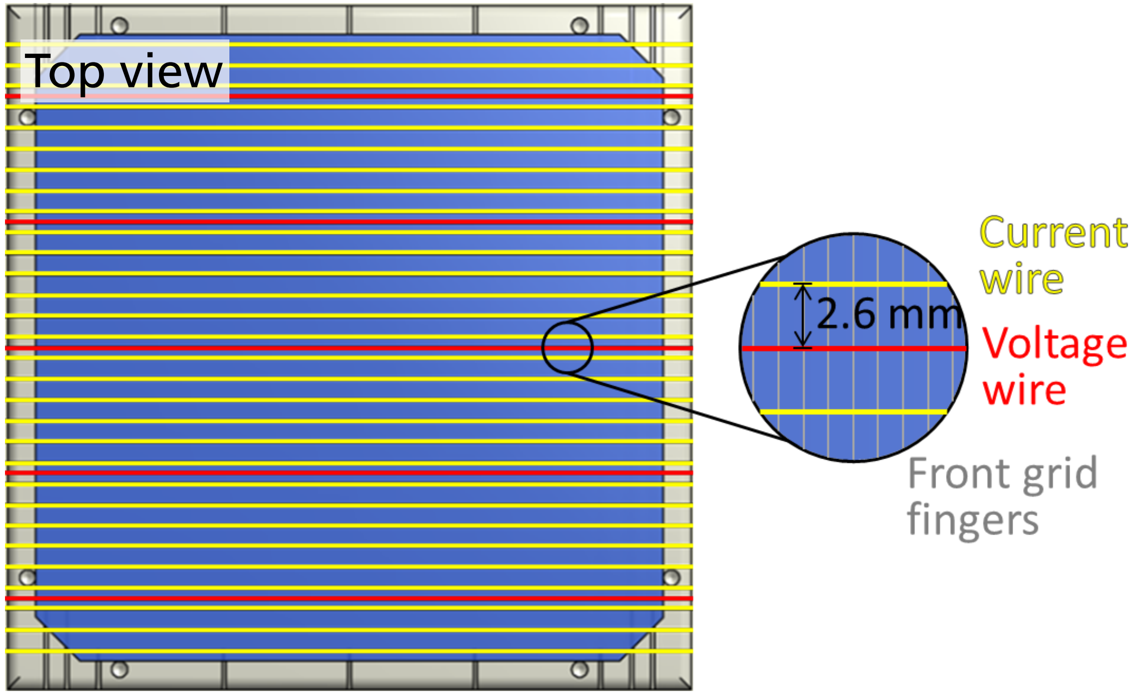


[1] N. Bassi, Proc. 29th EUPVSEC, 1180 (2014).

Measurement of Busbarless Silicon Solar Cells
Motivation

- Separate, electrically isolated current (*I*) and voltage (*U*) wires
  - **Ideal 4-wire sensing:** Distance $d_{\mathrm{ItoU}} = 0$ between *I* and *U* wires
  - **Sensing in reality:** Distance $d_{\mathrm{ItoU}} \neq 0$ between *I* and *U* wires due to constructional restrictions

→ **Aim of this work:** Evaluation of "non-ideal" distance between *I* and *U* wires

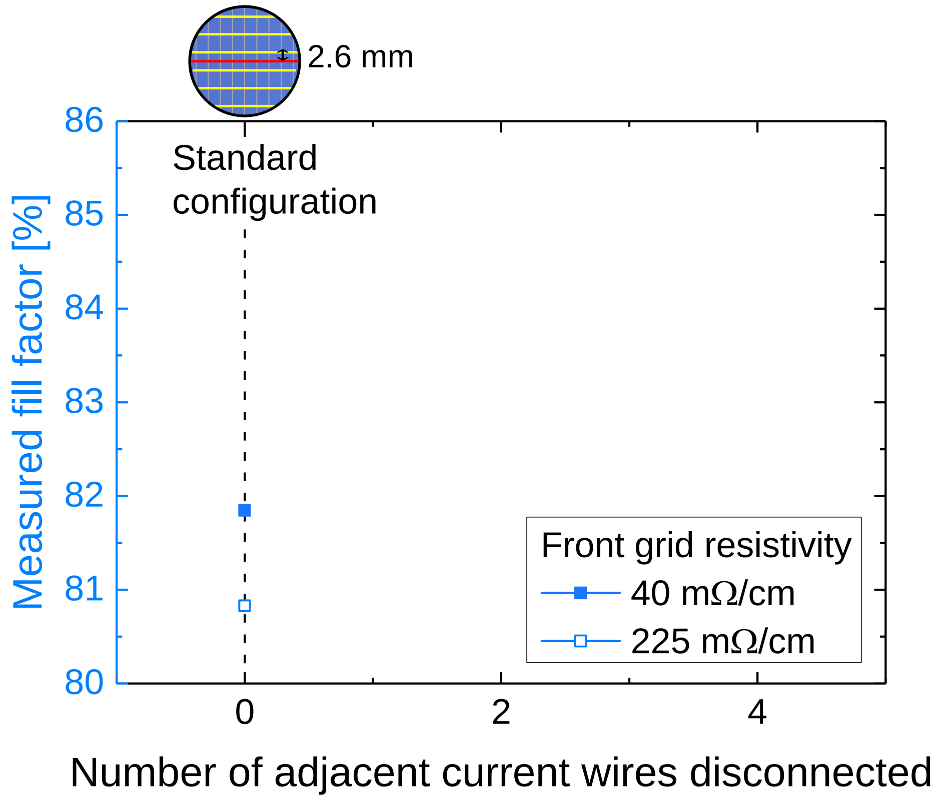


Experimental Investigation of Non-Ideal Sensing
Current-Voltage Measurement of Busbarless Solar Cells

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

Front grid paste	R_{grid} [mΩ/cm]
High-temperature, conventional	6
Low-temperature, conventional	20-40
Low-temperature, advanced	>200

- Finger resistivity several orders of magnitudes higher than busbar resistivity



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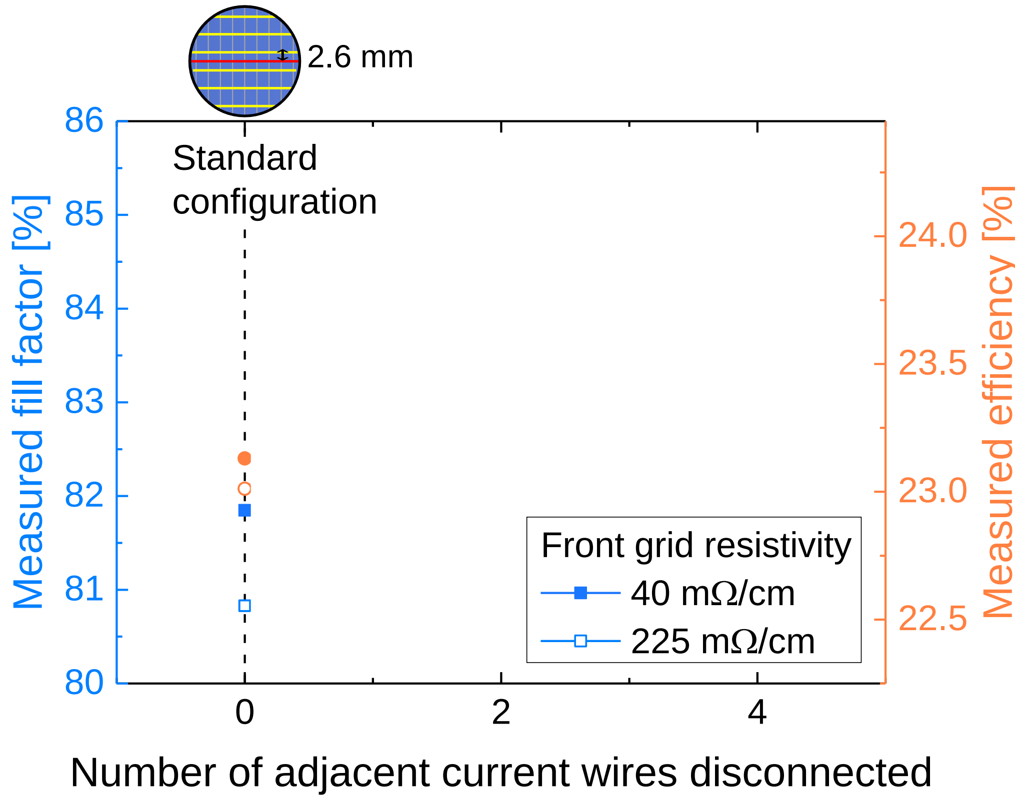
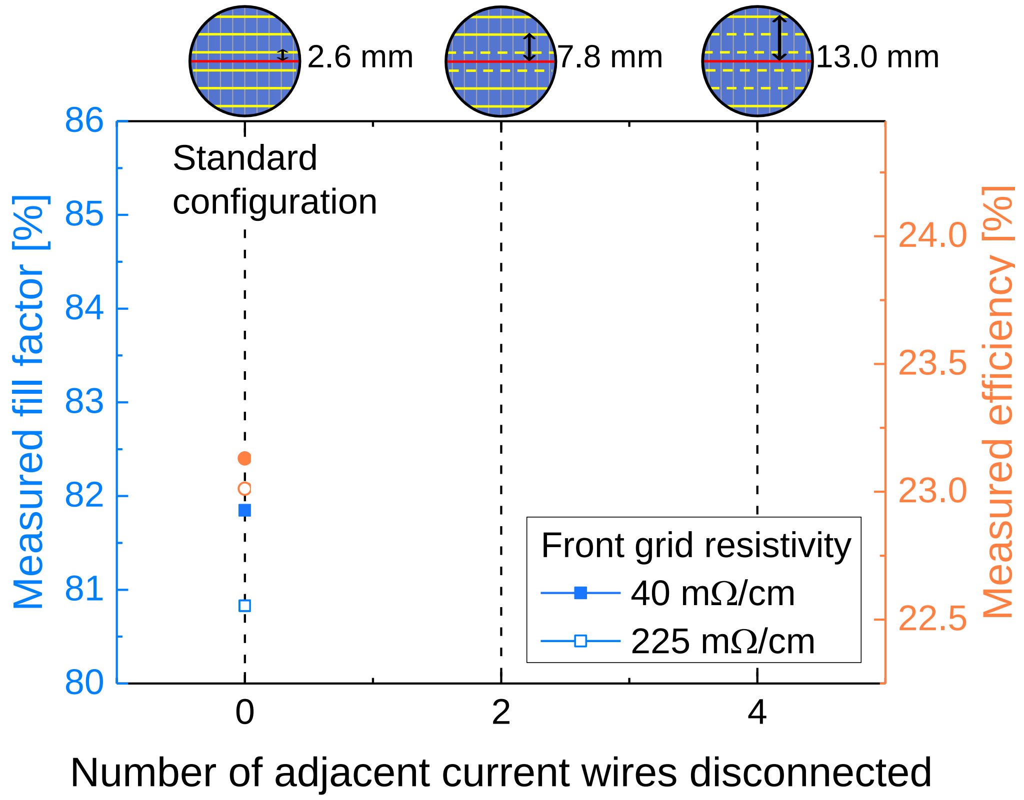


