Bifacial Solar Cells under Single- and Double-Sided Illumination: Effect of Non-Linearity in Short-Circuit Current

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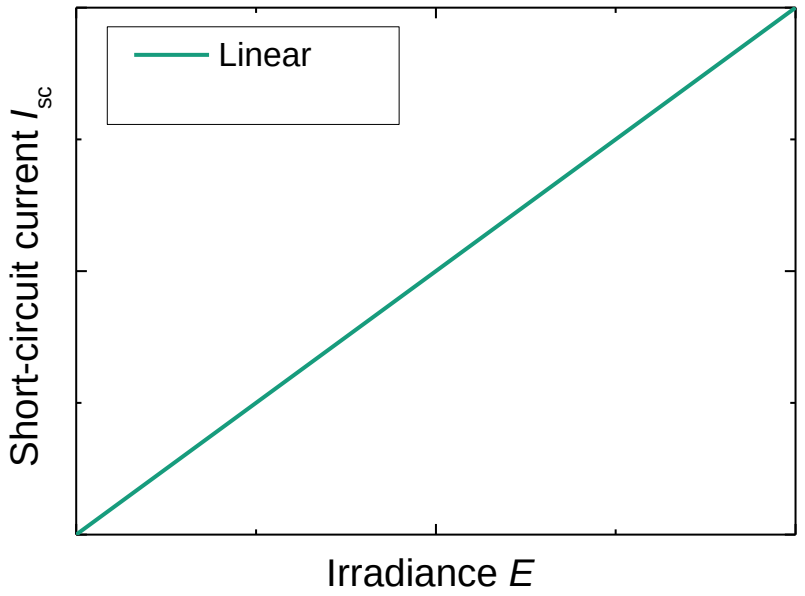
Linearity and Non-Linearity in Short-Circuit Current
Motivation

Linearity of short-circuit current with respect to irradiance:

$$I_{sc}(E) = \text{const} \cdot E$$



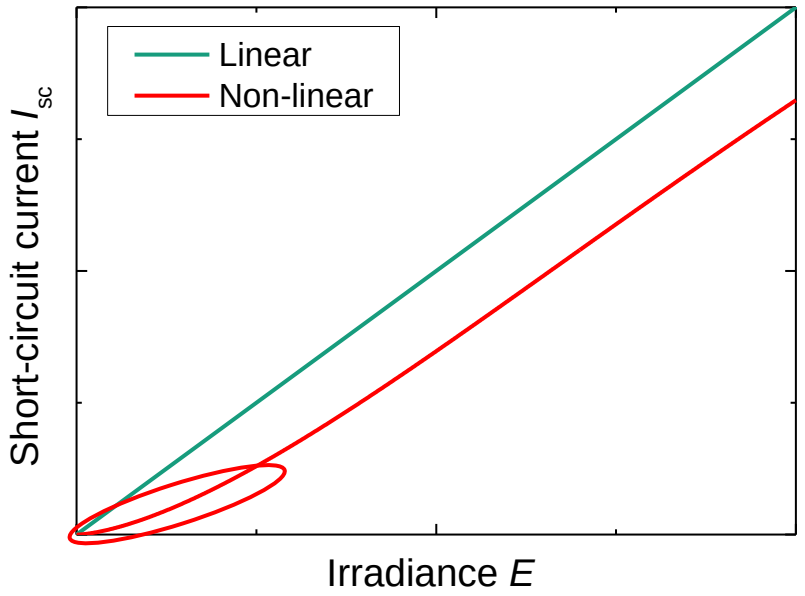
Linearity and Non-Linearity in Short-Circuit Current
Motivation

Linearity of short-circuit current with respect to irradiance:

$$I_{sc}(E) = \text{const} \cdot E$$

Non-linearity of short-circuit current with respect to irradiance:

$$I_{sc}(E) \neq \text{const} \cdot E$$



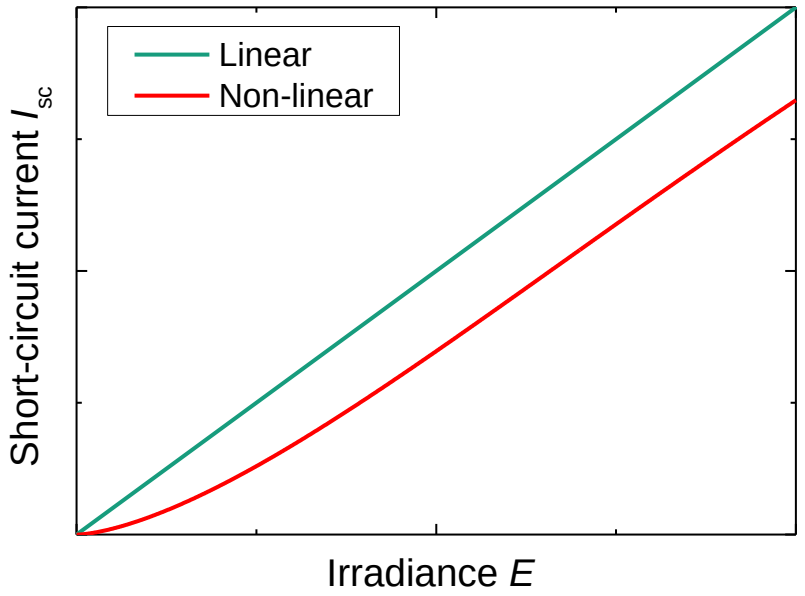
Weak low-light performance

Linearity and Non-Linearity in Short-Circuit Current
Motivation

Causes for non-linearity

- Injection-dependent bulk recombination[1]
- Injection-dependent surface recombination[2]
- Inversion layer shunting[3]
- Defects in floating junctions[4]

Why is that important for the measurement of bifacial solar cells?



[1] S. Winter, Dissertation, University of Brunswick (2003).
[2] S. Glunz et al., J. Appl. Phys. 86, 683 (1999).
[3] S. Dauwe et al., Prog. Photovolt: Res. Appl. 2002; 10:271.
[4] F. Granek et al, phys. stat. sol. (RRL), 2.4 (2008): 151.

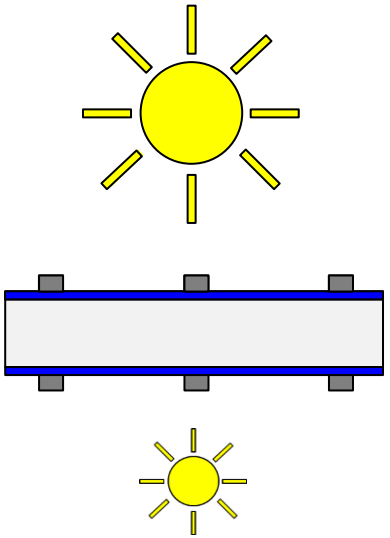
Measurement of Bifacial Solar Devices
Single- and Double-Sided Illumination

Two different approaches for indoor measurements[1,2]

- **Both-sided illumination** (*Bifacial method*)**:**

  Front irradiance: $E_{front} = 1000\ Wm^{-2}$

  Rear irradiance: $E_{rear} = 0 \ldots 400\ Wm^{-2}$



[1] Draft IEC standard 60904-1-2.
[2] V. Fakhfouri et al., 3rd bifi PV workshop, Miyazaki, Japan, (2016).