Experimental Investigation of Non-Ideal Sensing

Current-Voltage Measurement of Busbarless Solar Cells

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

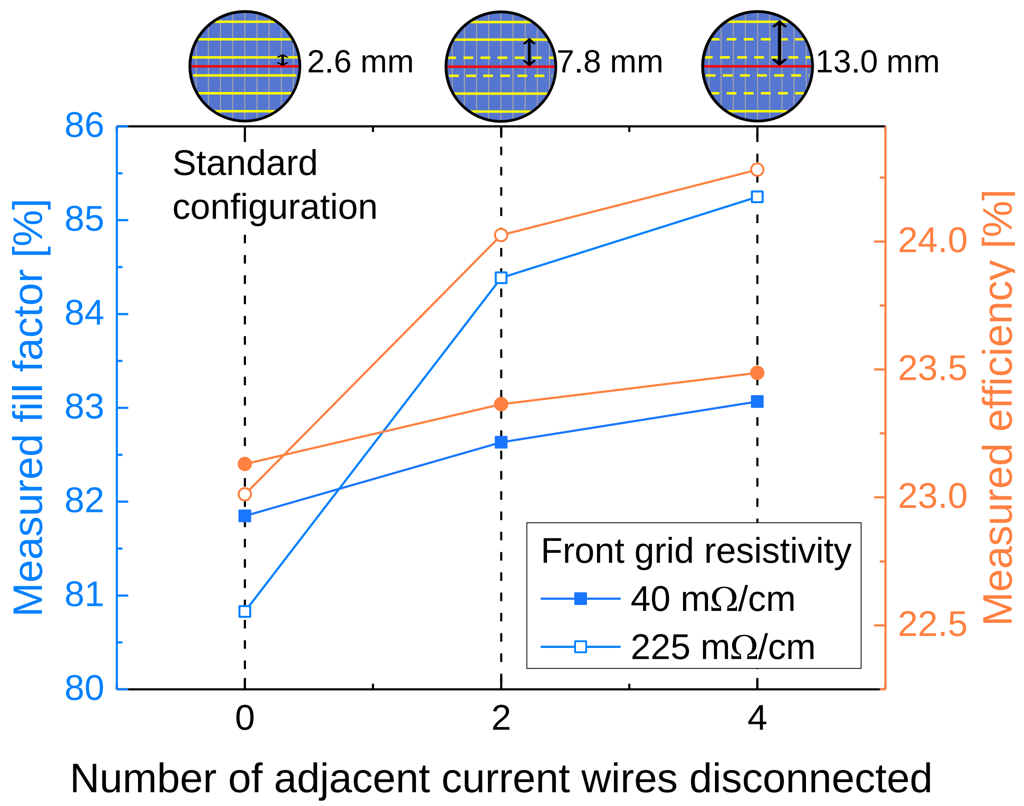
- Reducing number of current contacts leads to decrease in FF and η

Measurement:

- Strong increase in measured FF and η to artificially high values
- Increase the larger, the higher R_{grid}
- No effect on I_{sc} and V_{oc}

→ Position of *I* and *U* wires with very strong impact

→ **Overestimation of FF and η by non-ideal sensing**



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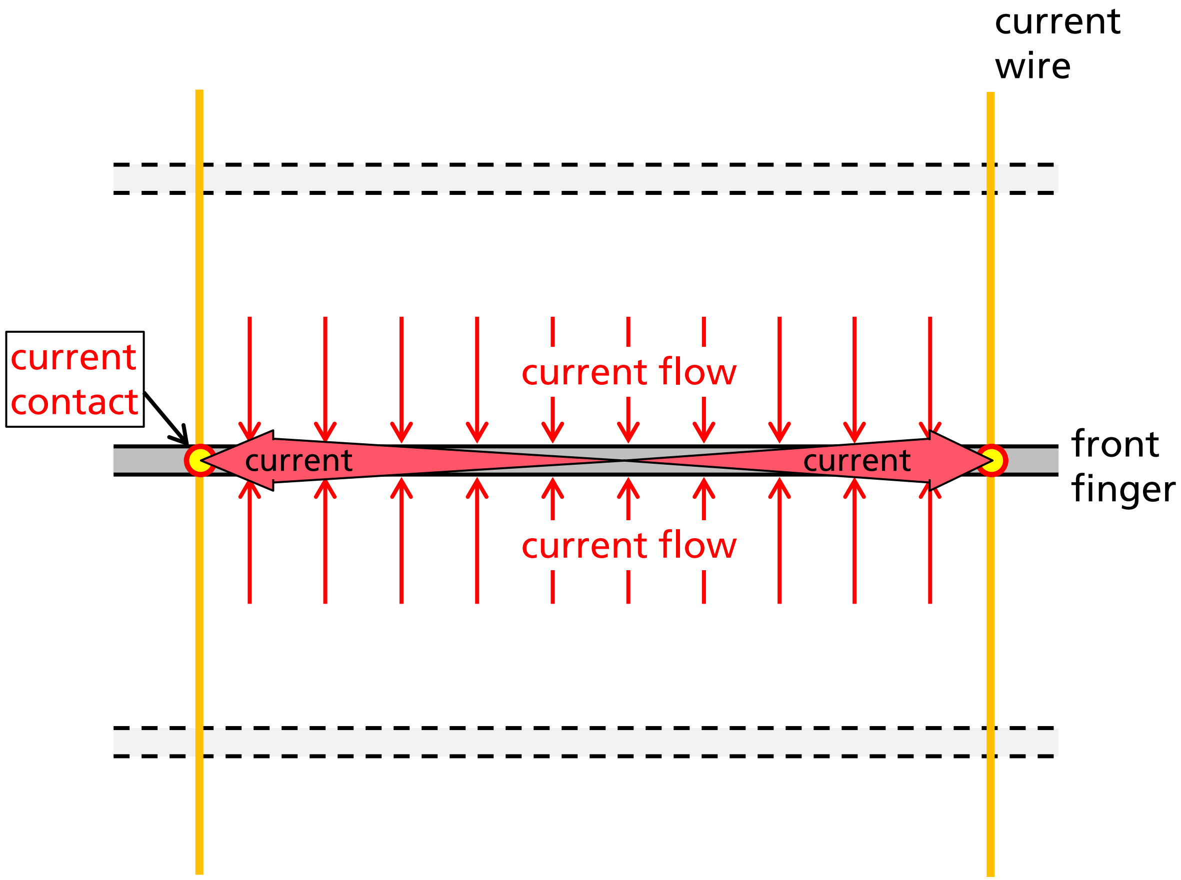
Why does FF and η depend so severely on distance between *I* and *U* wires?

Theoretical Investigation of Non-Ideal Sensing
Analytical Calculations

- Analytical calculations of *I-U* curves [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



[1] J. Hohl-Ebinger, Proc. 23rd EUPVSEC, 2012 (2008).
[2] C. Kruse, IEEE JPV 7.3, 747 (2017).

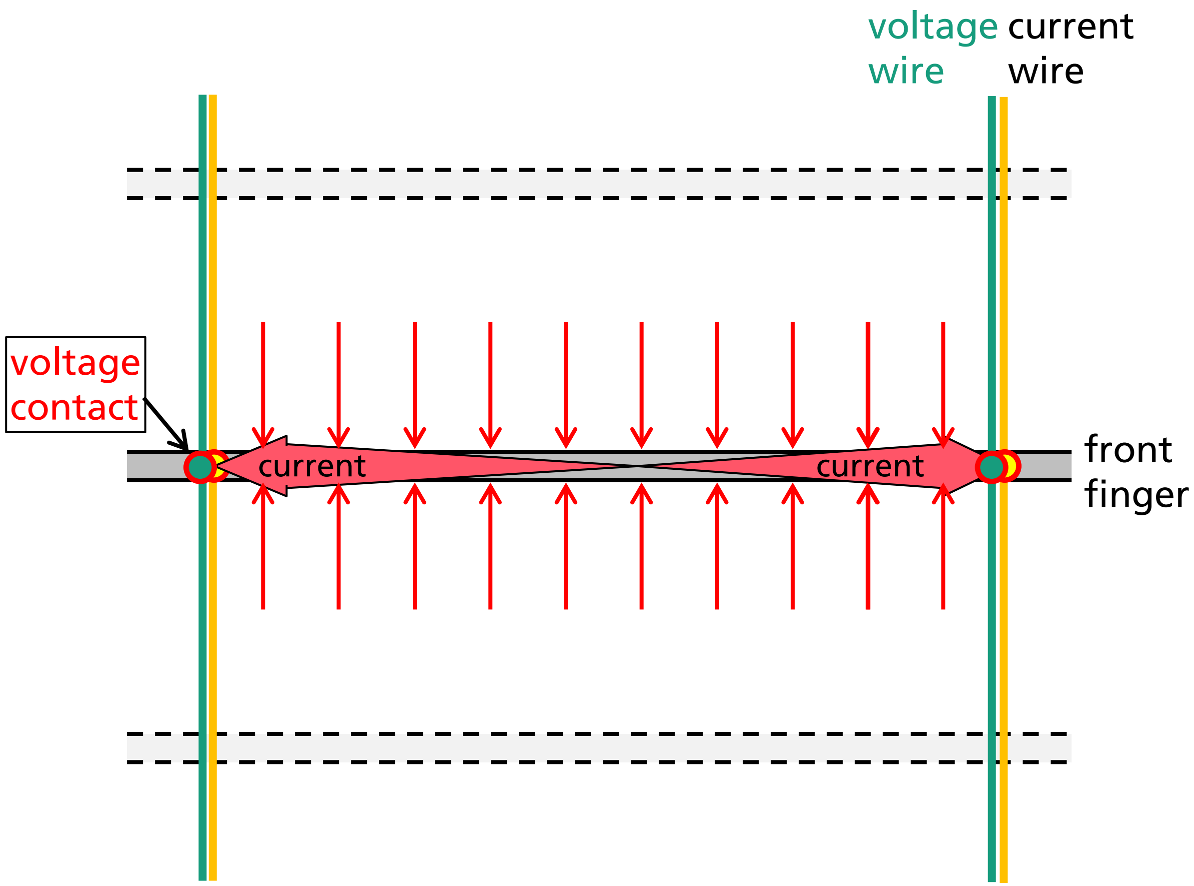
Theoretical Investigation of Non-Ideal Sensing

Calculation of Ideal Sensing

Ideal 4-wire sensing:

- Voltage and current contact at same position
- Contact arrangement similar to module interconnection

→ Reference configuration



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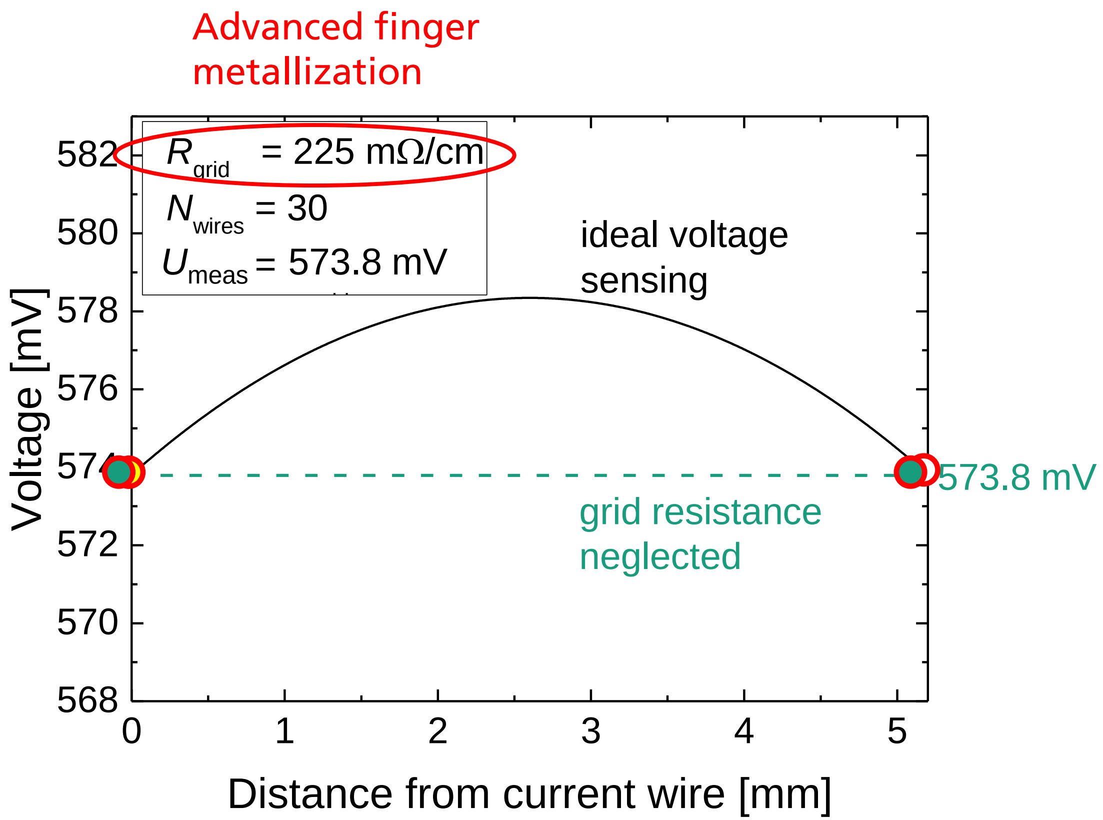
Theoretical Investigation of Non-Ideal Sensing