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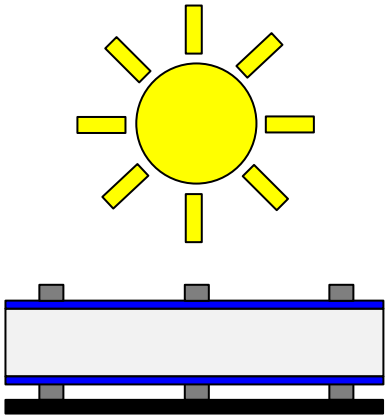

- **Single-sided illumination** (G_E *method*)**:**

  Front irradiance: $E_{\text{E}} = 1000\ \text{Wm}^{-2} + \frac{I_{\text{sc,rear}}}{I_{\text{sc,front}}} \cdot 0 \ldots 400\ \text{Wm}^{-2}$

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Measurement of Bifacial Solar Devices
Single- and Double-Sided Illumination

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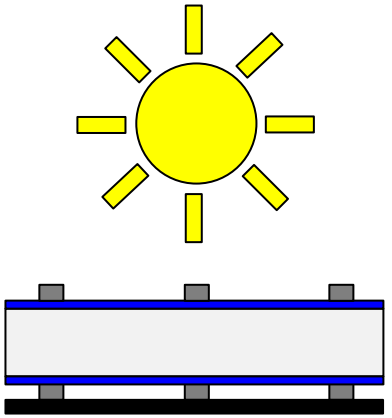

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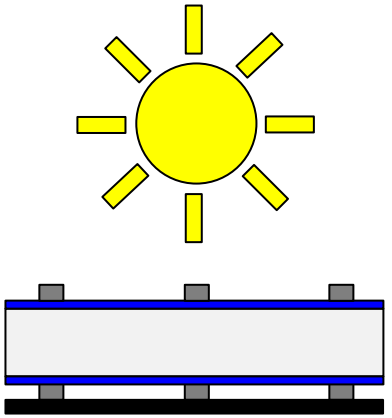
Linear solar cells:

$$I_{\text{sc,front}}(E_{\text{front}}) + I_{\text{sc,rear}}(E_{\text{rear}}) = I_{\text{sc,front}}(E_{\text{E}})$$

Measurement of Bifacial Solar Devices
Single- and Double-Sided Illumination

Two different approaches for indoor measurements



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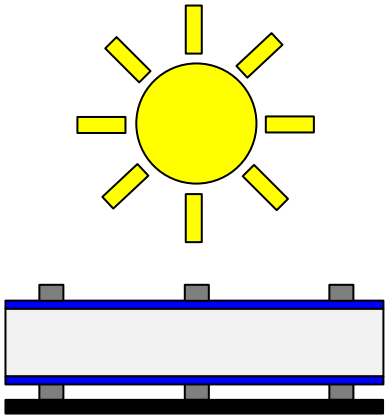
Linear solar cells:

$$I_{\text{sc,front}}(E_{\text{front}}) + I_{\text{sc,rear}}(E_{\text{rear}}) = I_{\text{sc,front}}(E_{\text{E}}) \quad \longleftarrow \text{Short calculation}$$

Measurement of Bifacial Solar Devices
Single- and Double-Sided Illumination

Two different approaches for indoor measurements



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Non-linear solar cells:

$$I_{\text{sc,front}}(E_{\text{front}}) + I_{\text{sc,rear}}(E_{\text{rear}}) = I_{\text{sc,front}}(E_{\text{E}}) + \text{Correction}(E_{\text{rear}})$$

Measurement of Bifacial Solar Devices
Single- and Double-Sided Illumination

Two different approaches for indoor measurements

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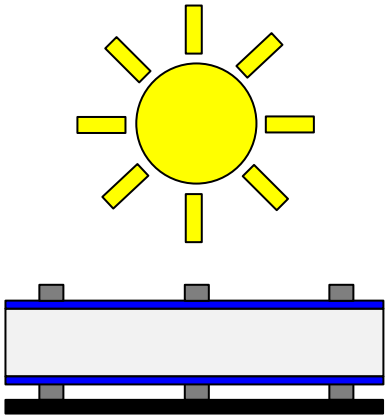

- **Single-sided illumination** (G_E *method*)**:**

  Front irradiance: $E_E = 1000\ \mathrm{Wm^{-2}} + \frac{I_{sc,rear}}{I_{sc,front}} \cdot 0 \ldots 400\ \mathrm{Wm^{-2}}$

→ Non-linearity leads to differences in I_{sc} between G_E method and bifacial method!

Measurement of Bifacial Solar Devices
Single- and Double-Sided Illumination

Two different approaches for indoor measurements

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  Front irradiance: $E_{front} = 1000\ \mathrm{Wm^{-2}}$

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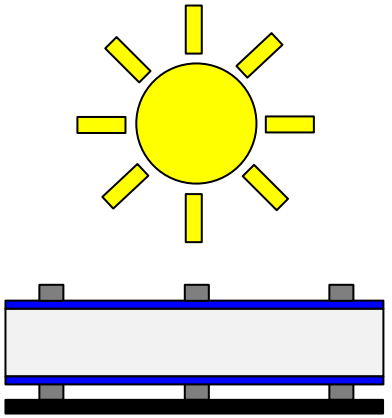

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  Front irradiance: $E_E = 1000\ \mathrm{Wm^{-2}} + \frac{I_{sc,rear}}{I_{sc,front}} \cdot 0 \ldots 400\ \mathrm{Wm^{-2}}$

How large are the differences between the measurement approaches?

Which bifacial solar cells can show non-linear characteristics?

Measurement of Bifacial Solar Devices
Single- and Double-Sided Illumination

Two different approaches for indoor measurements

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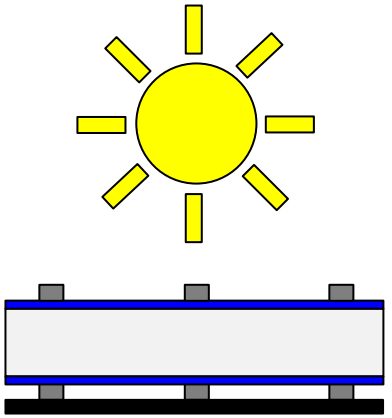

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→ **This work:** Investigation using *differential* spectral response (DSR) technique

Measurement of Bifacial Solar Devices
Single- and Double-Sided Illumination

Two different approaches for indoor measurements

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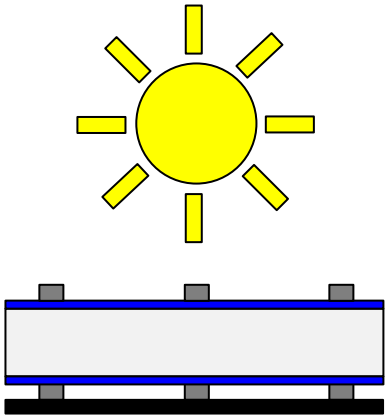

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→ **Goal:** Quantification of difference between G_E method and bifacial method

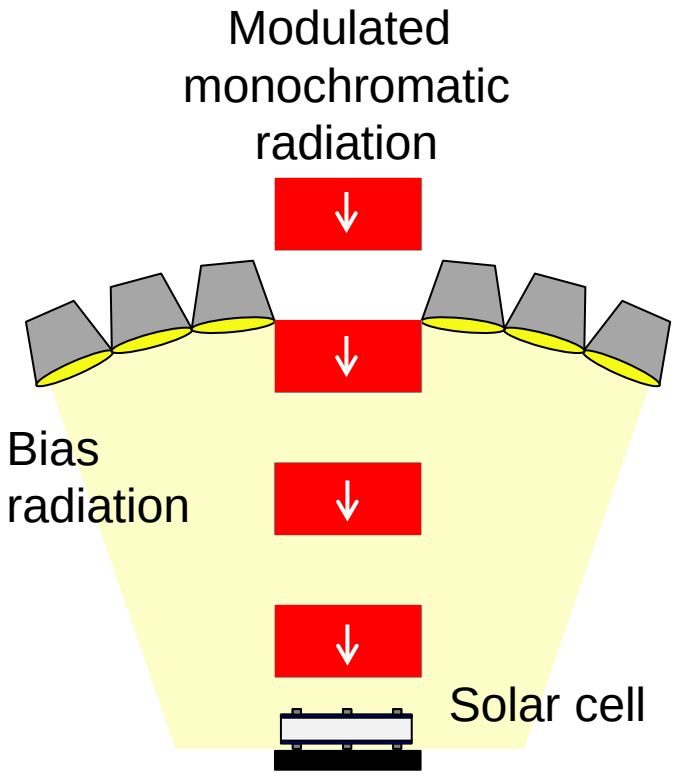
Differential Spectral Response Measurement of Linearity

Measurement Technique

Differential spectral response (DSR) technique[1]:

- Steady-state bias illumination with irradiance E_{bias}
- Feed-in of additional modulated monochromatic irradiance ΔE_{λ}

→ Determination of differential external quantum efficiency (EQE) for bias irradiance E_{bias}



[1] J. Metzdorf, Applied Optics 26.9 (1987): 1701.

Differential Spectral Response Measurement of Linearity

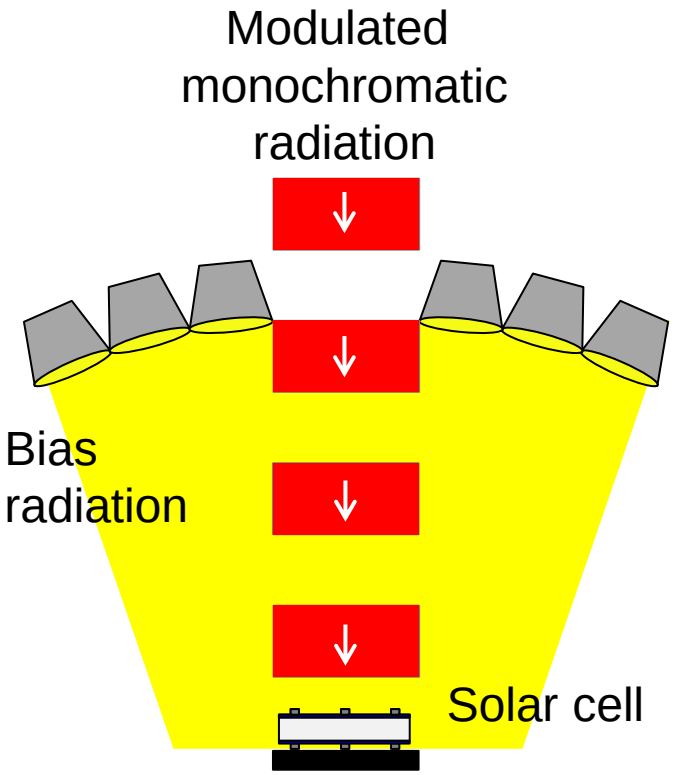
Measurement Technique

Differential spectral response (DSR) technique[1]:

- Variation of bias irradiance
- Measurement of differential EQE at different bias irradiances

→ Based on measurement of slope in I_{sc}: Slope particularly affected by non-linearity

→ DSR technique highly sensitive to non-linearity



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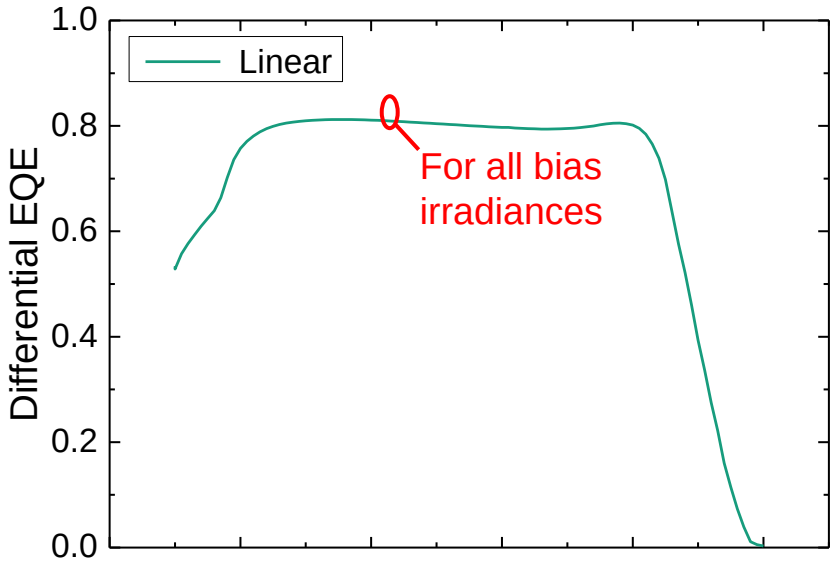
Differential Spectral Response Measurement of Linearity

Measurement Technique

Differential spectral response (DSR) technique:

Linear solar cells:

- Differential EQE without bias dependency



Differential Spectral Response Measurement of Linearity

Measurement Technique

Differential spectral response (DSR) technique:

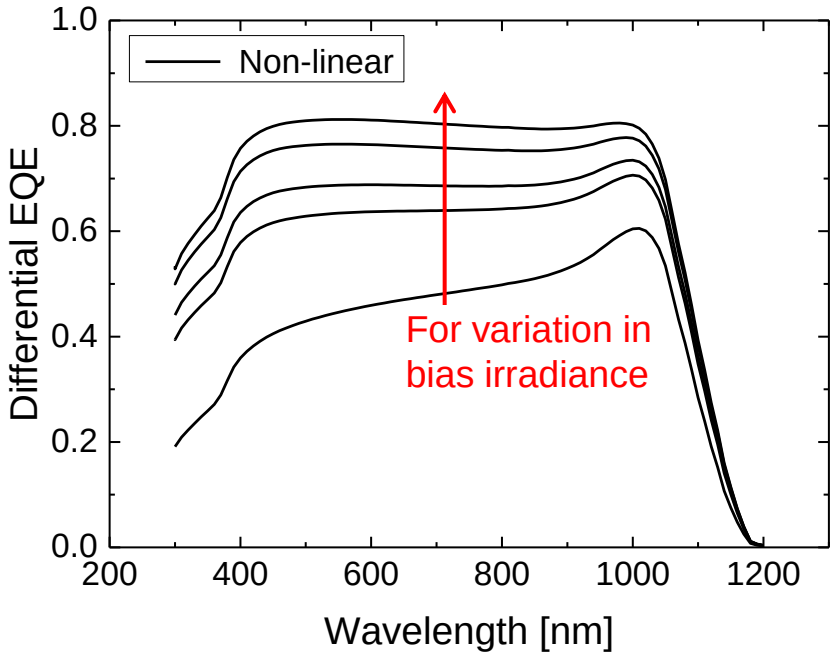
Linear solar cells:

- Differential EQE without bias dependency

Non-linear solar cells:

- Differential EQE depends on bias irradiance

→ Precise identification of non-linearity by evaluation of differential EQEs

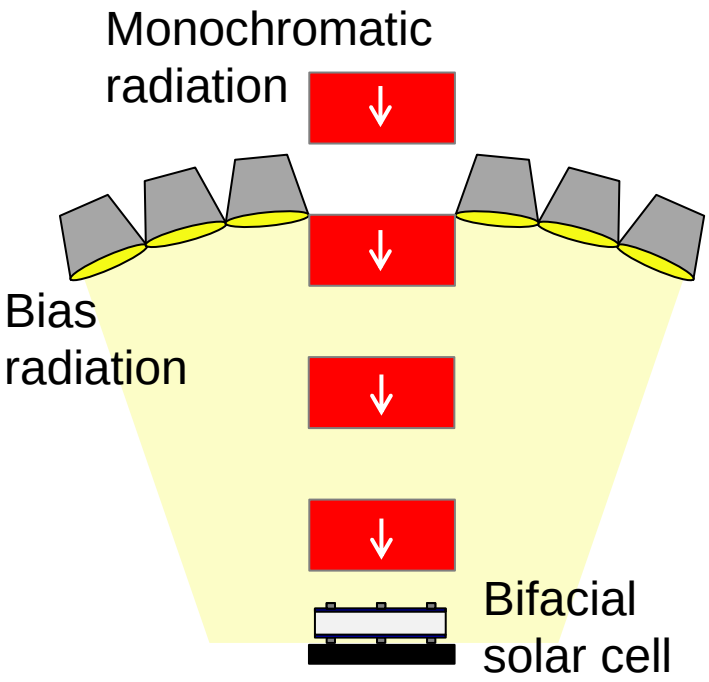


Differential Spectral Response Measurement of Linearity

Experimental

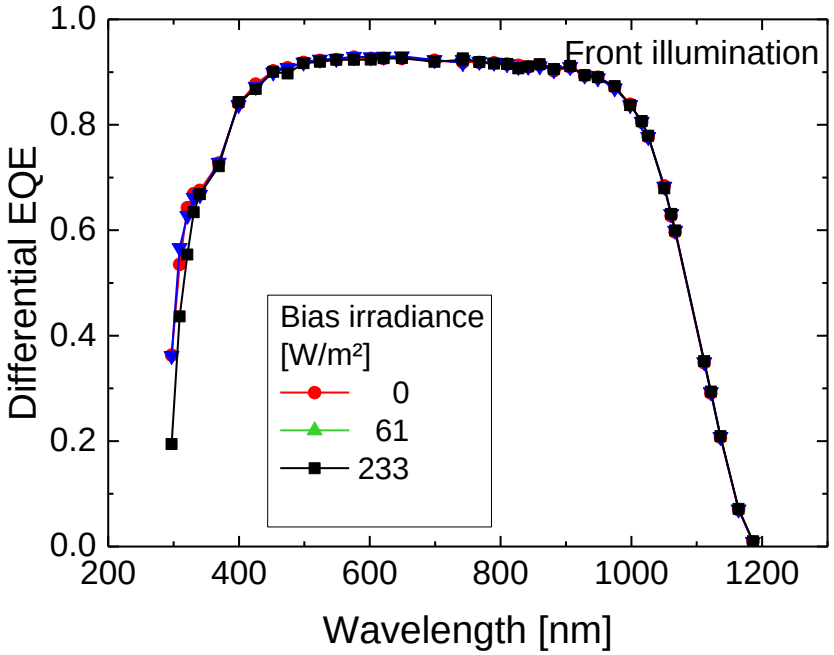
DSR measurements of differential external quantum efficiency (EQE):

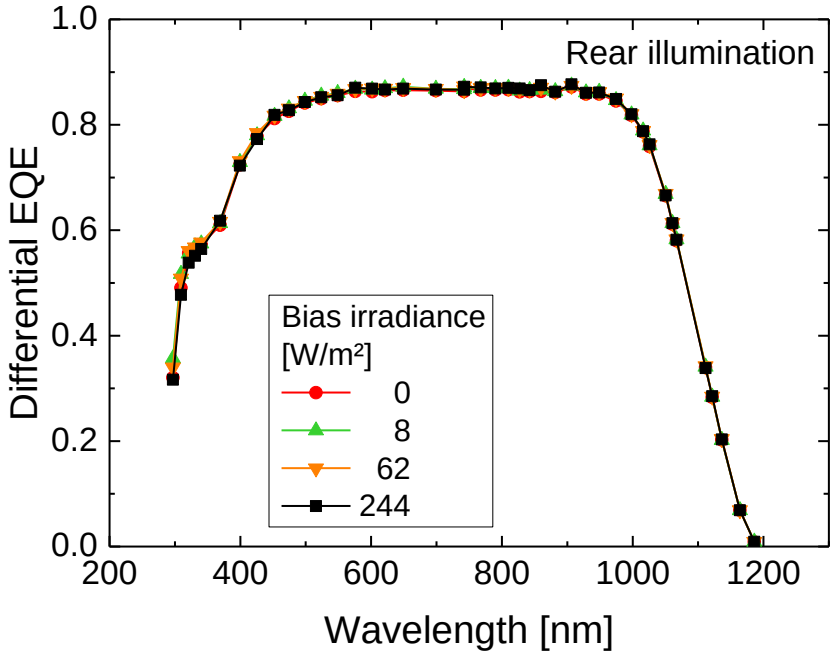
- Exemplary bifacial solar cells:
  - nPERT
  - HIT
  - Bifacial PERC
- Non-reflective chuck
- Different bias radiation intensities
- Front and rear measurements