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

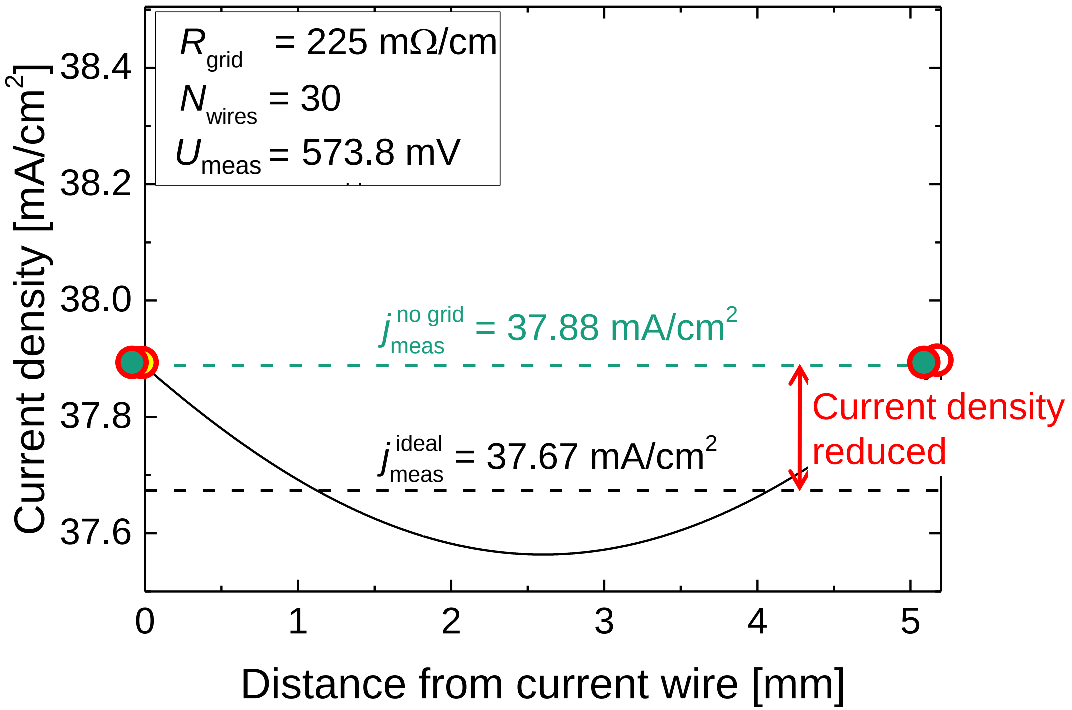
Ideal 4-wire sensing:

- Current distribution in finger

→ Lower current density between current contacts

- Measured current density is average over distribution

→ Measured current density reduced

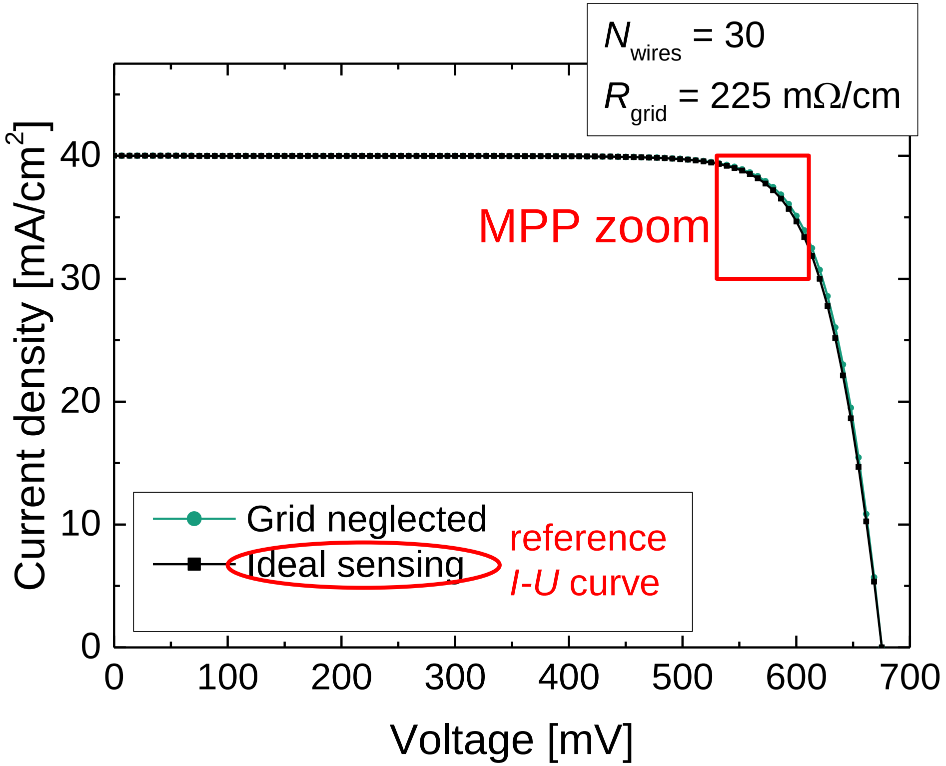


Theoretical Investigation of Non-Ideal Sensing

Calculation of Ideal Sensing

Ideal 4-wire sensing:

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



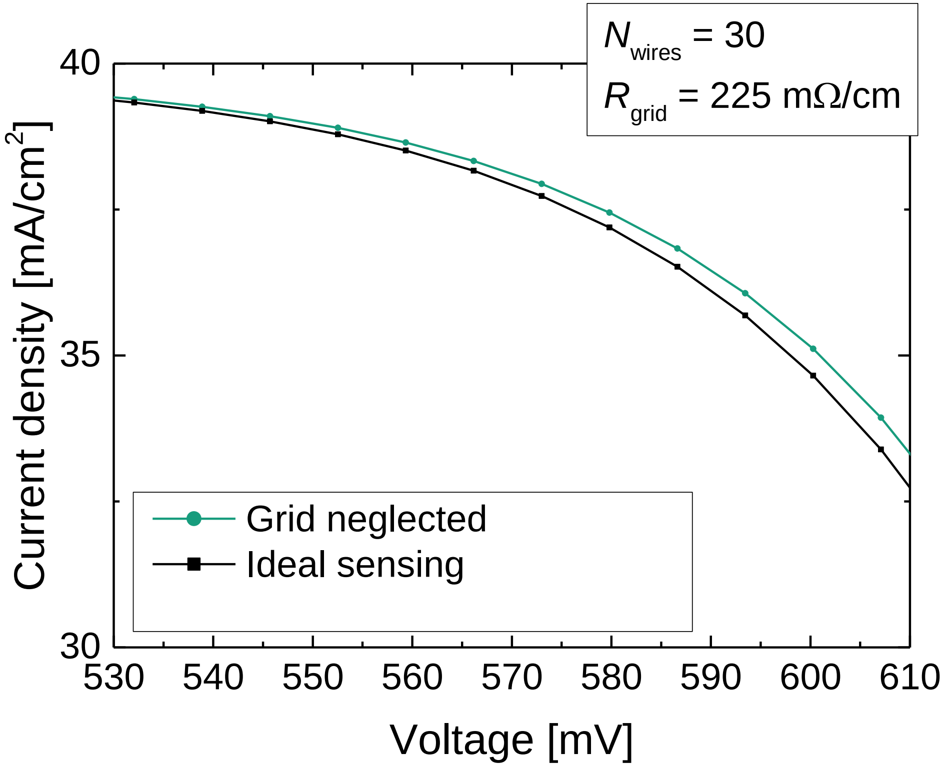
Theoretical Investigation of Non-Ideal Sensing
Calculation of Ideal Sensing

Ideal 4-wire sensing:

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

→ Grid resistance leads to *"distributed series resistance"* [1,2]

	FF [%] advanced paste
Grid neglected	80.48
Ideal sensing	80.05



[1] B. Fischer, Proc. 16th EUPVSEC, 1365 (2000).
[2] J. Greulich, Proc. 24th EUPVSEC, 2065 (2009).

Theoretical Investigation of Non-Ideal Sensing
Calculation of Ideal Sensing

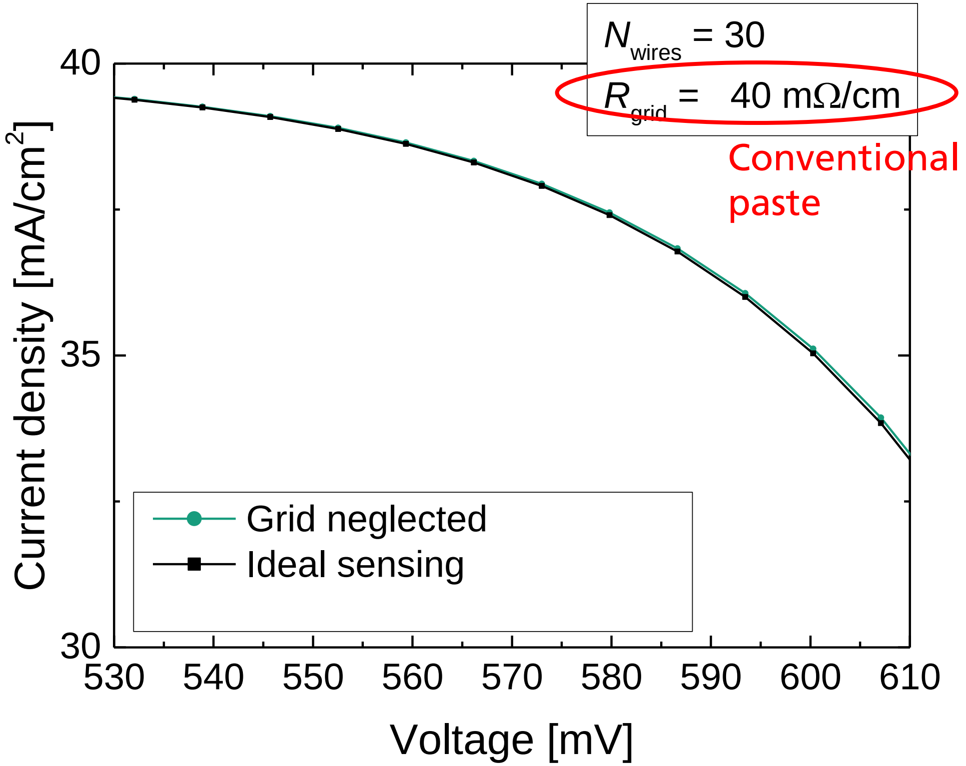
Ideal 4-wire sensing:

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

→ Grid resistance leads to *"distributed series resistance"* [1,2]

	FF [%] advanced paste	FF [%] conventional paste
Grid neglected	80.48	80.48
Ideal sensing	80.05	80.41