Differential Spectral Response Measurement of Linearity

Results



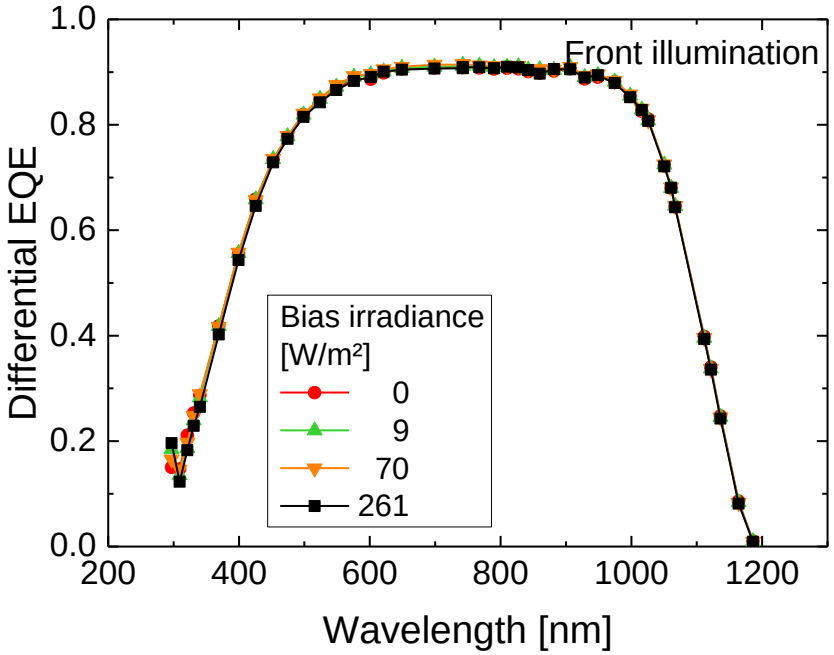


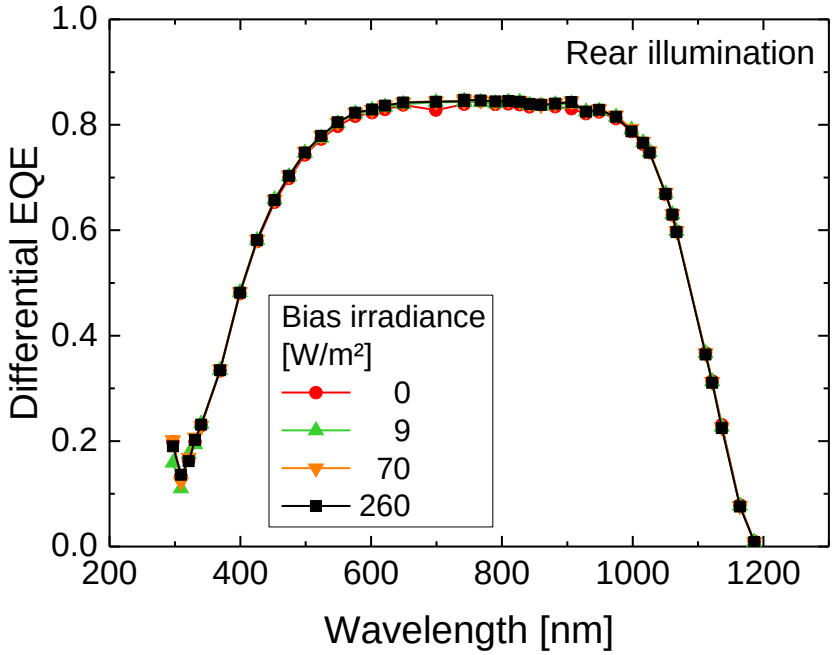
nPERT solar cell:

- No major bias dependency
- Solar cell linear in short-circuit current

Differential Spectral Response Measurement of Linearity

Results



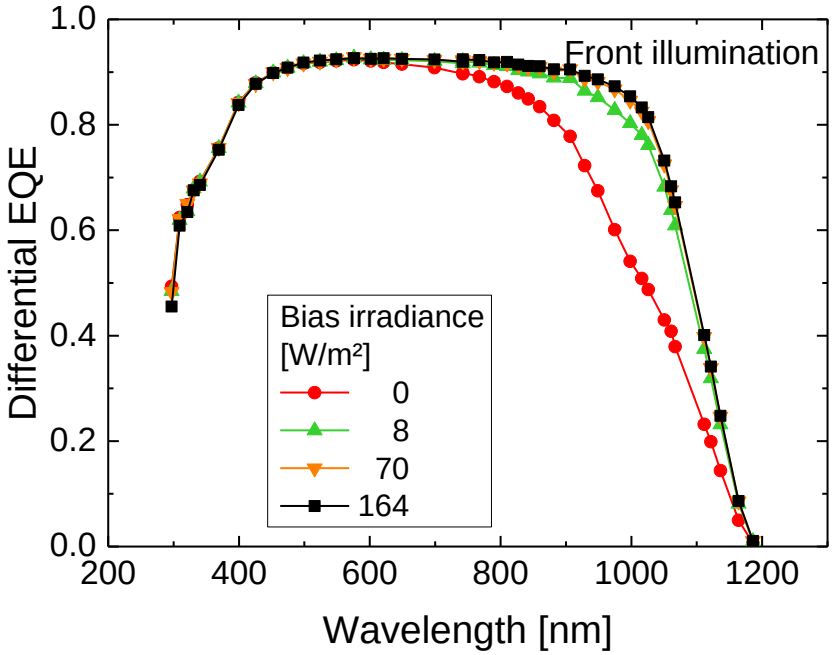


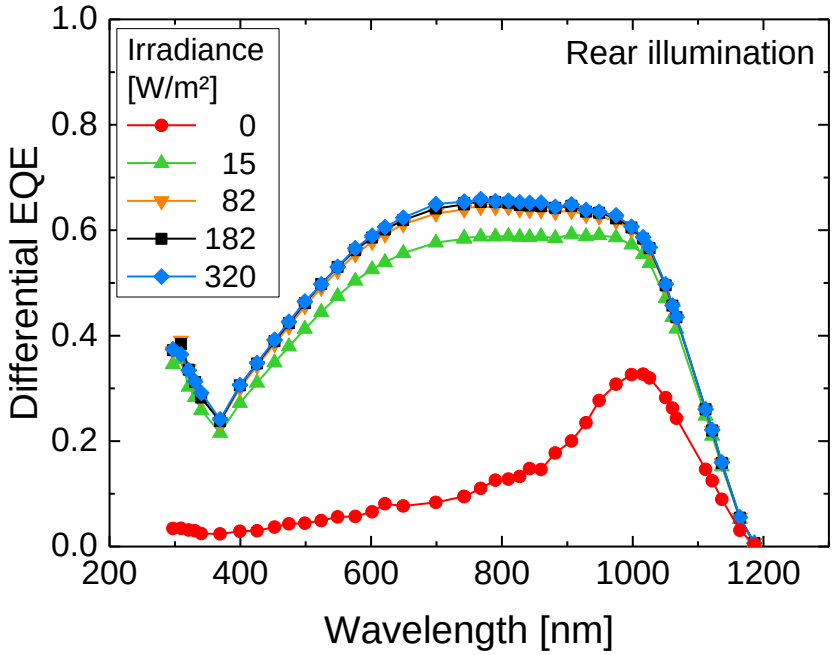
HIT solar cell:

- No major bias dependency
- Solar cell linear in short-circuit current

Differential Spectral Response Measurement of Linearity

Results



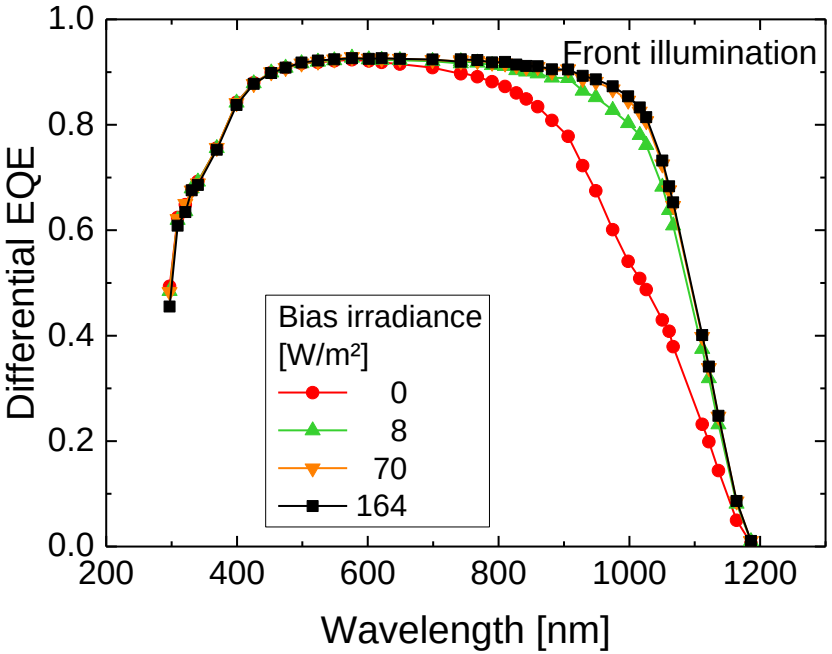


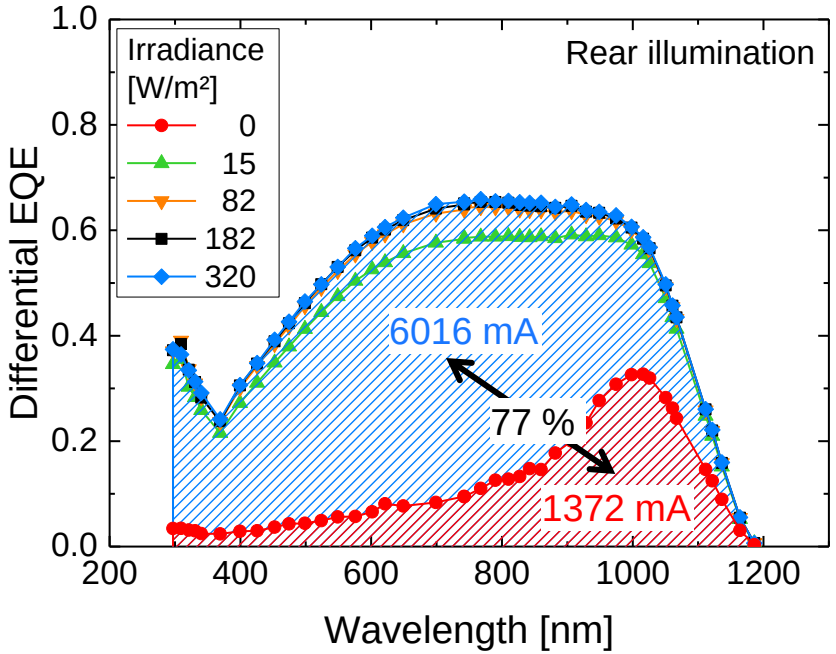
Bifacial PERC solar cell:

- Significant bias dependency

Differential Spectral Response Measurement of Linearity

Results





Bifacial PERC solar cell:

- Significant bias dependency

→ Effect on G_E and bifacial method? Investigation by PC1D simulations

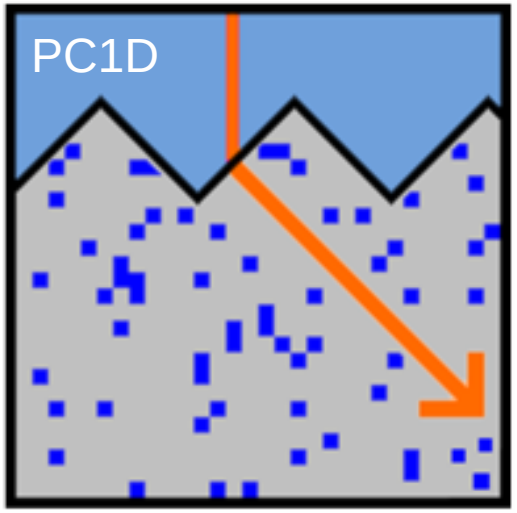
Non-Linearity of Bifacial PERC Solar Cells

Simulation of Non-Linear Characteristics

Bifacial PERC solar cell:

- Setting up simple solar cell model by PC1D simulations [1,2]
- Consideration of non-linearity by inversion layer shunting and defects in floating junction [3]

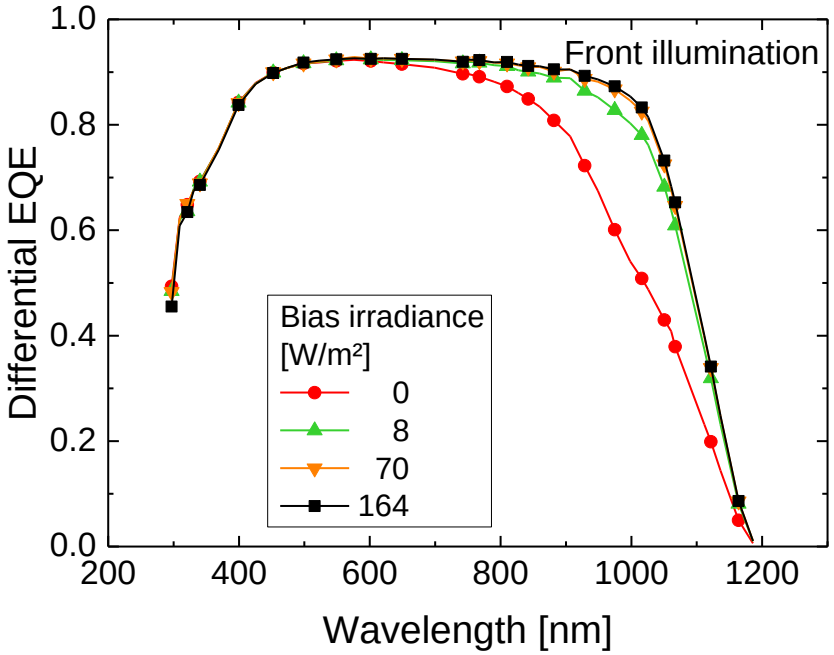
→ Simulation of differential EQE for different bias radiation intensities

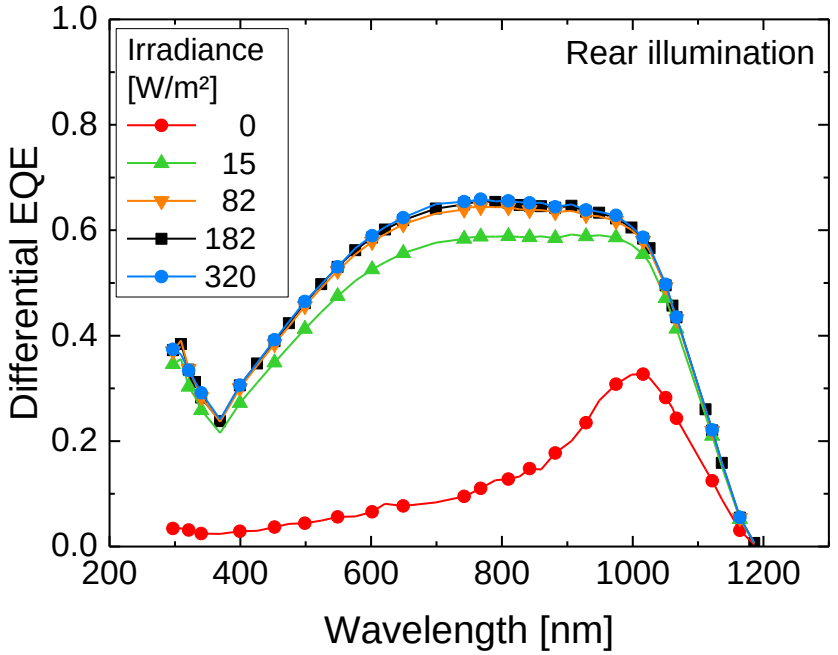


[1] D.A. Clugston et al., Proc. 26th IEEE PVSC, Anaheim, USA, (1997), 207.
[2] H. Haug, J. Greulich, Energy Procedia 92 (2016): 60.
[3] F. Granek et al, phys. stat. sol. (RRL), 2.4 (2008): 151.

Non-Linearity of Bifacial PERC Solar Cells

Simulation of Non-Linear Characteristics

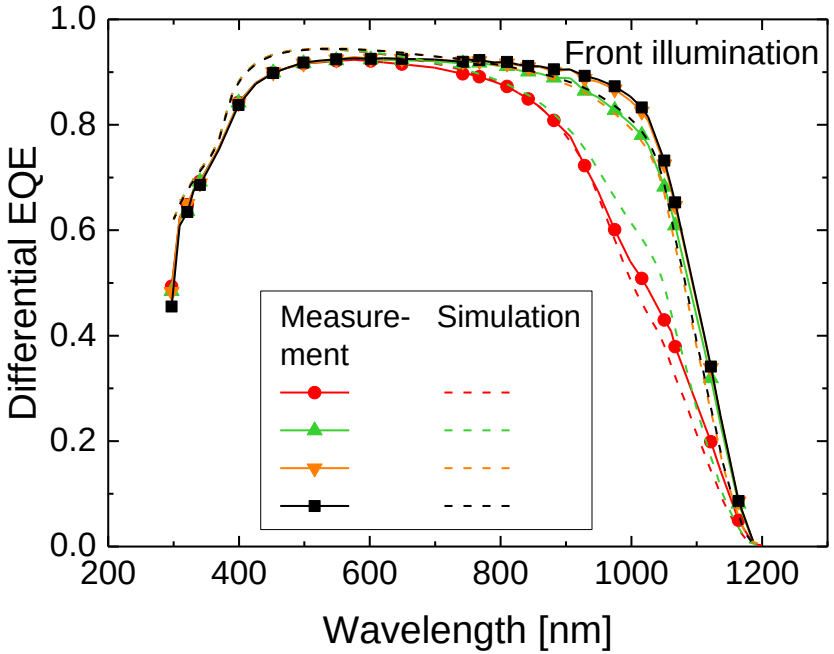


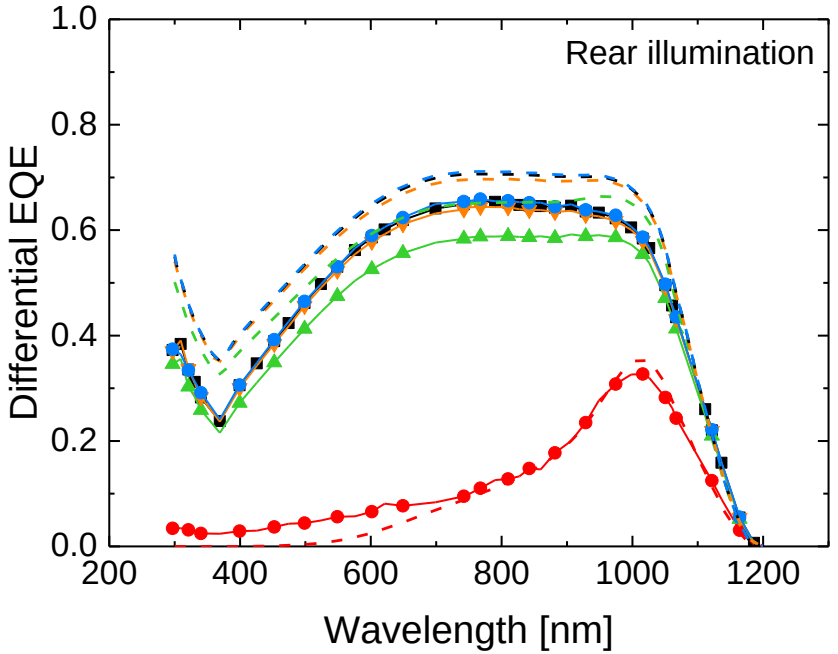


Bifacial PERC solar cell:

Non-Linearity of Bifacial PERC Solar Cells

Simulation of Non-Linear Characteristics





Bifacial PERC solar cell:

- PC1D model serves as worst-case scenario

→ Adequate accordance to measured data

Non-Linearity of Bifacial PERC Solar Cells
Effect on Measurement Approaches

Further PC1D Simulations:

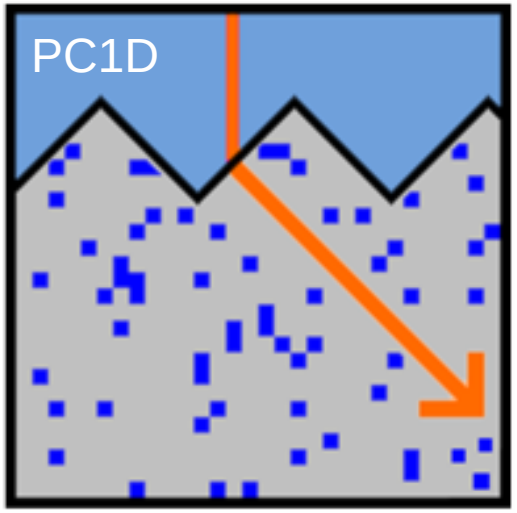
- Short-circuit current with bifacial method:

$$E_{\text{front}} = 1000\ \text{Wm}^{-2}$$

$$E_{\text{rear}} = 0 \ldots 400\ \text{Wm}^{-2}$$

- Short-circuit current with G_E method:

$$E_E = 1000\ \text{Wm}^{-2} + \frac{I_{\text{sc,rear}}}{I_{\text{sc,front}}} \cdot 0 \ldots 400\ \text{Wm}^{-2}$$