→ For ideal sensing reduction of FF compared to grid-free case



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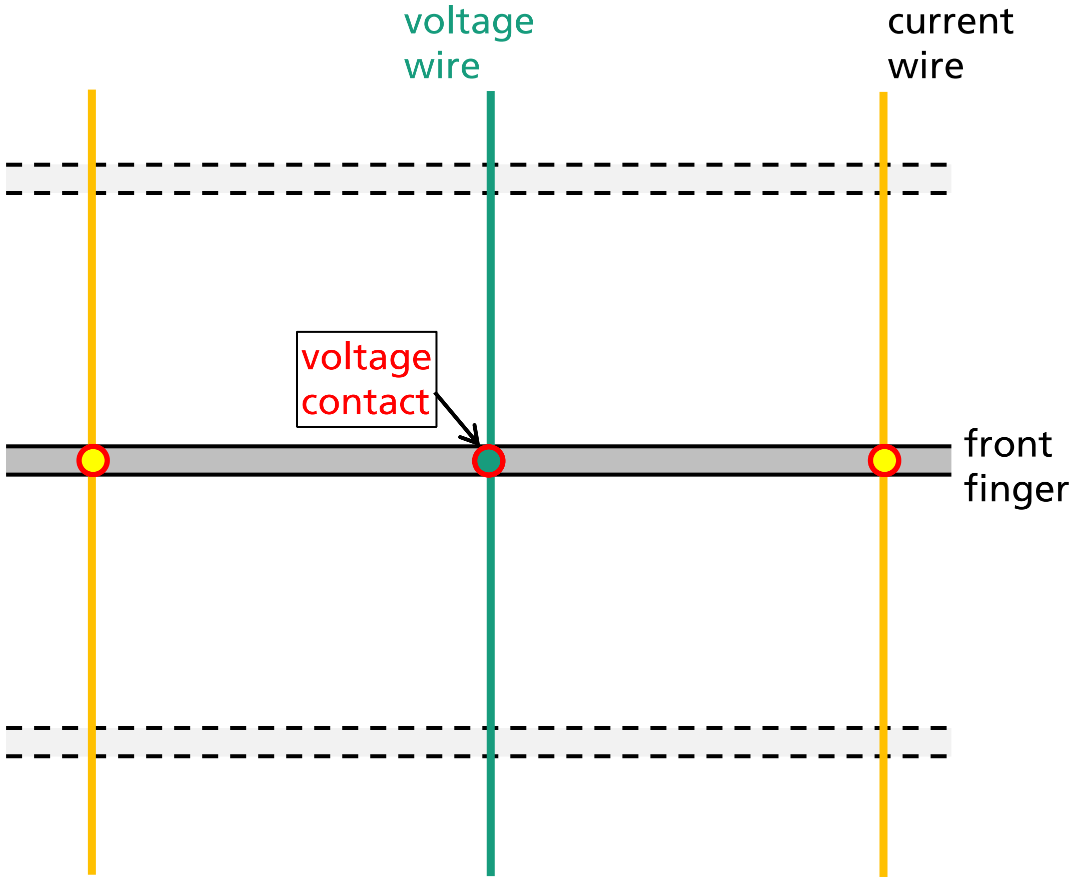
Theoretical Investigation of Non-Ideal Sensing
Calculation of Non-Ideal Sensing

Non-ideal 4-wire sensing:

- Voltage and current contact at different positions



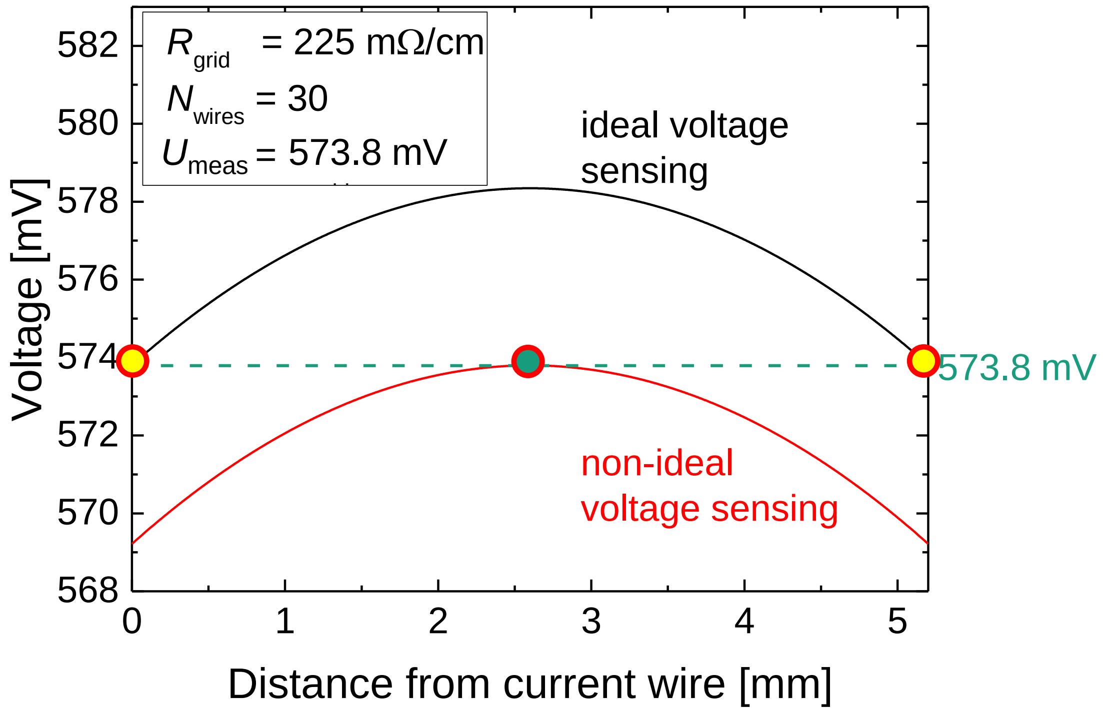
Theoretical Investigation of Non-Ideal Sensing

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



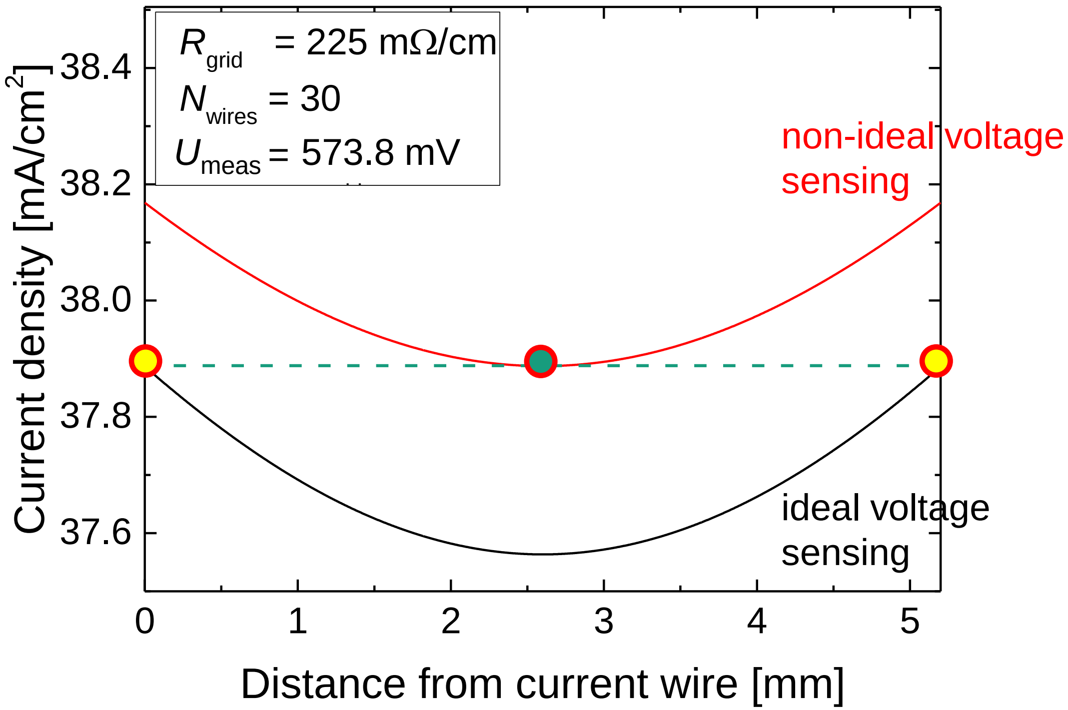
Theoretical Investigation of Non-Ideal Sensing

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



Theoretical Investigation of Non-Ideal Sensing

Calculation of Non-Ideal Sensing

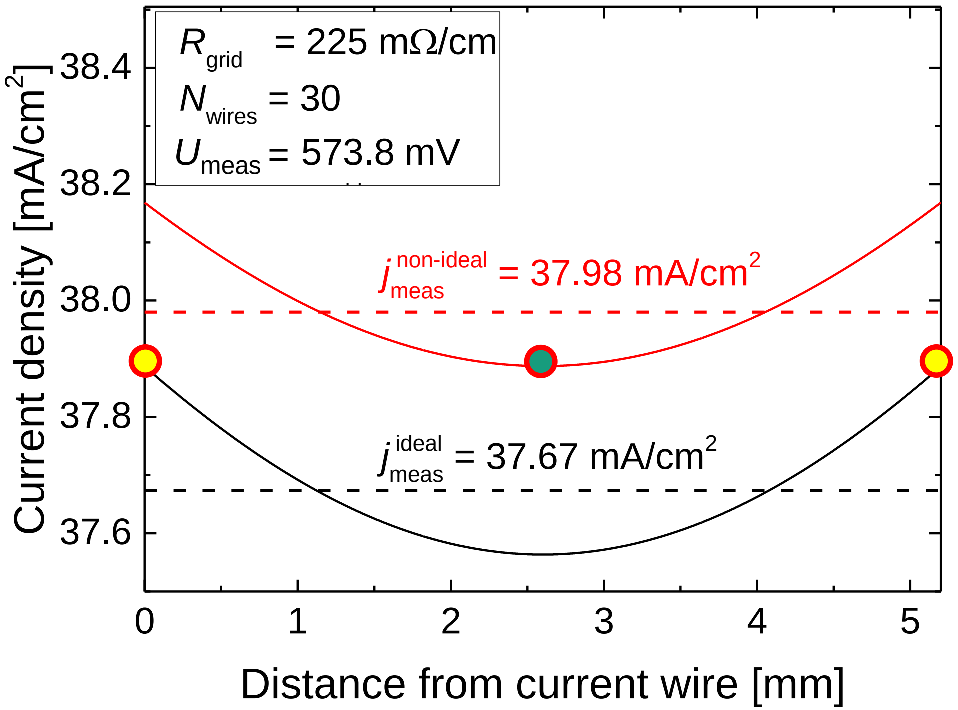
Non-ideal 4-wire sensing:

- Current density distribution different from ideal 4-wire sensing

→ Current density in finger locally increased

- Measured current density is average over distribution

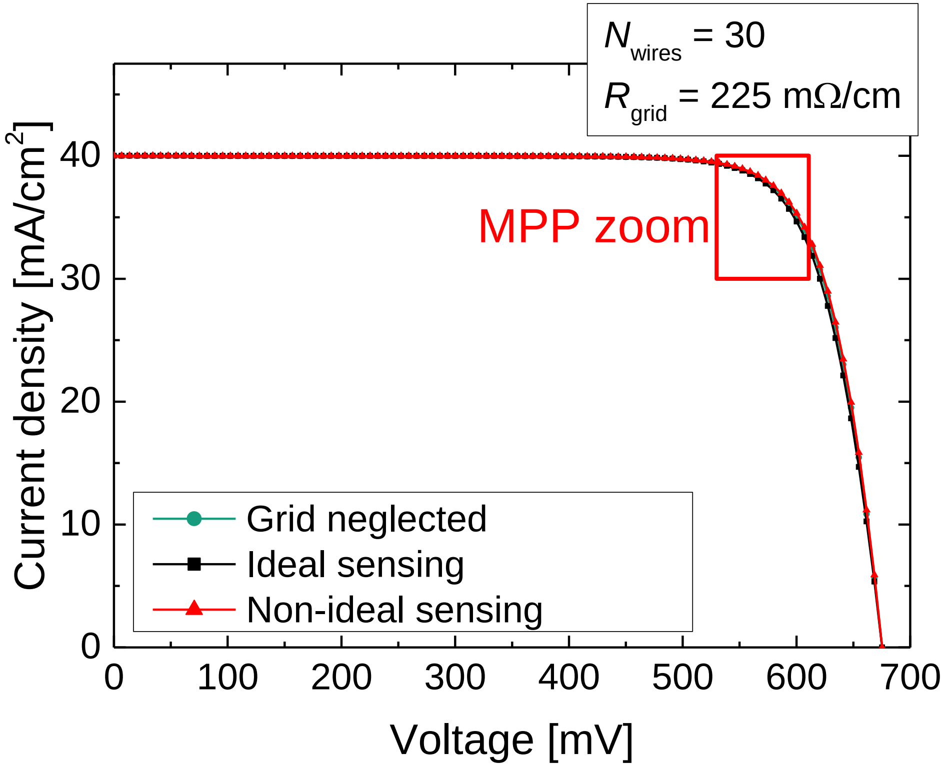
→ Measured current density overrated compared to ideal 4-wire sensing



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

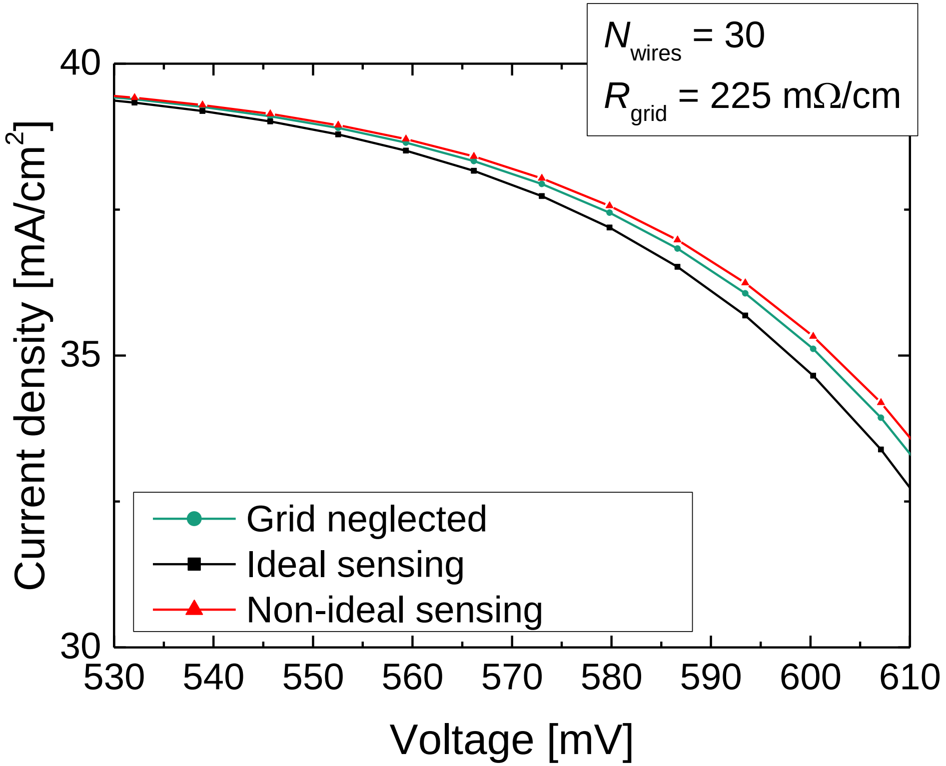


Theoretical Investigation of Non-Ideal Sensing
Calculation of Non-Ideal Sensing

Non-ideal 4-wire sensing:

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

	FF [%] advanced paste
Ideal sensing	80.05
Non-ideal sensing	80.69
FF overestimation	0.64



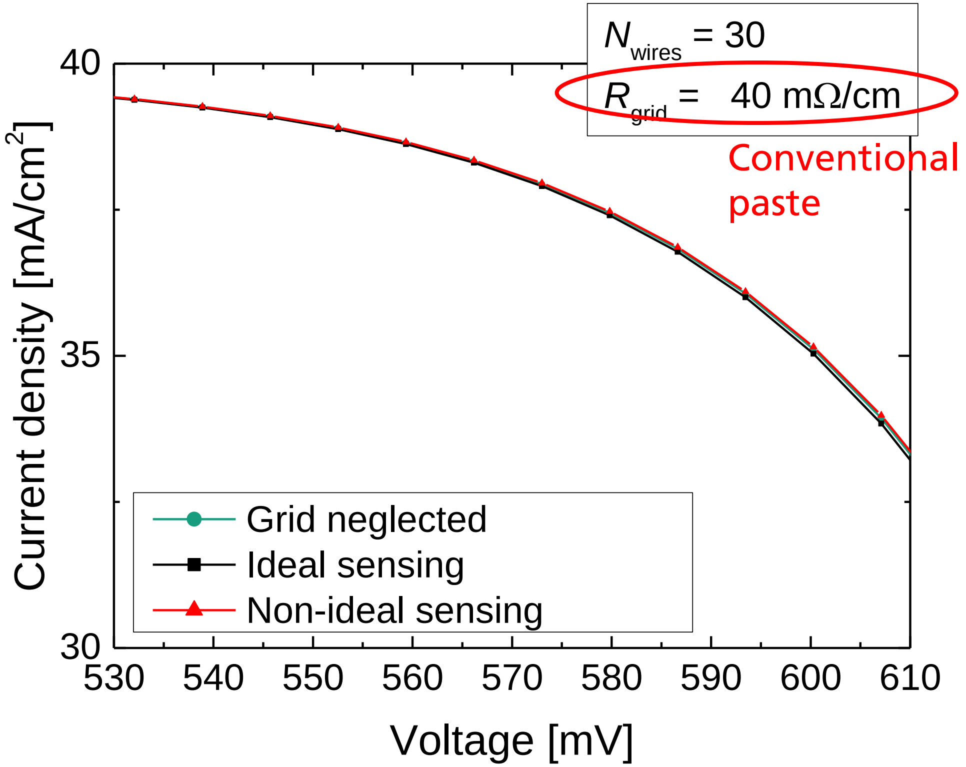
Theoretical Investigation of Non-Ideal Sensing

Calculation of Non-Ideal Sensing

Non-ideal 4-wire sensing:

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

	FF [%] advanced paste	FF [%] conventional paste
Ideal sensing	80.05	80.41
Non-ideal sensing	80.69	80.52
FF overestimation	0.64	0.11



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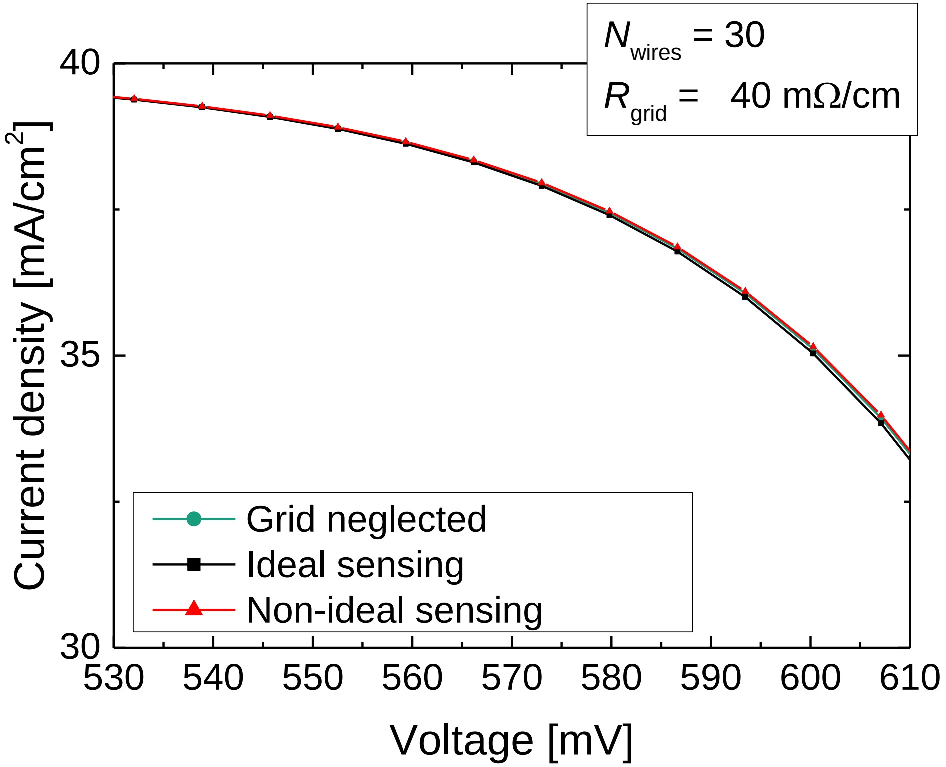
Theoretical Investigation of Non-Ideal Sensing

Calculation of Non-Ideal Sensing

Non-ideal 4-wire sensing:

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

	η [%] advanced paste	η [%] conventional paste
Ideal sensing	21.62	21.72
Non-ideal sensing	21.79	21.75
η overestimation	0.17	0.03



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

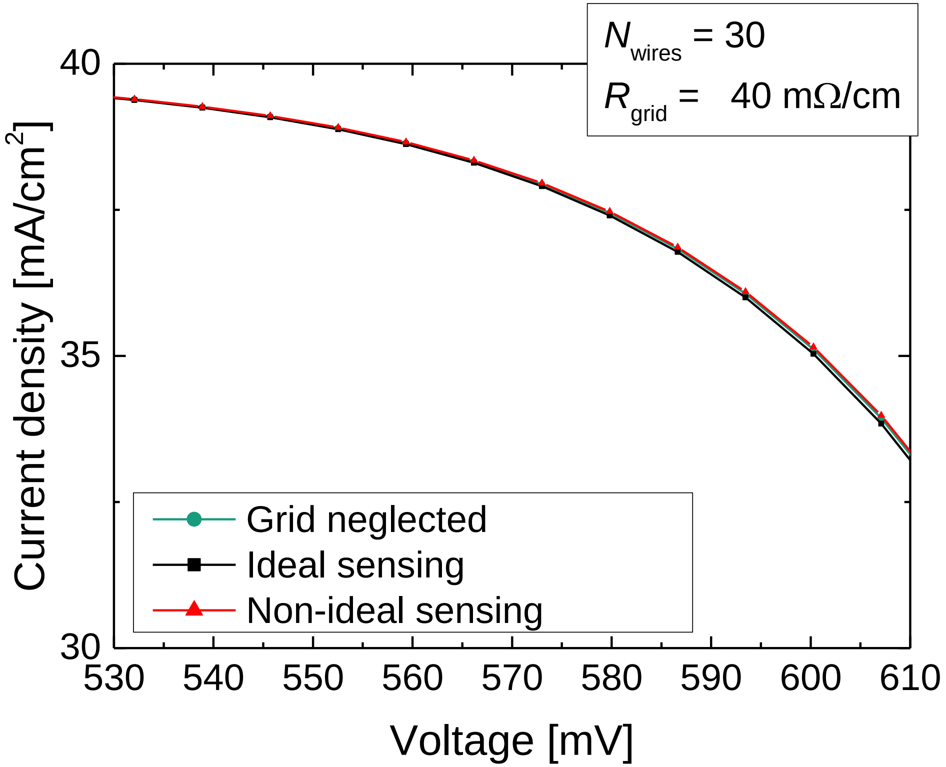
Non-ideal 4-wire sensing:

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

→ **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}



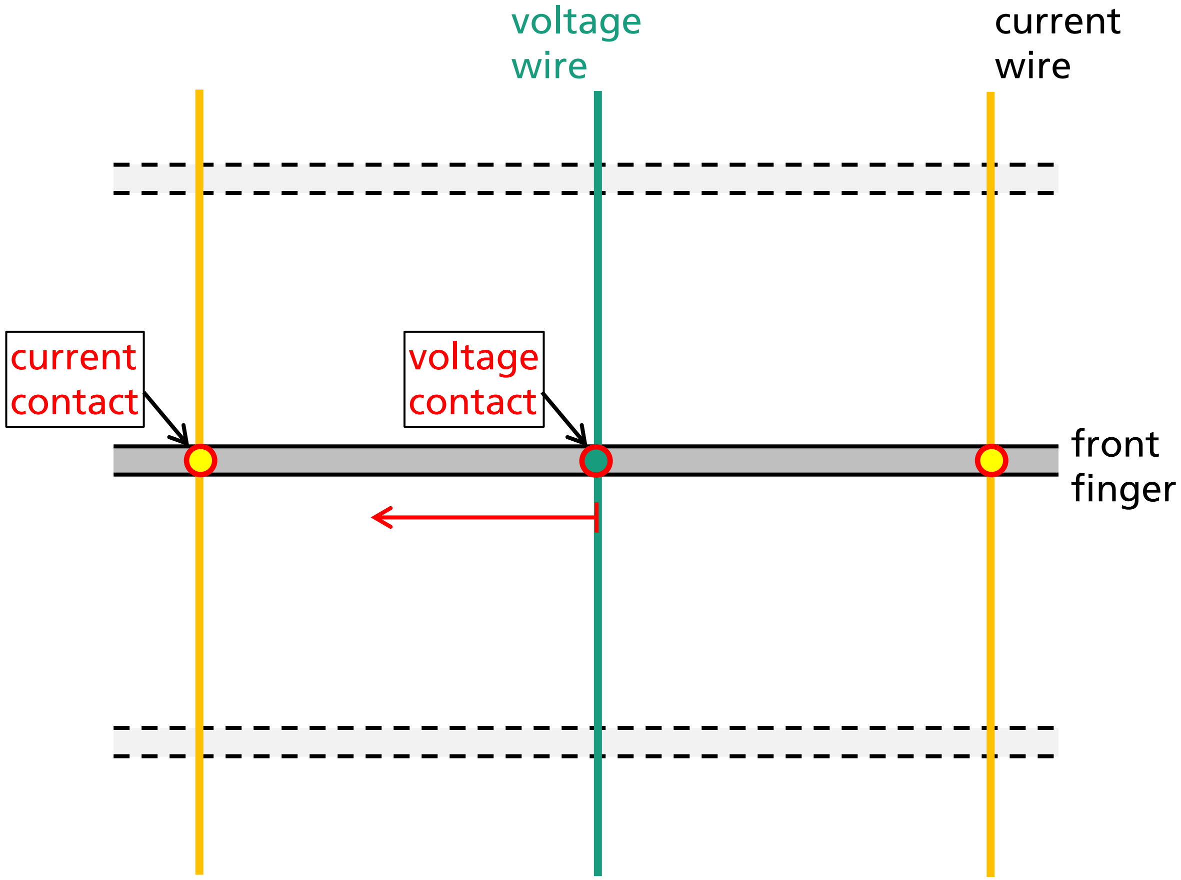
How can the measurement unit be improved?

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



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Approaches for Improving Contacting Unit

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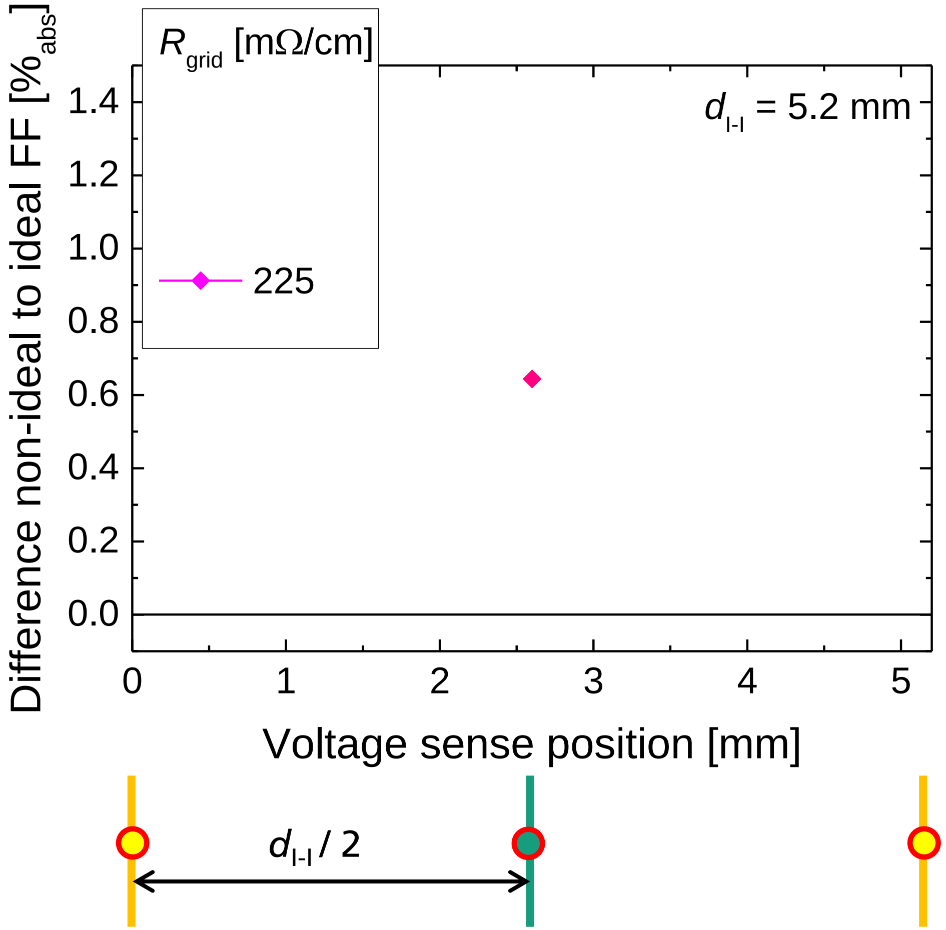
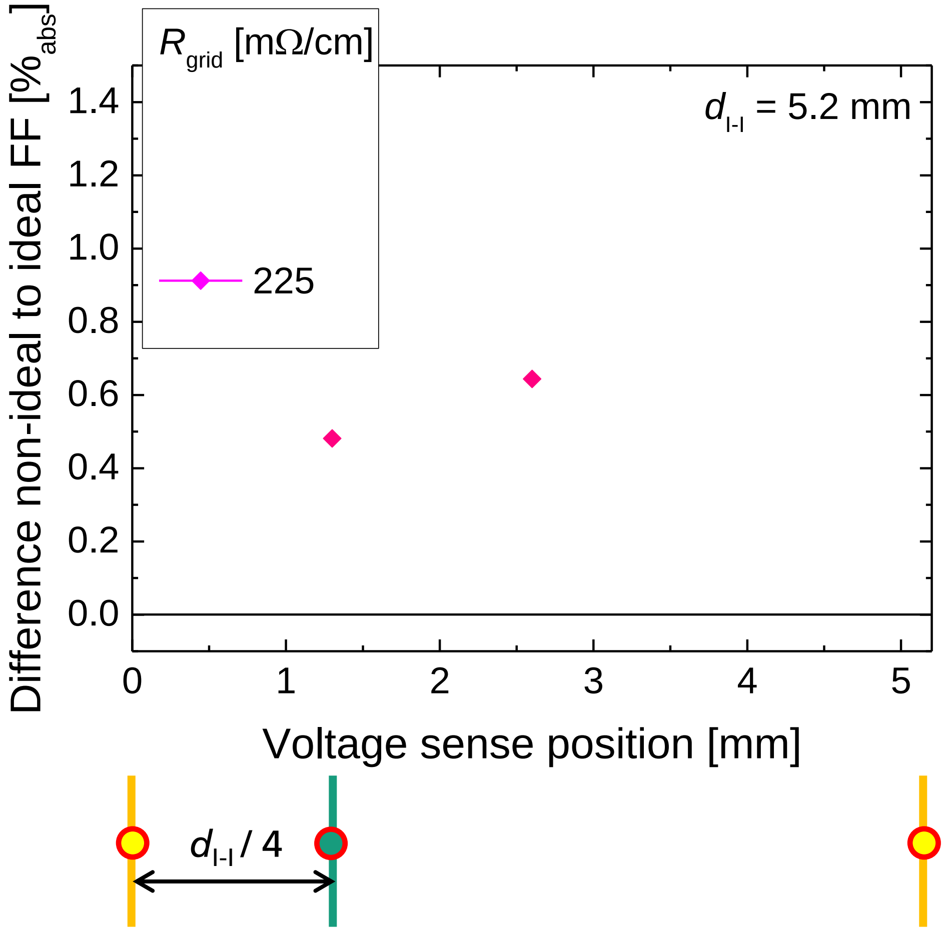


Theoretical Investigation of Non-Ideal Sensing

Approaches for Improving Contacting Unit

(1) Approaching voltage to current wire

- ΔFF decreases with square of distance from middle position



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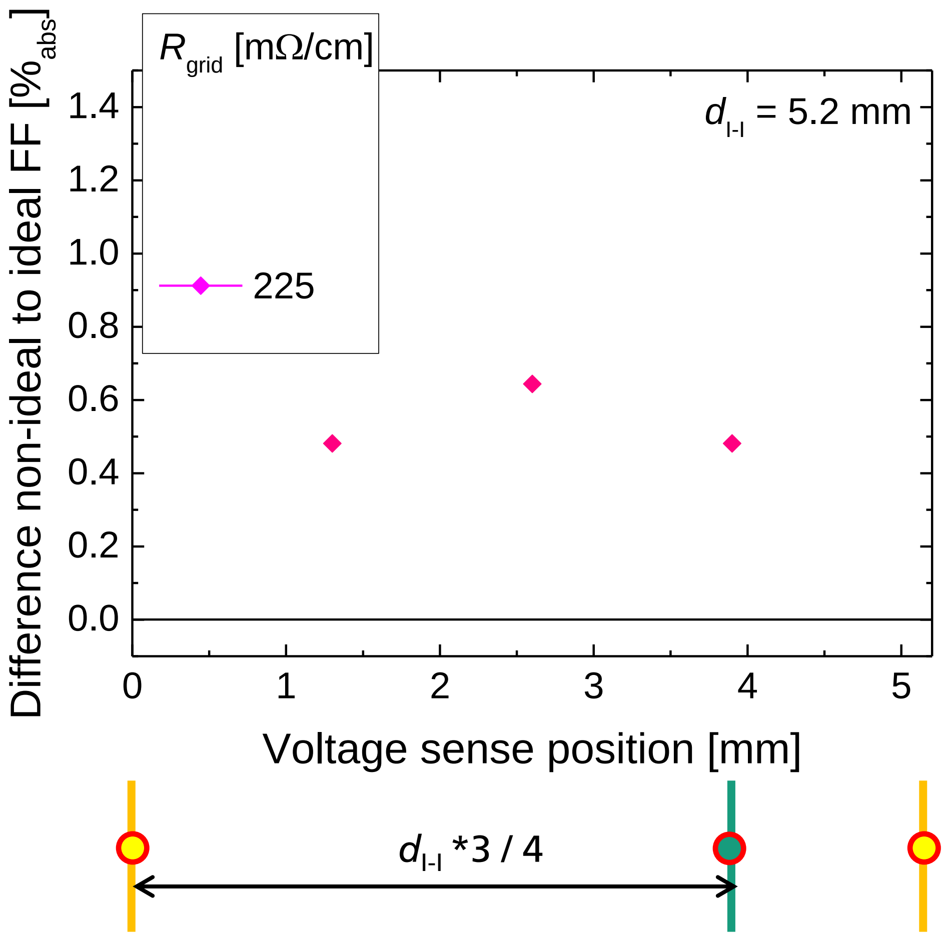