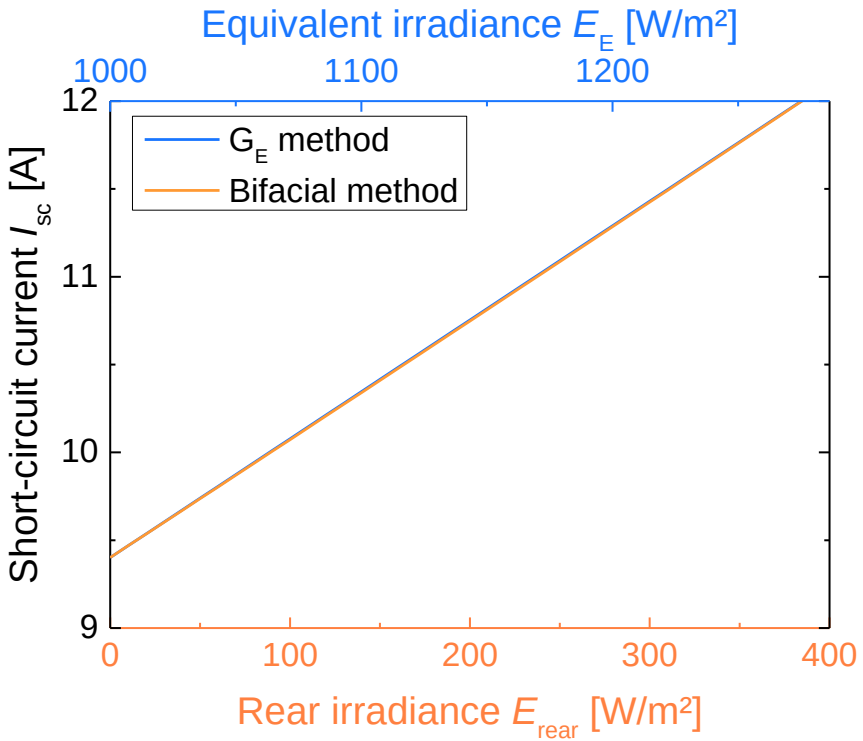


→ Variation of rear irradiance

→ Evaluation of effect of non-linearity on bifacial method and G_E method

Non-Linearity of Bifacial PERC Solar Cells
Effect on Measurement Approaches

- Short-circuit current similar for bifacial method and G_E method

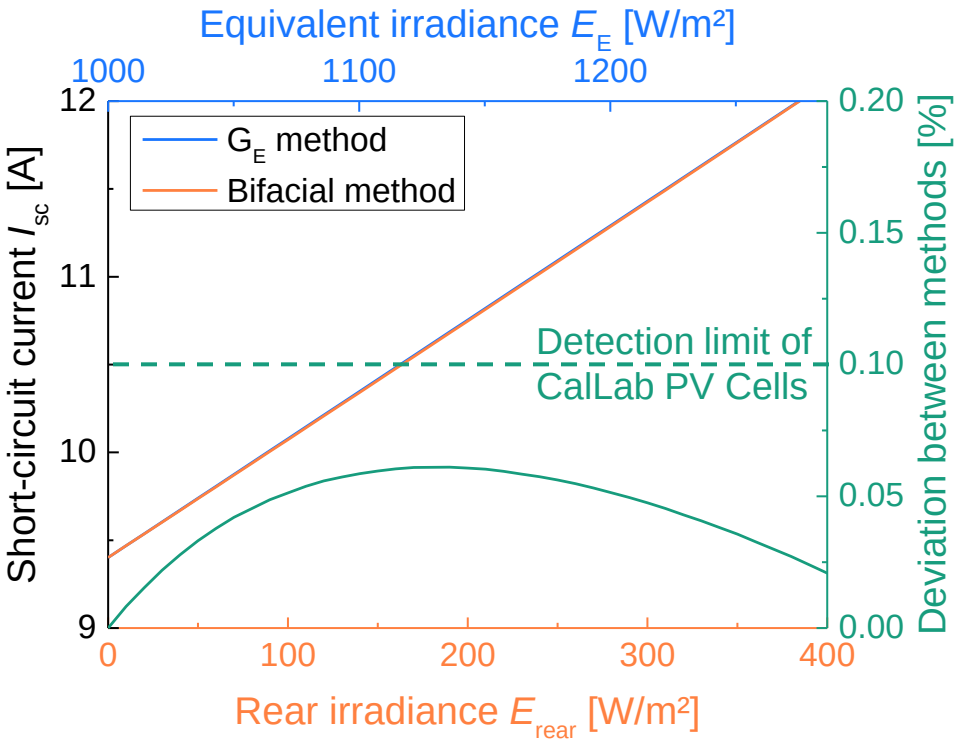


Non-Linearity of Bifacial PERC Solar Cells

Effect on Measurement Approaches

- Short-circuit current similar for bifacial method and G_E method
- Deviation between methods below detection limit of 0.1 % of CalLab PV Cells

→ Non-linearity without significant effect on I_{sc} determination by bifacial method and G_E method



- Exemplary measurements
- Difference between methods on fill factor not negligible [1]

[1] A. Schmid et al., Proc. 32nd EUPVSEC, Munich, Germany, (2016).

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Effect of Non-Linearity in Short-Circuit Current
Summary

- Effect of non-linearity in short-circuit current on bifacial and G_E method
  - Linear bifacial solar cells: Consistent I_{sc} determination
  - Non-linear bifacial solar cells: Consistency has to be evaluated
- Investigation of linearity for three major bifacial solar cell technologies
  - Differential spectral response (DSR) method highly sensitive to non-linearity
  - Significant non-linearity can occur
- Simulation of non-linear bifacial solar cells with PC1D
  - Adequate accordance to measured differential EQEs

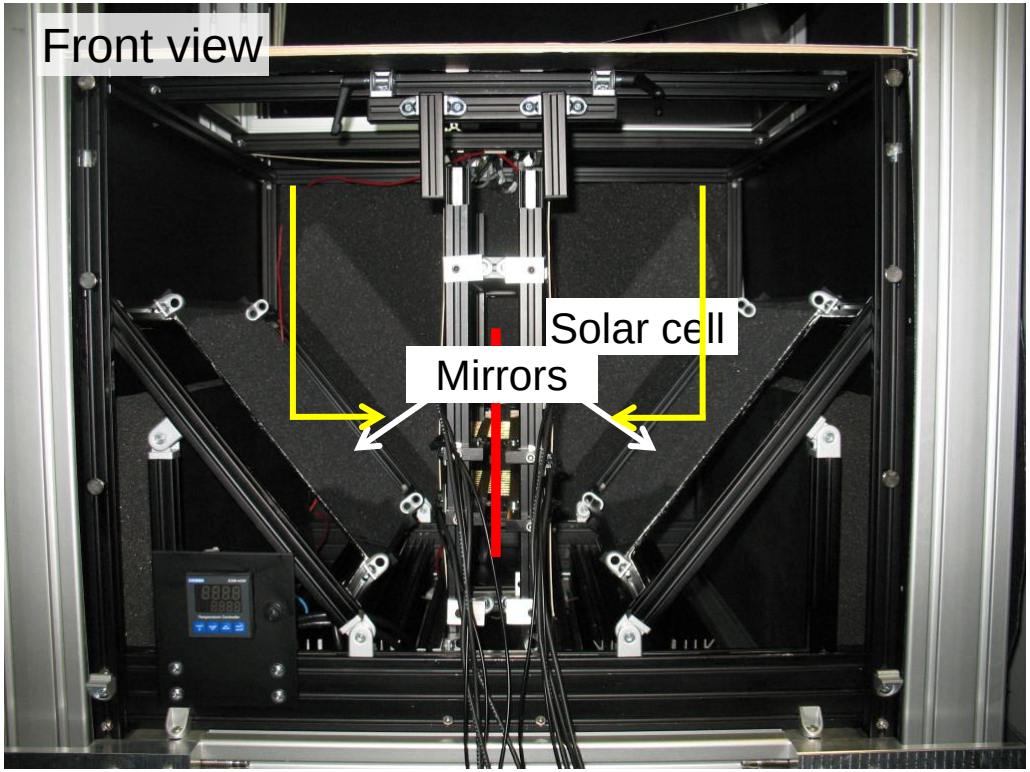
→ Detected non-linearity without significant effect on bifacial and G_E method

Effect of Non-Linearity in Short-Circuit Current
Outlook

- Installation of bifacial setup at CalLab PV Cells
- Illumination of solar cell via two mirrors [1-3]
- Temperature regulation by additional heating unit

→ Precise bifacial IV measurements available soon

→ Experimental validation of simulation results



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Thank you very much for your attention!

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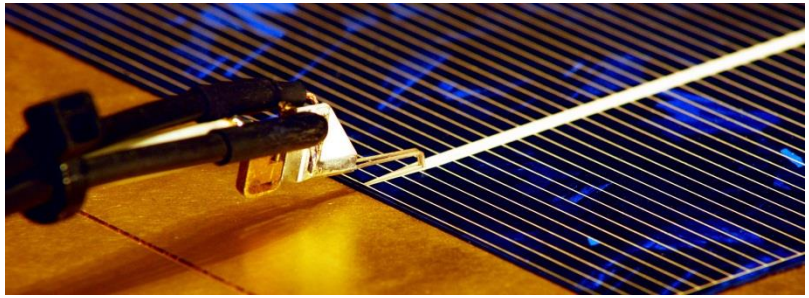

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EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Thank you very much for your attention!

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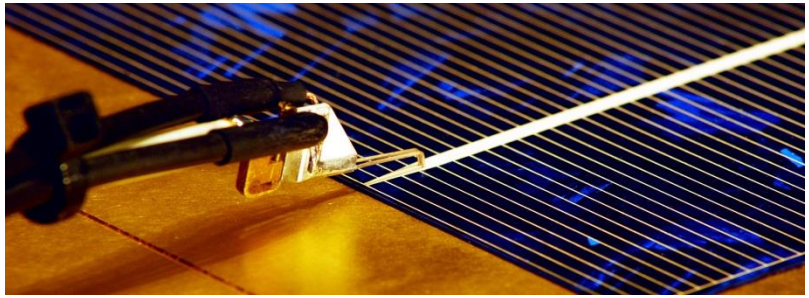

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→ Calibration services for research and industry
→ Measurements of all kinds of solar cells (single/multi junction)
→ Accredited as ISO 17025 DAkkS laboratory