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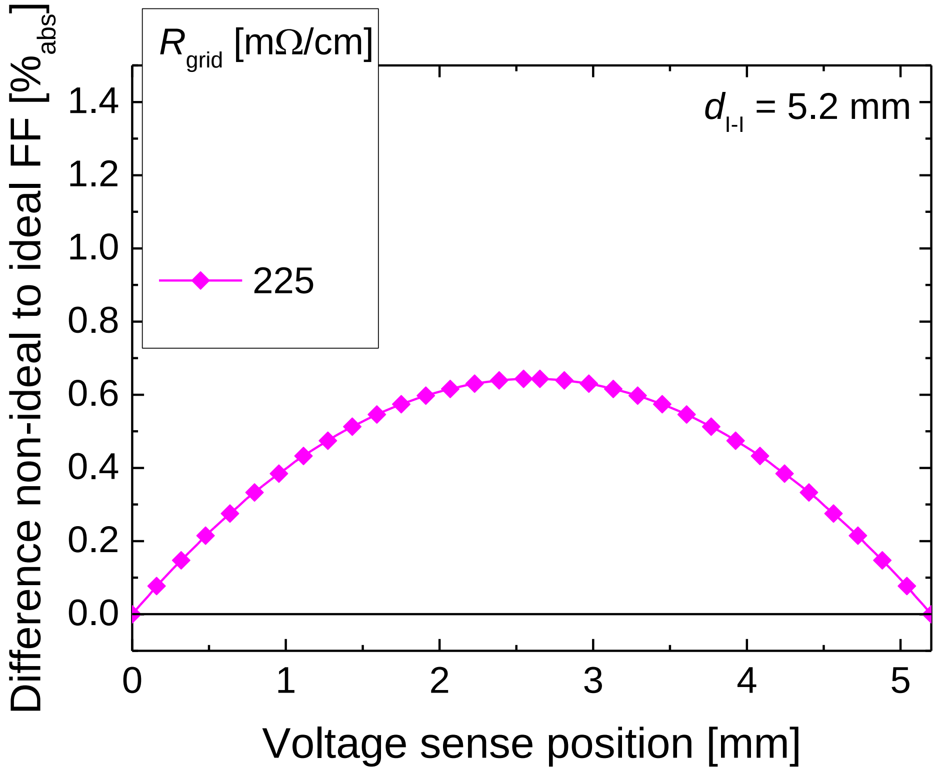
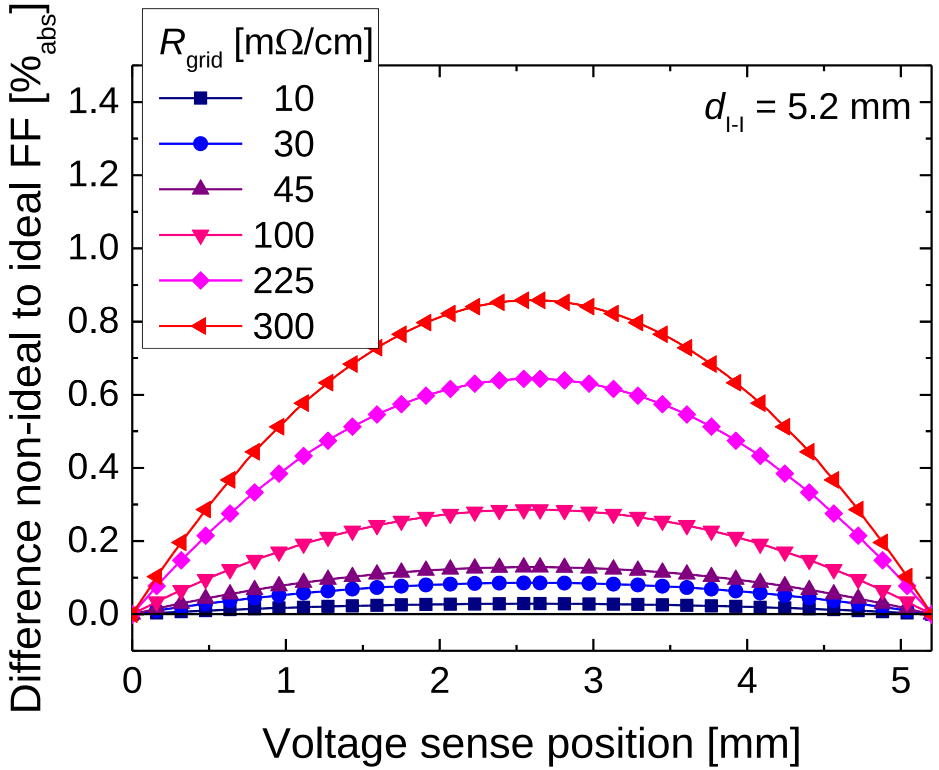


Theoretical Investigation of Non-Ideal Sensing
Approaches for Improving Contacting Unit

(1) Approaching voltage to current wire

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



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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
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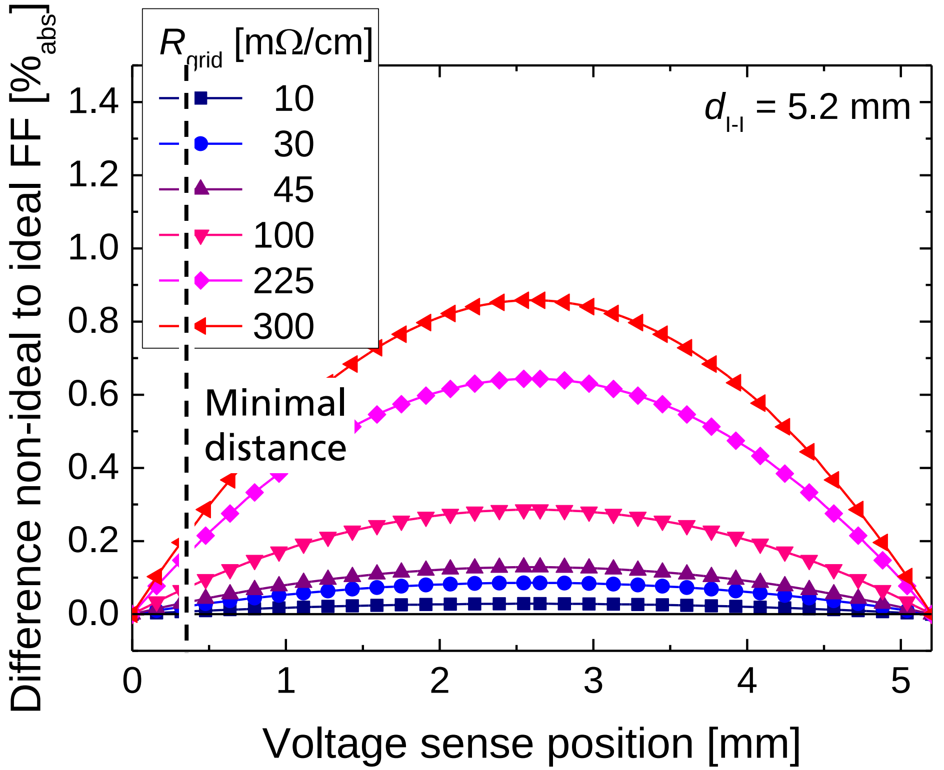
Improvement of measurement unit

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

→ **Approach not effective**



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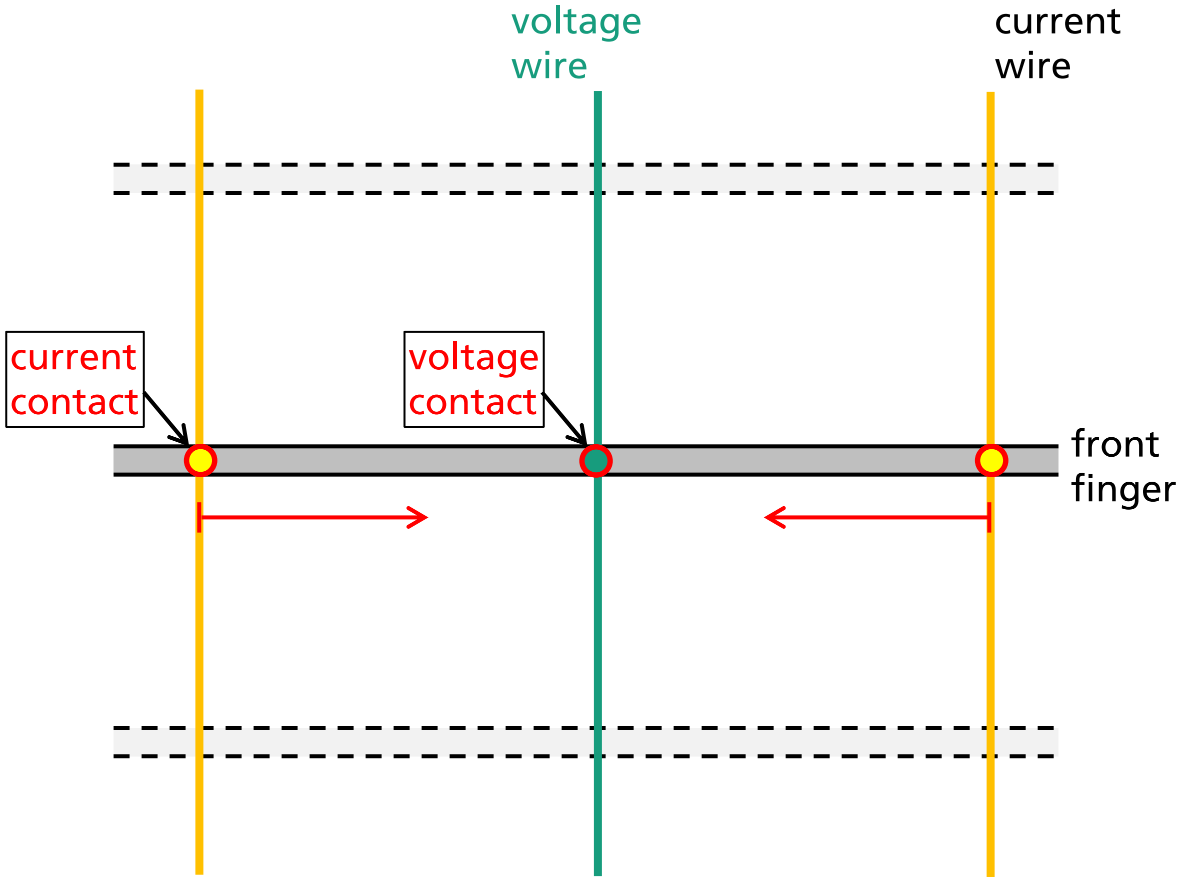
Theoretical Investigation of Non-Ideal Sensing
Approaches for Improving Contacting Unit

(2) Approaching of current wires

- Calculation of difference ΔFF between ideal and non-ideal voltage sensing



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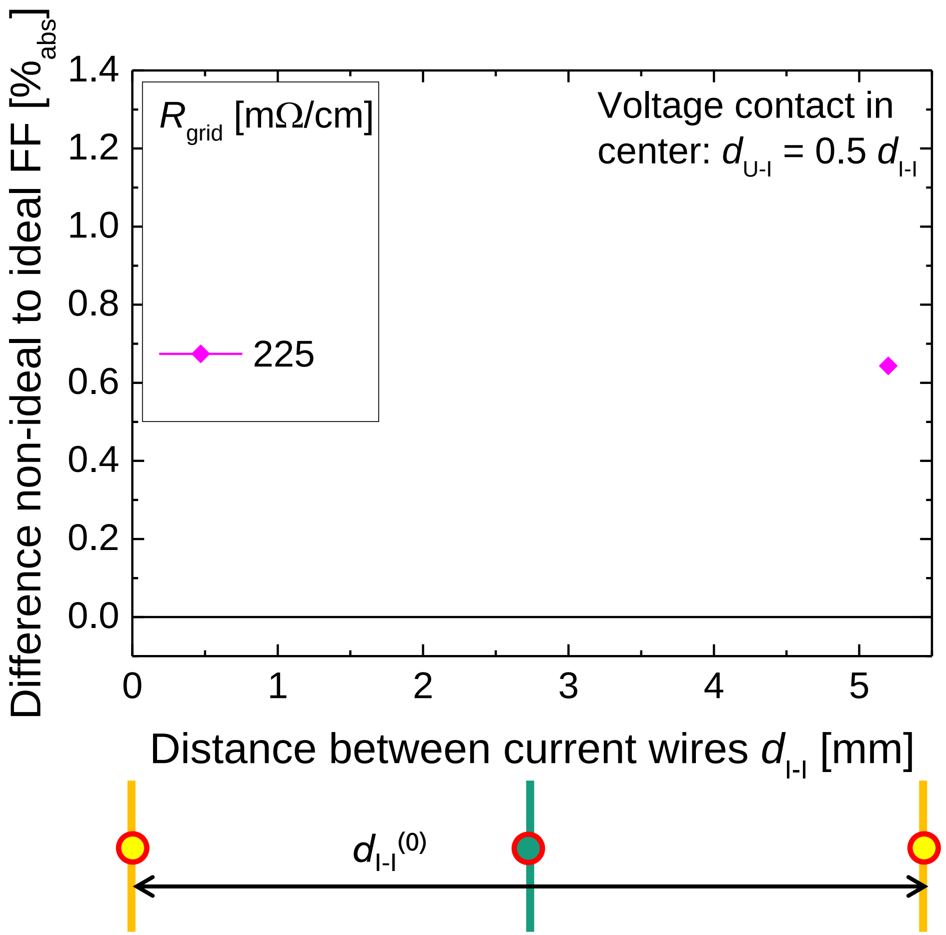
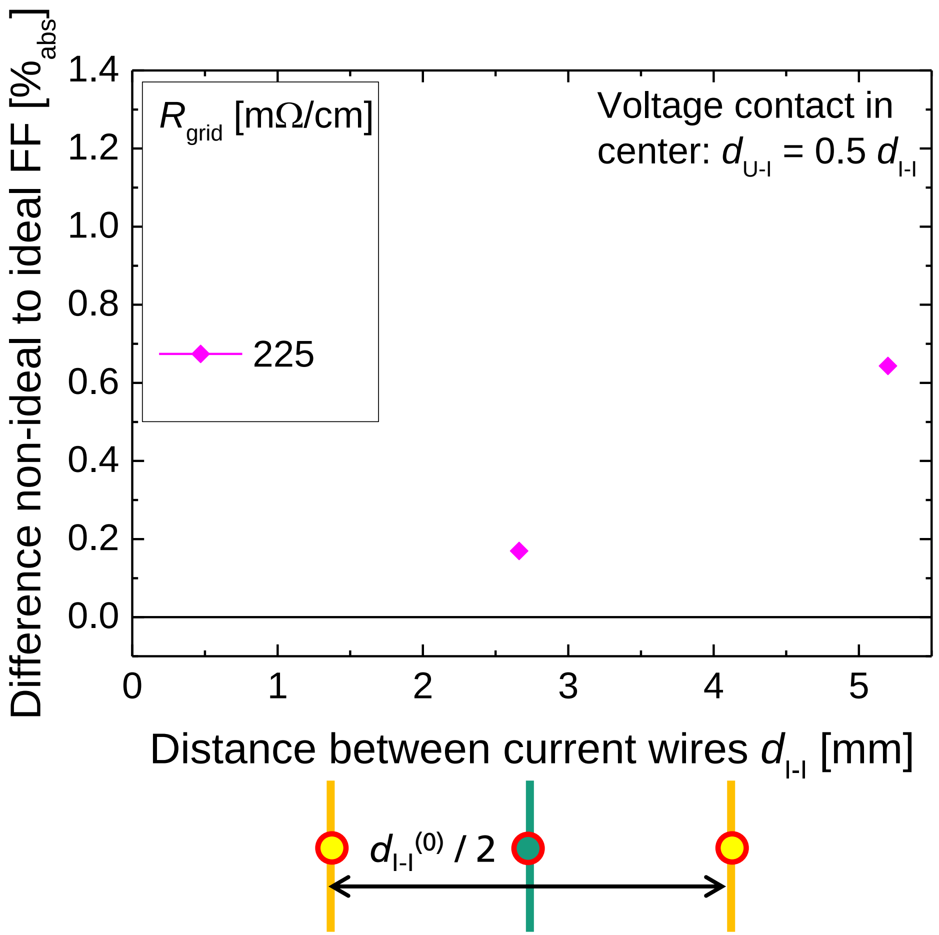


Theoretical Investigation of Non-Ideal Sensing
Approaches for Improving Contacting Unit

(2) Approaching of current wires

- ΔFF decreases strongly with distance between current wires



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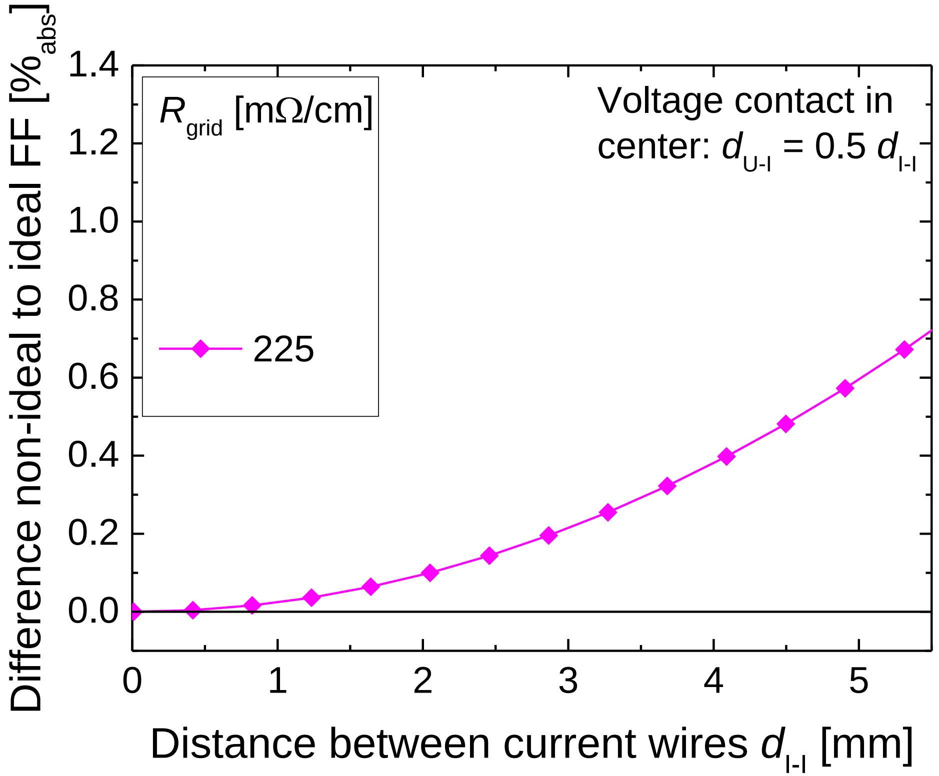

Theoretical Investigation of Non-Ideal Sensing

Approaches for Improving Contacting Unit

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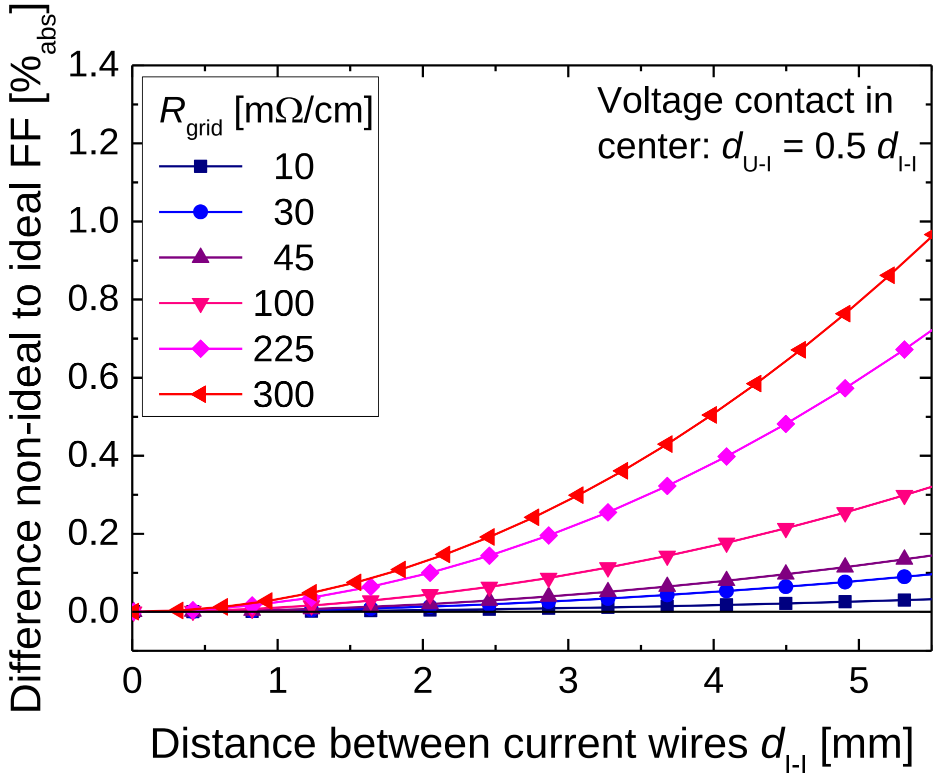

Theoretical Investigation of Non-Ideal Sensing

Approaches for Improving Contacting Unit

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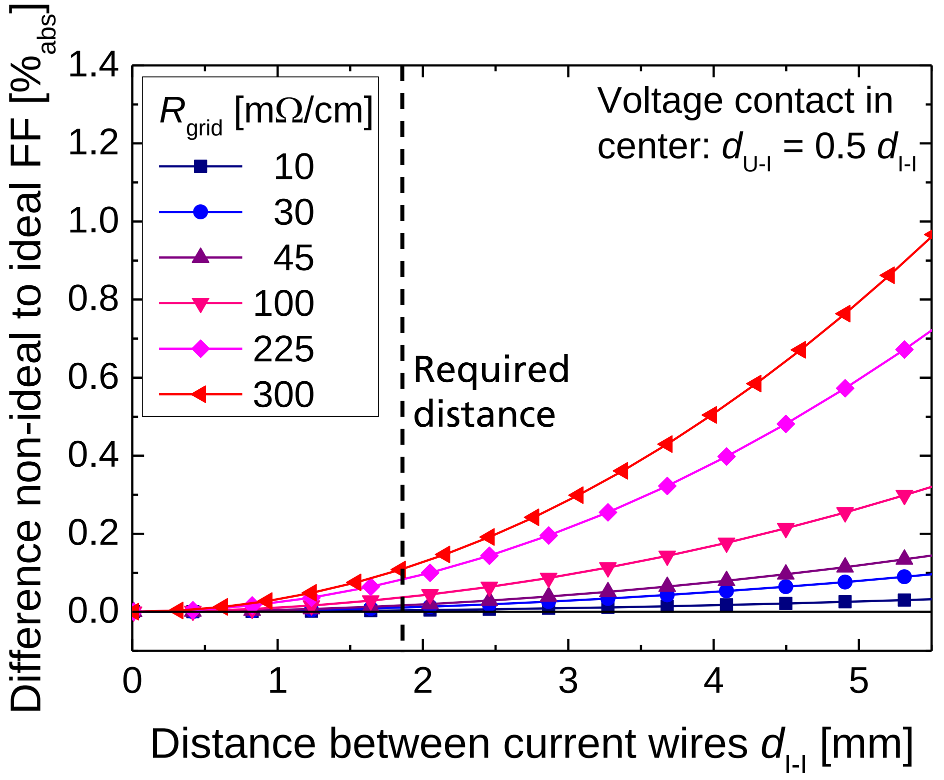


Improvement of measurement unit

- Already small reduction of distance with significant effect
- ΔFF < $0.1\%_{rel}$ for moderate distance of 2 mm

➞ **Approach promising, but implies asymmetric arrangement of *I* wires**

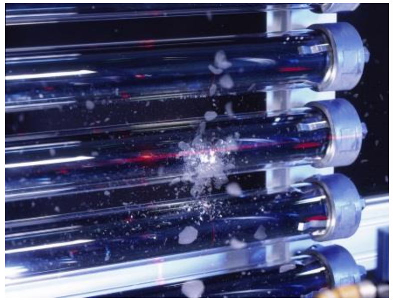
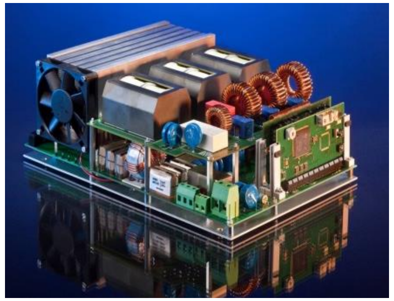
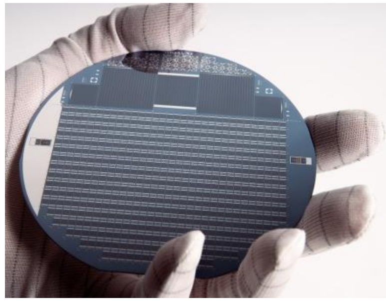
Summary

- 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 η 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!

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